THE BOOK OF SWARM

STORAGE AND COMMUNICATION INFRASTRUCTURE
FOR A SELF-SOVEREIGN DIGITAL SOCIETY

VIKTOR TRÓN

the book of swarm
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the swarm is headed toward us

Satoshi Nakamoto

Contents

LIST OF FIGURES

PROLEGOMENA

Intended audience

The primary aim of this book is to capture the wealth of output of the first phase of the Swarm project. It serves as a compendium for teams and individuals participating in bringing Swarm to life in the forthcoming stages.

The book is intended for technically inclined readers who are interested in incorporating Swarm into their development stack and understanding the motivation and design choices behind the technology. Moreover, we extend an invitation to researchers, academics, and decentralisation experts to review our reasoning and audit the coherence of Swarm's overall design. For core developers and those contributing to the wider ecosystem by building components, tooling, or client implementations, this book offers concrete specifications and insights into the thought process behind them.

Structure of the book

The book comprises two major parts. The Prelude (I) delves into the motivation behind the Swarm project by describing the historical context and laying the foundation for a fair data economy. We then present the Swarm vision.

The second part, Design and Architecture (II), offers a comprehensive and in-depth exploration of the design and architecture of the swarm. This part covers all areas relevant to Swarm's core functionality.

To complement the main content, the book includes valuable resources such as an index, a glossary defining technical terms and acronyms, and an appendix, providing readers with a well-rounded and complete compendium.

How to use the book

The Prelude and Design and Architecture sections have been seamlessly combined to form a cohesive and continuous narrative. For those wishing to jump right into the technology, they can start with the Design and Architecture part, skipping the Prelude.

On the other hand, Swarm client developers can use the book as background reading to gain a comprehensive understanding of the specifications. This approach proves valuable when seeking a wider context or when interested in the justification for the choices made in the development process.

Acknowledgments

Editing

Many have helped me write this book, but a few that took very active roles in making it happen are due credit. Daniel Nickless is the man behind all the diagrams; we enjoyed many hours of my giving birth to impromptu visualisations, and he was happy to redo them several times. Dan is a virtuoso of Illustrator and has also become a LaTeX expert to typeset some nice trees.

I am hugely indebted to Črt Ahlin who, beside managing the book project, has contributed some top-quality text. He also undertook many of the unrewarding, tedious jobs of compiling the indexes and glossaries. Both Črt and Dan (a native speaker of English), as well as Attila Lendvai and recently Noah Maizels, did an amazing job at proofreading and correcting mistakes and typos. The second edition has seen a major upgrade in text quality due to the arduous work of Andrea Robert. In addition to conceptualising and drafting the idea for the book's cover, she worked closely with Anna Csúthy, who brought the design to life with pixel-perfect implementation. Together with Gyuri Barabás, Andrea also oversaw the typesetting and prepared the whole package for the printing press.

Special thanks are due to Edina Lovas, whose support and enthusiasm have always helped push me along.

Authors

Swarm is co-fathered by my revered friend and colleague, the awesome DÁNIEL A. NAGY. Dániel invented the fundamental design of Swarm and should get the credit for quite a few major architectural decisions, innovative ideas, and formal insights presented in this book.

ARON FISHER's contribution to Swarm would be hard to overstate. Most of what Swarm is now started or got worked out in sessions with Aron. He not only contributed ingredients overall, but also co-authored the first few orange papers and, not least, was always at the forefront, presenting and explaining our tech in conferences and meetups.

I thank Dániel and Aron for bearing with me, enduring my sloppy, half-baked ideas, bringing clarity, and always understanding the maths. Without claiming full endorsement or any responsibility for what is written here, I would consider Dániel and Aron as co-authors of this book.

I owe deep gratitude to my partner in crime, GREGOR ŽAVCER, who has been running the project, currently serving as director of the Swarm Foundation. Gregor's honest fascination and unrelenting dedication to the project kept me going through many a low moment in the past. Our shared vision of a decentralised future data economy, ranging from technological innovation to ethical direction, served as the foundation for our collaboration. A substantial portion of this book has been shaped during our night-long brainstorming sessions. Gregor even contributed content to the book.

I would like to thank RINKE HENDRIKSEN and ÁBEL BODÓ, who contributed significant insight and innovation, mainly in the area of incentivisation. Further major contributions to both underlying concepts and their presentation came from FABIO BARONE, RALPH PILCHER on incentives, JAVIER PELETIER on feeds, and LOUIS HOLBROOK on feeds and pss. Last but not least, our resident genius VIKTOR TOTH, aka NUGAON, continues to amaze me with his creativity and ambition.

Feedback

The book benefited immensely from feedback. Those who went through the pain of reading early versions and provided comments on the work in progress, offering their criticism or pointing out areas of unclarity, deserve to be mentioned: HENNING DIETRICH, BRENDAN GRAETZ, ATTILA LENDVAI, people from IOV labs: MARCELO ORTELLI, SANTIAGO REGUSCI, VOJTĚCH ŠIMETKA; and people from the Swarm team: ÁBEL BODÓ, ELAD NACHMIAS, JANOŠ GULJAŠ, PETAR RADOVIĆ, LOUIS HOLBROOK, and ZAHOOR MOHAMED.

Conception and influences

The book of Swarm is itself an expression of the grand idea behind Swarm: [the pursuit of] the vision of a decentralised storage and messaging system built on top of the blockchain. The concept and initial formulation of Swarm as one of the pillars of a holy trinity to realise the Decentralised Web appeared before the launch of Ethereum in early 2015. It was by Ethereum founders VITALIK BUTERIN, GAVIN WOOD, and JEFFREY WILCKE that Swarm was trolled onto the slippery slope of bee jokes and geek humor. The protocol tags *bzz* and *shh* were both coined by Vitalik.

People who were close to the cradle of Swarm include ALEX LEVERINGTON and FELIX LANGE. Early discussions with them catalysed fundamental decisions that led to the design of Swarm as it now presents.

The foundations of Swarm were laid over the course of 2015. Dániel worked with ZSOLT FELFÖLDI, of light client fame, whose code is still being seen here and there in the Go Ethereum-based Swarm implementation. His ideas clearly have a hallmark on what Swarm set out to be.

We are hugely indebted to ELAD VERBIN, who for years has been acting as a scientific as well as strategic advisor to Swarm. Elad put considerable effort into the project, and his unparalleled insight and depth of understanding across all aspects of Swarm have been invaluable. Particularly, his understanding of the isomorphism between pointer-based functional data structures and content-addressed distributed data had a major impact on how we handle higher-level functionality. Our work on a swarm interpreter inspired the Swarm script.

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Early in the project, we spent quite some time with ALEX VAN DER SANDE and FABIAN VOGELSTELLER, engaging in discussions about Swarm and its potentials. Many ideas that came to life as a result, including manifests and the HTTP API, owe them credit. People in or around the Ethereum Foundation who shaped the idea of Swarm include TAYLOR GERRING, CHRISTIAN REITWIESSNER, STEPHAN TUAL, ALEX BEREGSZASZI, PIPER MERRIAM, and NICK SAVERS.

Team

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has been a keen follower and supporter of our project for many years. Gradually, he became an honorary member of the team, and played a pivotal role in implementing the initial version of the entire smart contract suite for swap, swear, and swindle. Additionally, he drove the development of blockchain interaction, bandwidth incentives, and key management.

Major kudos to Janoš Guljaš, who bravely took over the role of engineering lead and created a new killer team in Belgrade with the excellent Petar Radović, Svetomir Smiljković, and Ivan Vandot.

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The latest 'bee' codebase is mainly the work of the *four musketeers*: Alok Nerurkar, Esad Akar, Anatol Lupanescu, and Peter Mrekaj, recruited by the legendary and elusive Elad Nachmias. This core team received assistance from Vlado Pajić and Marko Blazević.

Special big thanks to the irreplaceable Gyuri Barabás, our resident stats and maths guru, whose contributions are of immense importance. Swarm would not have been anywhere without the legend Callum Toner, who pulled together all R&D efforts and led the project to deliver an actually working product virtually single-handedly.

Ecosystem

Swarm has always attracted a wide community of enthusiasts as well as an ecosystem of companies and projects whose support and encouragement kept us alive during some dark days. Special thanks goes to Jarrad Hope, Jacek Sieka, and Oscar Thoren of Status, Marcin Rabenda

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Backers

Thanks to my friend and colleague Péter Földiák for his continued support fuelled by his genuine faith in the project. He believed in Swarm before it even existed. Thanks to the ICO participants as well as early backers for their contribution to executing on our ambitious roadmap.

Legacy

Finally, my deepest gratitude goes to my mentors and teachers, András Kornai, László Kálmán, Péter Halácsy, and Péter Rebrus, who have shaped my thinking and skills. They will always be my intellectual heroes.

Part I

Prelude

1. THE EVOLUTION

This chapter provides background information about the motivation for and evolution of Swarm and its vision today. Section 1.1 lays out a historical analysis of the World Wide Web, focusing on how it became the place it is today. Section 1.2 introduces the concept and emphasises the importance of data sovereignty, collective information, and a fair data economy. It discusses the infrastructure a self-sovereign society will need to collectively host, move, and process data. Finally, Section 1.3 recaps the core values underlying the vision, spells out the requirements of the technology, and establishes the design principles that guide us in manifesting Swarm.

1.1 Historical context

While the Internet in general—and the World Wide Web (WWW) in particular—has dramatically reduced the costs of disseminating information, these costs are still not zero, and their allocation heavily influences who gets to publish what content and who will consume it.

In order to appreciate the problems we are trying to solve, a little journey into the historical evolution of the World Wide Web proves to be helpful.

1.1.1 Web 1.0

In the era of Web 1.0, in order to have your content accessible to the whole world, you would typically fire up a web server or use some free or cheap web hosting space to upload your content, which could then be navigated through a series of HTML pages. If your content was unpopular, you still had to bear the cost of maintaining the server or paying the hosting to keep it accessible. However, true disaster struck when, for one reason or another, it became popular (e.g. you got "slashdotted"). At this point, your traffic bill skyrocketed just before either your server crashed under the load or your hosting provider throttled your bandwidth to the point of making your content essentially unavailable for the majority of your audience. If you wanted to stay popular, you had to invest in high-availability clusters connected with fat pipes; your costs grew together with your popularity, without any obvious way to cover them. There were very few practical ways to allow (let alone require) your audience to directly share the ensuing financial burden.

The prevailing belief at the time was that the internet service provider (ISP) would come to the rescue and resolve these challenges. Since in the early days of the Web revolution, bargaining about peering arrangements between the ISPs often centred around the location of providers and consumers and which ISP was making money from which other's network. Indeed, when there was a sharp imbalance between originators of TCP connection requests (aka SYN packets), it was customary for the ISP originating the request to compensate the recipient ISP. This setup somewhat incentivised the recipient ISP to help support those hosting popular content. In practice, however, this incentive structure usually led to some ISPs putting a free *pr0n* or *warez* server in the server room to tilt back the scales of SYN packet counters. This meant that blogs catering to niche audiences had no way of competing and were generally left out in the cold. Note, however, that back then, creator-publishers still typically owned their content.

1.1.2 Web 2.0

The transition to Web 2.0 changed much of that. The migration from personal home pages running on one's own server, using Tim Berners-Lee's elegantly simplistic and accessible hypertext markup language, to server-side scripting using CGI-gateways, Perl, and the inexorable PHP, led to a departure from the beautiful idea that anyone could write and run their own website using simple tools. This divergence set the web on a path towards a prohibitively difficult and increasingly complex stack of scripting languages and databases. Suddenly, the world wide web wasn't a beginner-friendly place any more. At the same time, new technologies emerged, allowing the creation of web applications with simple user interfaces that enabled unskilled publishers to simply POST their data to the server and divorce themselves of the responsibilities of actually delivering the bits to their end users. This marked the birth of Web 2.0.

Capturing the initial maker spirit of the web, sites like MySpace and Geocities now ruled the waves. These platforms offered users a personalised corner of the internet to call their own, complete with as many scrolling text marquees, flashing pink glitter Comic Sans banners, and all the ingenious XSS attacks a script kiddie could dream of. It was like a web within the web—a welcoming and open environment for users to start publishing their own content, increasingly without the need to learn HTML, and without rules. Platforms abounded, and suddenly there was a place for everyone, a phpBB forum for every niche interest imaginable. The web became full of life and the dotcom boom showered Silicon Valley in riches.

Of course, this youthful naivete, the fabulous rainbow-coloured playground wouldn't last. The notoriously unreliable MySpace fell victim to its open policy of allowing scripting, leading users' pages to become unreliable and rendering the platform virtually unusable. When Facebook arrived with a clean-looking interface that simply worked, it became clear that MySpace's time was up, and people migrated in droves. The popular internet acquired a more self-important undertone, and we filed into the stark white corporate office of Facebook. But there was trouble brewing. While offering this service for "free," Mr. Zuckerberg and others had an agenda. In exchange for hosting our data, we (the dumb f*cks; Carlson 2010) would have to trust him with it. Obviously, we did. For the time being, there was ostensibly no business model beyond luring in more venture finance, amassing huge user-bases, and a "we'll deal with the problem later" attitude. But from the start, extensive and unreadable T&Cs granted all the content rights to the platforms. While in the Web 1.0 era, it was easy to keep a backup of your website and migrate to a new host, or simply host it from home yourself, now those with controversial views had a new problem to deal with: "deplatforming".

At the infrastructure level, this centralisation became evident through the emergence of unthinkably huge data-centres. Jeff Bezos evolved his book-selling business to become the richest man on Earth by providing solutions for those who struggled with the technical and financial hurdles of implementing increasingly complex and expensive infrastructure. This new constellation of web services was capable of dealing with those irregular traffic spikes which would have crippled widely successful content in the past. Soon enough, a significant portion of the web came to be hosted by a handful of large companies. Corporate acquisitions and an endless stream of VC money led to a greater and greater concentration of power. A forgotten alliance of open-source programmers, creators of the royalty-free Apache web server, and Google, which introduced paradigm-shifting methods for organising and accessing vast amounts of data, dealt a crippling blow to Microsoft's attempt to force the web into a hellish, proprietary existence forever imprisoned in Internet Explorer 6. Of course, Google eventually accepted "parental oversight," shelved its promise to "do no evil," succumbed to its very own form of megalomania, and began to eat the competition. Steadily, email became Gmail, online ads became AdSense, and Google crept into every facet of daily life on the web.

On the surface, everything was rosy. A technological utopia hyperconnected the world in a way no-one could have imagined. No longer was the web just for academics and the super 1337—it made the sum of human knowledge available to anyone, and now that smartphones became ubiquitous, it could be accessed anywhere. Wikipedia gave everyone superhuman knowledge, while Google allowed us to find and access it in a moment. Facebook gave us the ability to communicate with everyone we had ever known, for free. However, underneath all this, there was one problem buried just below the glittering facade. Google knew what they were doing. So were Amazon, Facebook and Microsoft. And so did some punks, since 1984.

After acquiring a massive number of users, the time had finally come for these behemoth platforms to cut a check to investors. They could no longer continue delaying to figure out a business model. To provide value back to shareholders, the platforms turned to advertising revenue as panacea. Google and the other platforms may have investigated other potential sources of income, however, no significant alternatives were adopted. Now the web started to get complicated, and distracting. Advertisements appeared everywhere, and the pink flashing glitter banners were back, this time pulling your attention from the content you came for to deliver you to the next user acquisition opportunity.

And as if this weren't enough, there were more horrors to come. The Web lost the last shred of its innocence when the proliferation of data became unwieldy, and algorithms were used to "improve" our access to the content we wanted. Now that the platforms had all our data, they were able to analyse it to work out what we wanted to see, seemingly knowing us even better than we knew ourselves. However, there was a hidden catch—these all-encompassing data sets and secret algorithms were available for sale to the highest bidder. Deep-pocketed political organisations could target swing voters with unprecedented precision and efficacy. Cyberspace became suddenly all too real, while consensus reality became a thing of the past. News not only became fake; it evolved into personally targeted manipulation, as often nudging us to act against our best interests, all without us even realising it. The desire to save on hosting costs turned everyone into a target to become a readily controllable puppet.

At the same time, more terrifying revelations lay in wait. The egalitarian ideals that once underpinned the construction of a trustful internet proved to be the most naive of all. The DoD, the very institution that facilitated its adoption since the early days, now sought to reclaim control. Edward Snowden walked out of the NSA with a virtual stack of documents, the contents of which no one could have imagined (unless, of course, you had thought the Bourne Conspiracy was a documentary). It turned out that the protocols had been subverted, and all the warrant canaries were long dead. The world's major governments had been running a surveillance dragnet on the entire global population—incessantly storing, processing, cataloguing, indexing, and providing on-demand access to the sum total of a person's online activity. It was all available at the touch of an XKeyscore button—an all-seeing, unblinking Optical Nerve determined to "collect it all" and "know it all", no matter who or what the context. Big Brother turned out to look like Sauron. This gross erosion of privacy, along with many other similar efforts by various power-drunk or megalomaniac state and individual actors across the world to track and censor oppressed people, political adversaries, and journalists, had provided impetus for the Tor project. An extraordinary collaboration between the US Military, MIT, and the EFF, the Tor project offered a means to obfuscate the origin of a request and deliver content in a protected, anonymous manner. While wildly successful and a household name in some niches, Tor has not seen much mainstream adoption due to its relatively high latency resulting from its inherent inefficiencies.

By the time of Snowden's revelations, the web had become ubiquitous and an integral part of almost every facet of human life, with the vast majority of it operated by large corporations. While reliability problems were now a thing of the past, there was a price to pay. Content producers were offered context-sensitive, targeted advertising models in a Faustian bargain. The offers came with a knowing grin, revealing that these corporations knew content producers had no choice. "We will give you scalable hosting that will cope with any traffic your audience throws at it", they sang, "but in return, you must give us control over your content. We are going to track each member of your audience and collect (and own, *whistle*) as much of their personal data as possible. We will, of course, decide who can and who cannot see it, as is our right, no less. Additionally, we will proactively censor it and share your data with authorities as necessary to protect our business." As a consequence, millions of small content producers created immense value for a handful of mega corporations, getting peanuts in return—typically, free hosting and advertisement. What a deal!

Setting aside the resulting FUD of the Web 2.0 data and news apocalypse that we witness today, there are also a couple of technical problems with the web's underlying architecture. The corporate approach has led to a centralist maxim, where all requests must be routed through some backbone somewhere, to a monolithic data-centre, and then passed around, processed, and finally returned back. Even if to simply send a message to someone in the next room. This client-server architecture has at best flimsy security and was so often breached that it became the new normal, leaving oil-slicks of unencrypted personal data and even plaintext passwords in its wake, spread all over the web. The last nail in the coffin is the sprawl of incoherent standards and interfaces this has facilitated. Today, spaghetti code implementations of growing complexity subdivide the web into multifarious micro-services. Even well-funded companies find it increasingly difficult to deal with the development bills, and it is common that fledgling start-ups drown in a feature-factory sea of spiralling technical debt. A modern web application's stack in all cases is a cobbled together Goldberg machine comprising so many moving parts that it is almost impossible even for a supra-nation-state corporation to maintain and develop these implementations without numerous bugs and regular security flaws. Well, except for Google and Amazon, to be honest. At any rate, we're well overdue for a reboot. In the end, it's the data describing our lives. They are already trying but yet they have no power to lock us into this mess.

1.1.3 Peer-to-peer networks

As the centralised Web 2.0 took over the world, the peer-to-peer (P2P) revolution was also gathering pace, quietly evolving in parallel. P2P traffic rapidly accounted for the majority of packets flowing through the pipes, overtaking the SYN-bait servers mentioned earlier. It proved that by working together to use their hitherto massively underutilised *upstream bandwidth*, end users could achieve the same availability and throughput for their content as previously only achievable with the help of big corporations and their data centres attached to the fattest pipes of the Internet's backbone. What's more, it could be realized at a fraction of the cost. Importantly, users retained far greater control and freedom over their data. Eventually, this mode of data distribution proved to be remarkably resilient even in the face of powerful and well-funded entities' desperate exertions to shut it down.

However, even the most evolved mode of P2P file sharing, tracker-less BitTorrent (Pouwelse et al. 2005) was only that: file-level sharing. This was not at all suitable for providing the kind of interactive, responsive experience that people were coming to expect from web applications on Web 2.0. Additionally, while becoming extremely popular, BitTorrent was not conceived of with economics or game theory in mind. It was very much a product of the era before the world took note of the revolution its namesake would precipitate: that is to say, before anyone understood blockchains and the power of cryptocurrency and incentivisation.

1.1.4 The economics of BitTorrent and its limits

The genius of BitTorrent lies in its clever resource optimisation (Cohen 2003): if many clients want to download the same content from a user, it gives them each different parts in the first phase. In the second phase, they can swap the parts between each other in a tit-for-tat fashion until everyone has all the parts. This way, the upstream bandwidth cost for a user hosting content (the seeder in BitTorrent parlance) remains roughly the same, regardless of how many clients download the content simultaneously. This solves the most problematic, ingrained issue of the ancient, centralised, master-and-slave design of Hypertext Transfer Protocol (HTTP), the protocol underpinning the World Wide Web.

Cheating (i.e. feeding your peers with garbage data) is discouraged by the use of hierarchical, piece-wise hashing. Each package offered for download is identified by a single short hash, and any part of it can be cryptographically verified to be a specific component of the package without requiring knowledge of other parts, and incurring only a very small computational overhead.

But this beautifully simple approach has five consequential shortcomings, all somewhat related (see Locher et al. 2006, Piatek et al. 2007):

lack of economic incentives
There are no built-in incentives for users to seed content for others to download. In particular, there is no way to exchange upstream bandwidth provided by seeding for the downstream bandwidth

required for downloading content. Effectively, the upstream bandwidth provided by seeding content to users is not rewarded. Because as much upstream bandwidth as possible can improve the experience with some online games, it can be a rational, if selfish choice to switch seeding off. Add some laziness, and it stays off forever.

initial latency

Typically, downloads start slowly and with some delay. Clients that are further ahead in downloading have significantly more to offer to newcomers than they can offer in return. I.e. the newcomers have nothing to download (yet) for those further ahead. The result of this is that BitTorrent downloads start as a trickle before turning into a full-blown torrent of bits. This peculiarity has severely limited the use of BitTorrent for interactive applications that require both fast responses and high bandwidth, even though it would otherwise constitute a brilliant solution for many games.

lack of fine-grained content addressing

Small chunks of data can only be shared as part of the larger file. They can be pinpointed for targeted that leaves the rest of a file out to optimise access. Peers for the download can only be found by querying the distributed hash table (DHT) for a desired *file*, and it is not possible to look for peers at the chunk-level. As the advertising of available content happens exclusively at the level of files, this leads to inefficiencies, as the same chunks of data can often appear verbatim in multiple files. So, while theoretically, all peers who have the chunk could provide it, there is no way to find those peers without the name or announced hash of the chunk's enveloping file.

no incentive to keep sharing

Nodes are not rewarded for their sharing efforts (storage and bandwidth) once they have achieved their objective, i.e. retrieving all desired files from their peers.

no privacy or ambiguity

Nodes publicly advertise exactly the content they are seeding, making it easy for attackers to discover the IP address of peers hosting content they would like to see removed. Any adversaries can then easily DDOS them, while corporations and nation states are able to petition the ISP for the physical location of the connection. This has led to a grey market of VPN providers helping users circumvent this. Although these services offer assurances of privacy, it is usually impossible to verify them as their systems are typically closed-source.

While spectacularly popular and useful, BitTorrent is only a rudimentary, albeit undoubtedly genius first step. It is amazing how far we can get simply by sharing our upstream bandwidth, hard-drive space, and tiny amounts of computing power–even despite the lack of proper accounting and indexing. However-–surprise!-–by adding just a few more emergent technologies to the mix, especially the blockchain, we get something that truly deserves the Web 3.0 moniker: a decentralised, censorship-resistant platform for sharing and collectively creating content while retaining full control over it. What's more, the cost of this is almost entirely covered by using and sharing the resources supplied by the breathtakingly powerful, underutilised super-computer (by yesteryear's standards :-)) that most of us already own.

1.1.5 Towards Web 3.0

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At 6:15 on the 3rd of January 2009, a mysterious Cypherpunk created the first block of a chain that would encircle the entire world, fundamentally changing the way we think about money, forever. The genie of *cryptocurrency* was out of the bottle. Satoshi Nakamoto had achieved something no one else could—the de facto (albeit small scale) disintermediation of banks through decentralised, trustless value transfer. Ever since that moment, we have effectively returned to the gold standard—everyone can now own *sound* money. Money that no-one can multiply or inflate out of your pocket. What's more, now we can even issue our own currency, complete with an arbitrary monetary policy and a globally deployed electronic transmission system. It is still not well understood how much this will change our economies, but the system attracted an unprecedented degree of wealth, withdrawn from traditional asset classes, leading to a total capitalisation of crypto surpassing the staggering one trillion US dollars.

This first step was a monumental turning point. Now we had authentication and value transfer baked into the system at its very core. But as much as it was conceptually brilliant, it had some minor and not-so-minor problems with utility. It allowed the transmission of digital value, one could even ’colour’ the coins or transmit short messages like the one above that marks the fateful date of the first block—but that’s it. And, regarding scale... every transaction must be stored on every node. Sharding was not built-in. Worse, the protection of the digital money made it necessary that every node processed exactly the same as every other node, all the time. This was the opposite of a parallelised computing cluster, and millions of times slower.

When Vitalik conceived of Ethereum, he accepted some of these limitations, but the utility of the system took a massive leap. He added the facility for Turing-complete computation via the Ethereum Virtual Machine (EVM) which enabled a cornucopia of applications that could run in this trustless setting. The concept was at once a dazzling paradigm shift and a consistent evolution of Bitcoin, which itself was based on a tiny virtual machine, with every single transaction really being—unbeknownst to many—a mini program. But Ethereum went all the way, and that again changed everything. The possibilities were numerous and alluring, and Web 3.0 was born.

However, there was still a problem to overcome to fully transcend the world of Web 2.0—storing data on the blockchain was prohibitively expensive for anything but a tiny amount. Both Bitcoin and Ethereum had taken the layout of BitTorrent and run with it, complementing the architecture with the capability to transact, but leaving consideration about storing non-systemic data for later. Bitcoin had introduced a less secure second circuit below the distribution of blocks: candidate transactions are shipped around without fanfare, as secondary citizens, literally without protocol. Ethereum went further, separating out the headers from the blocks, creating a third tier that ferried the actual block data as needed. Because both classes of data are essential to the operation of the system, these could be called critical design flaws. Bitcoin's maker probably didn't envision mining becoming the exclusive domain of a highly specialised elite. Any transactor would have been expected to be able to mine their own transactions. Ethereum's developers faced the even harder challenge of data availability, and perhaps assuming it could be addressed later, ignored it for the moment.

In other news, the straightforward data dissemination approach of BitTorrent was successfully implemented for web content distribution by ZeroNet (ZeroNet community 2019). However, because of the aforementioned issues with BitTorrent, ZeroNet turned out unable to support the responsiveness that users of modern web services have come to expect.

In an effort to enable responsive, distributed web applications (or dapps), the InterPlanetary File System or IPFS (IPFS 2014) introduced their own major improvements over BitTorrent. One stand-out feature was the highly web-compatible, URL-based retrieval scheme. In addition, the directory of the available data, the indexing, (like BitTorrent organised as a DHT) was vastly improved, allowing users to also search for small parts of any file, known as chunks.

There are numerous other efforts to fill the gap and provide a worthy Web 3.0 surrogate for the constellation of servers and services that Web 2.0 developers have come to expect—to offer a path to emancipation from the existing dependency on centralised architecture that enables the data reapers. These are not insignificant roles to supplant, as even the simplest web app today relies on a vast array of concepts and paradigms which have to be remapped into the trustless setting of Web 3.0. In many ways, this problem is proving to be perhaps even more nuanced than implementing trustless computation on the blockchain. Swarm responds to this with a variety of carefully designed data structures that enable application developers to recreate familiar Web 2.0 concepts. Swarm reimagines the current offerings of the web and reimplements them based on solid cryptoeconomic foundations.

Imagine a sliding scale, starting on the left with large file size, low frequency of retrieval, and a monolithic API. To the right are small data packets, high frequency of retrieval, and a nuanced API. On this spectrum, file storage and retrieval systems like a posix filesystem, S3, Storj, and BitTorrent live on the left hand side. Key–value stores like LevelDB and databases like MongoDB or Postgres live on the right. Building a useful app requires different modalities scattered across the scale. Furthermore, there must be the ability to combine data where necessary and ensure only authorised parties have access to protected data. In the centralised model, handling these problems initially is easy, but gets more difficult with growth, and each range of the scale has a solution from one piece of specialised software or another. However, in the decentralised model, all bets are off. Authorisation must be handled with cryptography, limiting the combination of data. As a result, in the nascent, evolving Web 3.0 stack of today, many solutions deal piecemeal with only part of this spectrum of requirements. In this book, you will learn how Swarm spans the entire spectrum while providing high-level tools for the new guard of Web 3.0 developers. The hope is that from an infrastructure perspective, working on Web 3.0 will feel like the halcyon days of Web 1.0, while delivering unprecedented levels of agency, availability, security, and privacy.

To address the need for privacy to be baked in at the core level in file-sharing—as it is so effectively attained in Ethereum—Swarm enforces anonymity at an equally fundamental and absolute level. Lessons from Web 2.0 have taught us that trust should be given responsibly and only to those that are deserving of it and will treat it with respect. Data is toxic (Schneier 2019), and we must treat it delicately in order to be responsible to ourselves and to those for whom we take responsibility. Later, we will explain how Swarm provides complete and fundamental user privacy.

Of course, to fully transition to a Web 3.0-decentralised world, we must address the dimensions of incentives and trust, which are traditionally "solved" by handing over responsibility to (often untrustworthy) centralised gatekeepers. As we have noted, BitTorrent also grappled with this problem and responded with various seed ratios and private (i.e., centralised) trackers.

The problem of lacking incentives for reliably hosting and storing content is apparent in various projects like ZeroNet or MaidSafe. Incentivising distributed document storage is still a relatively new research field, especially in the context of blockchain technology. The Tor network has seen suggestions for incentivisation schemes (Jansen et al. 2014, Ghosh et al. 2014) but they have mostly been academic exercises and not integrated into the heart of the underlying system. Bitcoin has been repurposed to drive other systems like Permacoin (Miller et al. 2014), while some have created their own blockchain, such as Sia (Vorick and Champine 2014) or Filecoin (2014) for IPFS. BitTorrent is currently testing the waters of blockchain incentivisation with its own token (Tron Foundation 2019, BitTorrent Foundation 2019). However, even with all of these approaches combined, many hurdles remain to fulfil the specific requirements of a Web 3.0 dapp developer.

Later on, we will explore how Swarm provides a full suite of incentivisation measures and implements other checks and balances to ensure that nodes work together for the benefit the entire... swarm. This includes the option to rent out large amounts of disk space to those willing to pay for it—irrespective of the popularity of their content—while also enabling the deployment of interactive dynamic content to be stored in the cloud, a feature we call upload and disappear.

The objective of any incentive system for peer-to-peer content distribution is to encourage cooperative behaviour and discourage freeriding: the uncompensated depletion of limited resources. The incentive strategy outlined here aspires to satisfy the following constraints:

- it is in the node's own interest, regardless of whether or not other nodes follow it
- it must be expensive to expend the resources of other nodes
- it does not impose unreasonable overhead
- it plays nice with "naive" nodes
- it rewards those that play nice, including those following this strategy

In the context of Swarm, storage and bandwidth are the two most important scarce resources, and this is reflected in our incentives scheme.

Bandwidth incentives aim to achieve speedy and reliable data provision, while storage incentives are designed to ensure long-term data preservation. This comprehensive approach caters to all web application development requirements and aligns incentives so that each individual node's actions benefit not only itself, but the whole of the network.

1.2 Fair data economy

In the era of Web 3.0, the Internet is no longer just a niche space where geeks play, but has become a vital conduit of value creation and has generated a huge share of overall economic activity. Yet, the data economy in its current state is far from fair, as the distribution of the spoils is controlled by those who control the data—mostly companies keeping it to themselves in isolated data silos. To achieve the goal of a fair data economy, many social, legal, and technological issues will have to be tackled. We will now present some of the issues as they currently exist, and describe how Swarm aims to address them.

1.2.1 The current state of the data economy

Digital mirror worlds already exist—virtual expanses that contain shadows of physical things, consisting of unimaginably large amounts of data (Economist 2020a). As more and more data continues to be synced to these parallel worlds, new infrastructure, markets, and business opportunities arise. Only relatively crude methods exist for measuring the size of the data economy as a whole, but one estimate places the financial value of data (including related software and intellectual property) in the USA at $1.4 trillion to 2 trillion in 2019 (Economist 2020a). The EU Commission projects the figures for the data economy in the EU27 for 2025 at €829 billion (up from €301 billion in 2018; European Commission 2020a).

Despite this huge amount of value, the asymmetric distribution of the wealth generated by the existing data economy has been put forward as a major humanitarian issue (Economist 2020c). While unceasing increases in quality and quantity of data have led to ever-greater levels of efficiency and productivity, the resulting profits have been distributed unequally. The larger the company's data set, the more it can learn from the data, the more users it can attract, and the more data it can accumulate. Currently, this is most apparent with the dominating large tech companies such as FAANG, but it is predicted to become increasingly significant in non-tech sectors and even in nation states. Hence, companies are racing to become dominant in their respective sectors, granting an advantage to the countries hosting these platforms. Since Africa and Latin America host so few of these, they risk becoming exporters of raw data and paying other countries to import the intelligence derived from it, as warned by the United Nations Conference on Trade and Development (Economist 2020c). Another problem arises when a large company monopolises a particular data market, as it can become the sole purchaser of data, exerting complete control over price setting. This control opens up the possibility of manipulating the "wages" offered for providing data, thereby keeping them artificially low. In many ways, we are already seeing evidence of this.

Flows of data are becoming increasingly blocked and filtered by governments, using the familiar reasoning based on the protection of citizens, sovereignty, and national economy (Economist 2020b). Leaks by several security experts reveal that for governments to properly give consideration to national security, data should be kept close to home and not left to reside in other countries. GDPR is one such instance of a "digital border" that has been erected—data may leave the EU only if appropriate safeguards are in place. Other countries, such as India, Russia, and China, have implemented their own geographic limitations on data. The EU Commission has pledged to closely monitor the policies of these countries and address any restrictions to data flows during trade negotiations. Additionally, the EU Commission takes necessary measures within the World Trade Organization (European Commission 2020b) to advocate for fair and unrestricted data exchange practices.

Despite the growing interest in the ebb and flow of data, the big tech corporations maintain a firm grip on much of it, and the devil is in the details. Swarm's privacy-first model ensures that no data needs to be divulged to any third parties, and everything is end-to-end encrypted out of the box, preventing service providers from aggregating and leveraging giant data sets. As a result, instead of being concentrated with the service provider, control of the data remains decentralised and with the individual to whom it pertains. And with that, so does the power. Expect bad press.

1.2.2 The current state and issues of data sovereignty

As a result of the Faustian bargain described above, the current model of the World Wide Web suffers from several flaws. Unforeseen circumstances of economies of scale in infrastructure provisioning and network effects in social media have turned platforms into massive data silos, holding large amounts of user data that are retained, shared, or deleted at the whim of a single organisation. This 'side effect' of the centralised data model empowers large private corporations to collect, aggregate, and analyse user data with their data siphons positioned right at the central bottleneck—the cloud servers where everything meets. This is exactly what David Chaum predicted in 1984, which ignited the Cypherpunk movement, serving as a vital inspiration for Swarm.

The increasing shift from human-mediated interactions to computer-mediated ones, combined with the rise of social media and smartphones, has led to more and more information about our personal and social lives becoming readily accessible to the companies provisioning the data flow. They have access to lucrative data markets where user demographics are linked with underlying behaviours, enabling them to understand users better than they understand themselves. This is the ultimate treasure trove for marketeers.

Data companies, including large tech corporations and other entities involved in collecting, aggregating, and analysing vast amounts of user data, have meanwhile evolved their business models, now focusing on capitalising on data sales rather than the service they initially provided. Their primary source of revenue is now selling the results of user profiling to advertisers, marketeers, and others who seek to "nudge" members of the public. The cycle is continued through eerily tailored advertisements served to users on the same platforms, measuring their reaction, and using their reactions to better elicit the desired behaviour in future advertisements, thus creating an unending feedback loop. A whole new industry has grown out of this torrent of information, sophisticated systems have emerged to predict, guide, and influence users to capture their attention and money. The industry openly and knowingly exploits human cognitive biases, often resorting to highly developed and cynically calculated psychological manipulation. The undisputable truth is that mass manipulation in the name of commerce has led to our modern reality where not even the most aware can truly exercise their freedom of choice and preserve their intrinsic autonomy of preference regarding consumption of content, goods, and services.

The shift in the platforms' focus towards advertisements rather than their intended primary purposes is also reflected in the declining quality of service for users. The needs of users have become secondary to the needs of the "real" customers: the advertisers. This declining user experience and quality of service is exacerbated in the case of social platforms where the inertia of network effect promotes user lock-in. Correcting these misaligned incentives is imperative to providing users with the same services without the unfortunate incentives inevitably resulting from the centralised data model.

Moreover, the lack of control over one's data has serious consequences on the economic potential of the users. Some refer to this situation, somewhat hysterically, as data slavery. But they are technically correct: our digital twins are held captive by these corporations and exploited for revenue generation. As users, we give up a great deal of agency, as the data we freely share is used to manipulate us and make us less well-informed and free.

The current system of keeping data in disconnected data sets has various drawbacks:

Unequal opportunity
: Centralised entities increase inequality as they siphon away a disproportionate amount of profit from the actual creators of the value.

Lack of fault tolerance
: These datasets have a single point of failure in terms of technical infrastructure, notably security.

Corruption
: The concentration of decision-making power makes these datasets easier targets for social engineering, political pressure, and institutionalised corruption.

Single attack target
: The concentration of large amounts of data under the same security system attracts attacks as it increases the potential reward for hackers.

Lack of service continuity guarantees
: Service continuity is in the hands of the organisation and is only weakly incentivised by reputation. This introduces the risk of inadvertent termination of service due to bankruptcy or regulatory/legal action.

Censorship
: Centralised control of data access allows for, and in most cases eventually leads to, decreased freedom of expression.

Surveillance
: Data flowing through centrally-owned infrastructure offers perfect access to traffic analysis and other methods of monitoring.

Manipulation
: Monopolisation of the display layer enables data harvesters to manipulate opinions by controlling the presentation, order, and timing of data, calling into question the sovereignty of individual decision-making.

1.2.3 Towards self-sovereign data

We believe that decentralisation is a game-changer that effectively addresses many of the problems listed above.

We argue that blockchain technology is the final missing piece in the puzzle to realise the cypherpunk ideal of a truly self-sovereign Internet. As outlined in the *Cypherpunk Manifesto* by Eric Hughes in 1993 (Hughes

1993), "We must come together and create systems which allow anonymous transactions." One of the goals of this book is to demonstrate how decentralised consensus and peer-to-peer network technologies can be combined to form a rock-solid base-layer infrastructure. This foundation is not only resilient, fault tolerant and scalable, but also egalitarian and economically sustainable with a well-designed system of incentives. The low barrier of entry for participants ensures adaptive incentives, leading to prices that automatically converge to the marginal cost. On top of this, add Swarm's strong value proposition in the domain of privacy and security.

Swarm is a Web 3.0 stack that is decentralised, incentivised, and secure. In particular, the platform caters to participants with comprehensive solutions for data storage, transfer, access, and authentication—services that are becoming increasingly crucial in economic interactions. Offering universal access with robust privacy guarantees and no limitations from borders or external restrictions, Swarm fosters the spirit of global voluntarism and serves as the foundational *infrastructure for a self-sovereign digital society.*

1.2.4 Artificial intelligence and self-sovereign data

Artificial Intelligence (AI) holds great promise for our society, bringing new business opportunities and augmenting the tool sets used by various professions. On the one hand, it also poses a potential threat as it might displace certain professions and jobs (Lee 2018).

For the prevalent type of AI, machine learning (ML), particularly deep learning, three essential "ingredients" are required: computing power, models, and data. Today, computing power is readily available, and specialised hardware is being developed to further facilitate processing. An extensive headhunt for AI talent has been taking place for more than a decade, and a few companies have managed to corner the market for workers with the specialised talents needed to build models and analyse data. However, the dirty secret of today's AI, and deep learning, is that the algorithms, the 'intelligent math' is already commoditised. It is Open Source and freely available to everyone. It is not what Google or Palantir make their money with. The true ’magic trick’ of these companies lies in getting access to the largest possible data sets to unleash the full potential of their AI systems for profitable gains.

The major players in the data economy have been systematically amassing vast amounts of data. They often offer free applications with some utility such as search engines or social media platforms, while secretly collecting and stockpiling user data without explicit consent or awareness. This monopoly on data has allowed multinational companies to make unprecedented profits, with only feeble motions to share the financial proceeds with the individuals whose data they have sold. Potentially much worse though, this hoarded data remains untapped, depriving both individuals and society as a whole of its potential transformative value.

It is perhaps not a coincidence that the major data and AI "superpowers" are the American and Chinese governments, along with major corporations within their respective borders. An AI arms-race is unfolding in full view of the citizens of the world, leaving most other countries lagging behind as "data colonies" (Harari 2020). There are warnings that the current trajectory will lead to China and the United States accumulating an insurmountable advantage as AI superpowers (Lee 2018).

It doesn’t have to be so. In fact, it likely won’t because the status quo is a bad deal for billions of people. Decentralised technologies and cryptography offer a path towards data privacy while nurturing a fair data economy that retains the benefits of the current centralised system but without its pernicious drawbacks. This is the goal that many consumer and tech organisations across the globe are aiming for. They are working to support the push-back against the big data behemoths as more users begin to realise that they have been swindled into giving away their data. Swarm’s infrastructure will play a pivotal role in facilitating this liberation.

Self-sovereign storage might well be the only way that individuals can reclaim control over their data and privacy. It is the first step towards breaking free from filter bubbles and reconnecting with one’s own culture. Addressing various challenges of today’s Internet and the distribution and storage of data, Swarm is built for privacy from the ground up, incorporating powerful data encryption and ensuring secure and completely leak-proof communication. Furthermore, it enables users to selectively share specific data with third parties at their discretion, allowing for the possibility of financial compensation in return. Payments and incentives are therefore also integral aspects of Swarm.

As Hughes wrote, "privacy in an open society requires anonymous transaction systems. ... An anonymous transaction system is not a secret transaction system. An anonymous system empowers individuals to reveal their identity when desired and only when desired; this is the essence of privacy."

Using Swarm enables leveraging a fuller set of data to create better services while still having the option to contribute to the global good with self-verifiable anonymisation. It's the best of all worlds.

This newfound availability of data, benefitting young academic students and startups with disruptive ideas in the AI and big-data sectors, has immense potential to drive advancements in the entire field. This holds great promise for progress in science, healthcare, the eradication of poverty, environmental protection, disaster prevention, and more. However, despite the eye-catching successes attracting robber barons and rogue states, many sub-fields are currently facing challenges and stagnation. Swarm's data liberation has the potential to break this impasse and unleash the sector's contributions to various domains.

The facilities that Swarm provides will open up a new set of powerful options for companies and service providers. With the widespread decentralisation of data, we can collectively own the extremely large and valuable data sets that are needed to build state-of-the-art AI models. Embracing data portability, a trend already hinted at in traditional tech, will foster competition and personalised services for individuals. The playing field will be levelled for all, driving innovation in line with the demands of the twenty-first century's third decade.

1.2.5 Collective information

While collective information has been steadily accumulating since the inception of the Internet, the concept has only recently gained recognition and is now being discussed under a variety of headings such as *open source, fair data*, or *information commons*.

A collective, as defined by Wikipedia, is:

> "A group of entities that share or are motivated by at least one common issue or interest, or work together to achieve a common objective."

The internet allows the formation of collectives on a previously unthinkable scale, transcending geographical location, political convictions, social status, wealth, even general freedom, and other demographics. The data produced by these collectives through interactions on public forums, reviews, votes, code repositories, articles, and polls, along with the emergent metadata, all contribute to collective information. Since most of these interactions are currently facilitated by for-profit entities running centralised servers, the collective information ends up stored in data silos owned by commercial entities, often concentrated in the hands of a few large technology companies. And while the actual work results are often in the open, the metadata, which can often be more valuable, powerful, and potentially dangerous, is usually held and monetised in secrecy.

These "platform economies" have already become essential and are only becoming ever more important in a digitised society. However, the information that commercial players acquire about their users is increasingly being leveraged against the users' best interests. To put it mildly, this calls into question whether these corporations can handle the ethical responsibility that comes with the power of managing our collective information.

While many state actors are trying to obtain unfettered access to the collective mass of individuals' personal data, with some countries going as far as demanding magic key-like back-door access, there are exceptions.

Since AI has the potential for misuse and ethically questionable use, a number of countries have started "ethics" initiatives, regulations, and certifications for AI use, such as the German Data Ethics Commission or Denmark's Data Ethics Seal.

Yet, even if corporations could be made to act more trustworthy, as would be appropriate in light of their great responsibility, the mere existence of data silos stifles innovation. The basic shape of the client-server architecture itself has led to this problem by defaulting to centralised data storage on "servers" within their "farms" (see 1.1.1 and 1.1.2). In contrast, effective peer-to-peer networks like Swarm (1.1.3) make it possible to alter the very topology of this architecture, enabling the collective ownership of collective information.

1.3 The vision

Swarm is infrastructure for a self-sovereign society.

1.3.1 Values

Self-sovereignty implies freedom. If we break it down, this implies the following metavalues:

Inclusivity
  public and permissionless participation
Integrity
  privacy, provable provenance
Incentivisation
  alignment of interest of node and network
Impartiality
  content and value neutrality

These metavalues can be thought of as systemic qualities which contribute to empowering individuals and collectives to gain self-sovereignty.

Inclusivity means that we aspire to include the underprivileged in the data economy and lower the barrier of entry for defining complex data flows and building decentralised applications. Swarm is a network with open participation for providing services and permissionless access to publishing, sharing, and investing your data.

While having the freedom to express their intentions as "actions" and retain full authority to decide if they want to remain anonymous or share their interactions and preferences, users must also uphold the integrity of their online persona.

Economic incentives ensure that participants' behaviour align with the desired emergent behaviour of the network (see 3).

Impartiality guarantees the neutrality of content and prevents gatekeeping. It also reaffirms that the other three values are not only necessary but also sufficient: it eliminates any values that may treat any particular group as privileged or express a preference for specific content or data from a particular source.

1.3.2 Design principles

The information society and its data economy bring about an age where online transactions and big data are indispensable to everyday life, making the technical infrastructure supporting them essential for a functional society. It is imperative therefore, that this base-layer infrastructure be *future-proof* and equipped with robust guarantees for long-term continuity.

Persistence of the technical infrastructure is achieved by the following generic requirements expressed as *systemic properties*:

Stable
: The specifications and software implementations are stable and resilient to changes in participation, or politics (political pressure, censorship).

Scalable
: The solution is able to accommodate many orders of magnitude more users and data as it scales, without adversely impacting performance or reliability during mass adoption.

Secure
The network is resistant to deliberate attacks, remains impervious to social pressure and political influences, and demonstrates fault tolerance in its technological dependencies (e.g. blockchain, programming languages).

Self-sustaining
The solution runs by itself as an autonomous system, not depending on individual or organisational coordination of collective action or any legal entity's business, nor exclusive know-how, hardware, or network infrastructure.

1.3.3 Objectives

When we talk about the "flow of data," a core aspect of this is how information has provable integrity across modalities, see Table 1.1. This corresponds to the original Ethereum vision of the world computer, constituting the trust-less (i.e. fully trustable) fabric of the coming data scene: a global infrastructure that supports data storage, transfer, and processing.

dimension	model	project area
time	memory	storage
space	messaging	communication
symbolic	manipulation	processing

Table 1.1: Swarm's scope and data integrity aspects across 3 dimensions.

With the Ethereum blockchain as the CPU of the world computer, Swarm is best thought of as its "hard disk". Of course, this model belies the complex nature of Swarm, which is capable of much more than simple storage, as we will discuss.

The Swarm project sets out to bring this vision to completion and build the world computer's storage and communication.

1.3.4 Impact areas

In what follows, we identify feature areas of the product that best express or facilitate the four values of inclusivity, integrity, incentivisation, and impartiality introduced above.

Inclusivity in terms of permissionless participation is best guaranteed by a decentralised peer-to-peer network.

Allowing nodes to provide service and get paid for doing so will offer a zero-cash entry to the ecosystem: new users without currency can serve other nodes until they accumulate enough currency to use services themselves. A decentralised network providing distributed storage without gatekeepers is also inclusive and impartial in that it allows content creators, who would otherwise risk being deplatformed by repressive authorities, to publish without their right to free speech being violated.

The system of economic incentives built into the protocols works best if it tracks the actions that incur costs in the context of peer-to-peer interactions. Bandwidth sharing as evidenced in message relaying is one such action where immediate accounting is possible as a node receives a message that is valuable to them. On the other hand, promissory services such the commitment to preserve data over time must be rewarded only upon verification. In order to avoid the tragedy of the commons problem, such promissory commitments should be guarded against by enforcing individual accountability through the threat of punitive measures, i.e. by allowing staked insurers.

Integrity is maintained by ensuring easy provability of authenticity while still maintaining anonymity. Provable inclusion and uniqueness are fundamental to allowing trustless data transformations.

1.3.5 The future

In today's digital society, many challenges lie ahead for humanity, leaving the future uncertain. Nonetheless, to be sovereign and in control of our destinies, nations and individuals alike must retain access and control over their data and communication.

Swarm's vision and objectives are rooted in the values of the decentralised tech community. Originally conceived as the file storage component in the trinity which would form the world computer alongside Ethereum and Whisper, Swarm embraces its role in building a resilient decentralised digital ecosystem.

It provides the necessary responsiveness for dapps running on users' devices, while also offering incentivised storage utilising various storage infrastructures ranging from smartphones to high-availability clusters. Continuity will be guaranteed with well-designed incentives for bandwidth and storage.

Content creators will receive fair compensation for the content they offer, and content consumers will pay for it. By eliminating the middlemen providers who currently benefit from the network effects, the benefits will be spread throughout the network.

But it will be much more than that. Every individual and every device leaves a trail of data, which is collected and stored in silos, whose potential is used up only in part and to the benefit of large players.

Swarm will serve as the go-to platform for digital mirror worlds, providing individuals, societies, and nations with a cloud storage solution that is independent of any one large provider.

Individuals will have full control over their own data. They will no longer be trapped in the current system of data slavery, where personal data is exchanged for services on opaque and exploitative platforms. Moreover, they will be able to form data collectives or data co-operatives, sharing their resources in the form of *data commons* to achieve shared objectives.

Nations will establish self-sovereign Swarm clouds as data spaces to cater to the emerging artificial intelligence paradigm—in industry, health, mobility, and other sectors. These clouds will operate in a peer-to-peer manner, potentially within exclusive regions, and third parties will not be able to interfere by monitoring, censoring, or manipulating the flow of data. However, authorized parties will have access to the data, aiming to level the playing field for AI and services based on it.

Swarm can, paradoxically, serve as the "central" place to store data. Embracing this technology will empower individuals and society with robust accessibility, control, and fair value distribution of data, allowing for the leveraging of data for the collective benefit of all.

In the future society, Swarm will become ubiquitous, transparently and securely serving data from individuals and devices to data consumers within the fair data economy.

Part II

Design and architecture

The Swarm project is set out to build a permissionless storage and communication infrastructure for the self-sovereign digital society of tomorrow. From a developer's perspective, Swarm is best seen as public infrastructure that powers real-time interactive web applications familiar from the Web 2.0 era. It provides a low-level API to primitives that serve as building blocks of complex applications, as well as the basis for the tools and libraries for a Swarm-based Web 3.0 development stack. Designed to allow access from any traditional web browser, the API and tools ensure that Swarm can swiftly offer a private and decentralised alternative to today's World Wide Web (WWW).

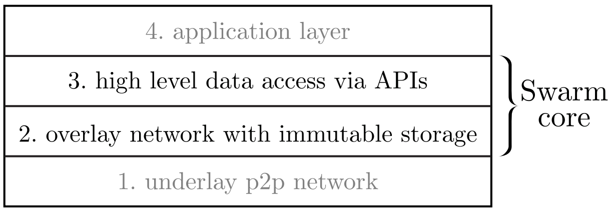

4. application layer
3. high level data access via APIs
2. overlay network with immutable storage
1. underlay p2p network
Swarm core

Figure 1.1: Swarm's layered design

This part details the design and architecture of the system. In accordance with the principles laid out in 1.3.2, we prioritise a modular design approach for Swarm, conceiving it with clearly separable layers, each dependent on the previous one (see Figure 1.1):

(1) A peer-to-peer network protocol to serve as underlay transport.
(2) An overlay network with protocols powering a distributed immutable storage of chunks (fixed size data blocks).
(3) A component providing high-level data access and defining APIs for base-layer features.
(4) An application layer defining standards and outlining best practices for more elaborate use-cases.

We regard (2) and (3) as the core of Swarm. Since the network layer relies on it, we will also formulate the requirements for (1), but consider the detailed treatment of both (1) and (4) outside the scope of this book.

Central to the design is the architecture of Swarm's overlay network (layer 2 in Figure 1.1), which is discussed in Chapter 2. Chapter 3 complements this by describing the system of economic incentives which makes Swarm self-sustaining. In Chapter 4, we introduce the algorithms and conventions that allow Swarm to map data concepts onto the chunk layer to enable the high-level functionalities for storage and communication, notably data structures such as filesystems and databases, access control, indexed feeds, and direct messaging which comprise layer 3 of Swarm. In Chapter 5, we present ways to prevent garbage-collected chunks from disappearing from the network, including: erasure codes, pinning and insurance, and also provide ways to monitor, recover and re-upload them using missing chunk notifications and insurance challenges. Finally, in Chapter 6, we will look at functionality from the perspective of the developer who builds on Swarm.

2. NETWORK

This chapter elaborates on how the Swarm overlay network is built on top of a peer-to-peer network protocol to form a topology that allows for the routing of messages between nodes (2.1). In 2.2, we describe how such a network can serve as a scalable distributed storage solution for data chunks (2.2.1) and present the logic underpinning the protocols for retrieval/download and syncing/upload (2.3).

2.1 Topology and routing

This section sets the scene (2.1.1) for the overlay network of Swarm by making explicit the assumptions about the underlay network. 2.1.2 introduces the overlay address space and explains how nodes are assigned an address. In 2.1.3, we present the Kademlia overlay topology (connectivity pattern) and explain how it solves routing between nodes. In 2.1.4, we show how nodes running the Swarm client can discover each other, bootstrap, and then maintain the overlay topology.

2.1.1 Requirements for underlay network

Swarm is a network operated by its users. Each node in the network is supposed to run a client complying with the protocol specifications. On the lowest level, the nodes in the network connect using a peer-to-peer network protocol as their transport layer. This is called the underlay network. In its overall design, Swarm is agnostic of the particular underlay transport used as long as it satisfies the following requirements:

Addressing
: Nodes are identified by their underlay address.

Dialling
: Nodes can initiate a direct connection to a peer by dialing them on their underlay address.

Listening
: Nodes can listen to other peers dialing them and can accept incoming connections. Nodes that do not accept incoming connections are called light nodes.

Live connection
: A node connection establishes a channel of communication, indicating that the remote peer is online and accepting messages until explicitly disconnected.

Channel security
: The channel provides identity verification and implements encrypted and authenticated transport resisting man-in-the-middle attacks.

Protocol multiplexing
: The underlay network service can accommodate several protocols running on the same connection. Peers communicate the protocols with the name and versions that they implement, and the underlay service identifies compatible protocols and starts up peer connections on each matched protocol.

Delivery guarantees
: Protocol messages have guaranteed delivery, i.e. any delivery failures due to network problems prompt direct error responses. The sequence in which messages are delivered is guaranteed within each protocol, and ideally, the underlay protocol provides prioritisation. If protocol multiplexing takes place on the same transport channel, framing is likely implemented to prevent long messages from blocking higher-priority ones.

Serialisation
: The protocol message construction supports arbitrary data structure serialisation conventions.

The libp2p library can provide all the needed functionality and is the designated underlay connectivity driver in the specification.[1]

2.1.2 Overlay addressing

While clients use the underlay address to establish connections to peers, each node running Swarm is additionally identified with an overlay address. It is this address that determines which peers a node will connect to and also directs the way messages are forwarded. The overlay address is assumed to be stable as it defines a node's identity across sessions and ultimately affects which content is prioritised for storage in the node's local storage.

The node's overlay address is derived from an Ethereum account by hashing the corresponding elliptic curve public key with the bzz network ID using the 256-bit Keccak algorithm. The inclusion of the bzz network ID is rooted in the fact that there can be multiple Swarm networks (e.g. test net, main net, or private Swarms). It serves to ensure that the same address cannot be used across different networks. Assuming any sample of base accounts are independently selected, the resulting overlay addresses are expected to have a uniform distribution in the address space of 256-bit integers. It is important to derive the address from a public key, as it allows the nodes to issue commitments associated with an overlay location using cryptographic signatures that are verifiable by third parties.

Using the long-lived communication channels of the underlay network, Swarm nodes form a network with *quasi-permanent* peer connections.

[1] Swarm's initial Golang implementation uses Ethereum's devp2p/rlpx which satisfies the above criteria and uses TCP/IP with custom cryptography added for security. The underlay network address that devp2p uses is represented using the enode URL scheme. Devp2p dispatches protocol messages based on their message ID. It uses RLP serialisation which is extended with higher level data type representation conventions. In order to provide support for the Ethereum 1.x blockchain and for storing its state on Swarm, we may provide a thin devp2p node that proxies queries to the new libp2p-based Swarm client, or just uses its API. Otherwise we expect the devp2p networking support to be discontinued.

The resulting connectivity graph can then realise a particular topology defined over the address space. The overlay topology chosen is called Kademlia: It enables communication between any two arbitrary nodes in the Swarm network by providing a strategy to relay messages using only underlay peer connections. The protocol that describes how nodes share information with each other about themselves and other peers is called 'hive'. How nodes use this protocol to bootstrap the overlay topology is discussed in 2.1.4.

It is crucial that the overlay address space encompasses the full range of 256-bit integers. One central concept in Swarm is proximity order (PO), which quantifies the relatedness of two addresses on a discrete scale.[2] Given two addresses, x and y, $PO(x, y)$ counts the matching bits of their binary representation starting from the most significant bit up to the first one that differs. The highest proximity order is therefore 256, designating the maximum relatedness, i.e. where $x = y$.

2.1.3 Kademlia routing

Kademlia topology can be used to route messages between nodes in a network using overlay addressing. It has excellent scalability as it allows for universal routing such that both (1) the number of hops and (2) the number of peer connections are always logarithmic to the size of the network.

In what follows, we show the two common flavours of routing: *iterative/-zooming* and *recursive/forwarding*. Swarm's design crucially relies on the latter, forwarding flavour, which sets it apart as a less common approach compared to the more prevalent iterative flavour found in much of the peer-to-peer literature and used in most other implementations (see Maymounkov and Mazieres 2002, Baumgart and Mies 2007, Lua et al. 2005). To provide a comprehensive understanding, we will walk the reader through both approaches to reveal their idiosyncrasies.

[2]Proximity order is the discrete logarithmic scale of proximity, which, in turn is the inverse of normalised XOR distance.

Iterative and forwarding Kademlia

Let R be an arbitrary binary relation over nodes in a network. Nodes that are in relation R with a particular node x are called peers of x. Peers of x can be indexed by their proximity order (PO) relative to x. The equivalence classes of peers are called proximity order bins, or just bins for short. Once arranged in bins, these groups of peers form the Kademlia table of the node x (see Figure 2.1).

Node x has a saturated Kademlia table if there is a $0 \leq d_x \leq maxPO$ called the neighbourhood depth such that (1) the node has at least one peer in each bin up to and excluding proximity order bin d_x and (2) all nodes at least as near as d_x (called the nearest neighbours) are peers of x. If each node in a network has a saturated Kademlia table, then we say that the network has Kademlia topology.

Let R be the "is known to" relation: y "is known to" x if x has both overlay and underlay addressing information for y. In iterative Kademlia routing, the requestor node iteratively extends the graph of peers that are known to it. Using their underlay address, the requestor node will contact the peers that they know are nearest the destination address for peers that are further away (commonly using UDP). On each successive iteration, the peers become at least one order closer to the destination (see Figure 2.3). Because of the Kademlia criteria, the requestor will eventually discover the destination node's underlay address and can then establish direct communication with it. This iterative strategy[3] critically depends on the nodes' ability to find peers that are currently online. In order to find such a peer, a node needs to collect several candidates for each bin. The best predictor of availability is the recency of the peer's last response, so peers in a bin should be prioritised according to this ordering.

Swarm uses an alternative flavour of Kademlia routing, first described in Heep (2010) and then expanded on and worked out by Trón et al.

[3]The iterative protocol is equivalent to the original Kademlia routing that is described in Maymounkov and Mazieres (2002).

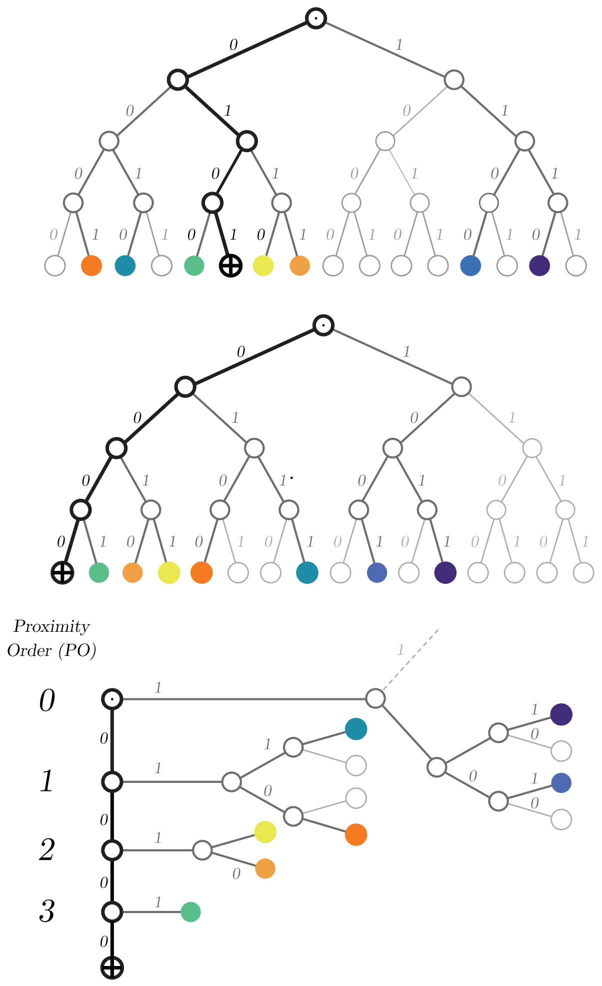


Figure 2.1: From overlay address space to Kademlia table. **Top**: the overlay address space is represented with a binary tree, colored leaves are actual nodes. The path of the pivot node (+) is shown with thicker lines. **Centre**: peers of the pivot nodes are shown keyed by the bits of their xor distance measured from the pivot. Here, 0s represent a matching bit with the pivot, and 1s show a differing bit. The leaf nodes are ordered by their xor distance from the pivot (leftmost node). **Bottom**: the Kademlia table of the pivot: the subtrees branching off from the pivot path on the left are displayed as the rows of the table representing proximity order bins in increasing order.

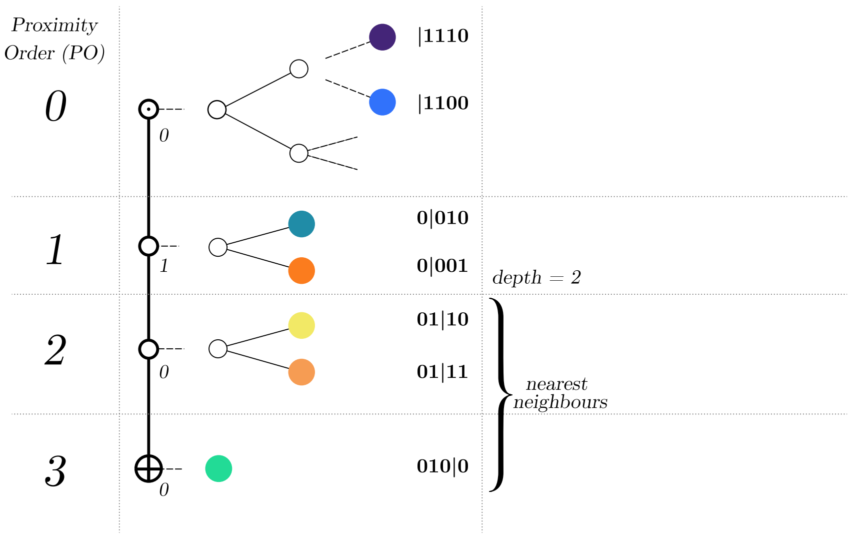
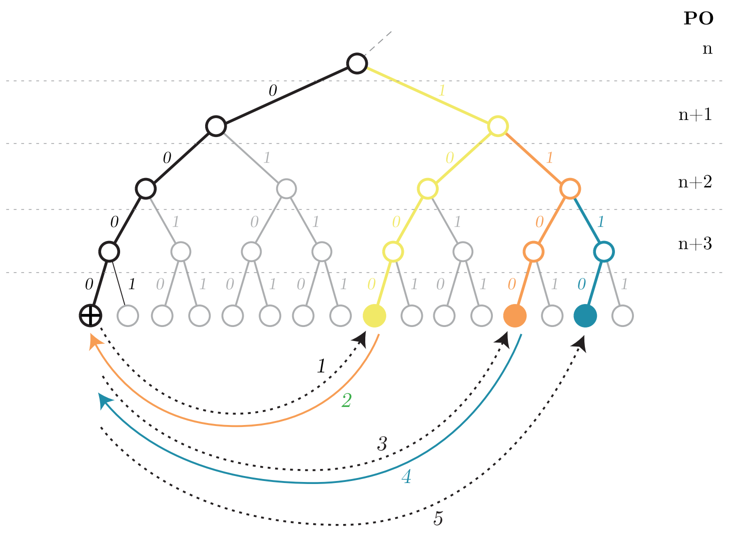


Figure 2.2: Nearest neighbours in a 4 bit network with $d = 2$

(2019b). Here, a recursive method is employed, whereby the successive steps of the iteration are "outsourced" to a downstream peer. Each node recursively passes a message to a direct peer at least one proximity order closer to the destination. Thus, routing using this approach simply means relaying messages via a chain of peers which are ever closer to the destination, as shown in Figure 2.3.

In this way, Swarm's underlay transport offers quasi-stable peer connections over TCP with communication channels that are kept alive. These open connections can then be used as R to define another notion of a peer. The two criteria of healthy Kademlia connectivity in Swarm translate as: For each node x, there exists a neighbourhood depth d_x such that (1) node x has an open connection with at least one node for each proximity order bin up to but excluding d_x, and (2) is connected to all the online nodes that are at least as near as d_x. If each node in the network has a saturated Kademlia table of peers, then the network is said to have Kademlia topology. Since connected peers are guaranteed to be online, the recursive step consists solely of forwarding the message to a connected peer strictly closer to the destination. We can call this alternative forwarding Kademlia.



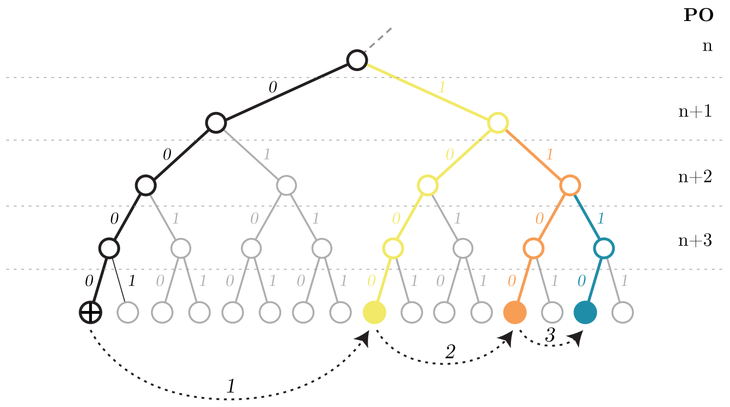


Figure 2.3: Iterative and Forwarding Kademlia routing: A requestor node shown with a cross in the circle at address ...0000... wants to route to a destination address ...1111... to which the closest peer online is the blue circle at ...1110... These initial ellipses represent the prefix shared by requestor and destination addresses which is n bits long. **Top:** In the iterative flavour, the requestor contacts the peers (Step 1, dotted black arrows) that they know are nearest the destination address. Peers that are online (yellow) respond with information about nodes that are even closer (green arrow, Step 2) so the requestor can now repeat the query using these closer peers (green, Step 3). On each successive iteration, the peers (yellow, green and blue) are at least one PO closer to the destination until eventually the requestor is in direct contact with the node that is nearest to the destination address. **Bottom:** In the forwarding flavour, the requestor forwards a message to the connected peer they know that is nearest to the destination (yellow). The recipient peer does the same. Applying this strategy recursively relays the message via a chain of peers (yellow, green, blue) each at least one PO closer to the destination.

In a forwarding Kademlia network, a message is said to be *routable* if there exists a path from sender to destination through which the message can be relayed. In a mature subnetwork with Kademlia topology every message is routable. If all peer connections are stably online, a thin Kademlia table, i.e. a single peer for each bin up to d, is sufficient to guarantee routing between nodes. In reality, however, networks are subject to churn, i.e. nodes are expected to go offline regularly. In order to ensure routability in the face of churn, the network needs to maintain Kademlia topology. This means that each individual node needs to have a saturated Kademlia table at all times. By keeping several connected peers in each proximity order bin, a node can ensure that node dropouts do not damage the saturation of their Kademlia table. Given a model of node dropouts, we can calculate the minimum number of peers needed per bin to guarantee that nodes are saturated with a probability that is arbitrarily close to 1. The more peers a node keeps in a particular proximity order bin, the more likely that the message destination address and the peer will have a longer matching prefix. As a consequence of forwarding the message to that peer, the proximity order increases more quickly, and the message ends up closer to the destination than it would with less peers in each bin (see also Figure 2.4).

With Kademlia saturation guaranteed, a node will always be able to forward a message and ensure routability. If nodes comply with the forwarding principles (and that is ensured by aligned incentives), the only case when relaying could possibly break down is when a node drops out of the network after having received a message but before it managed to forward it.[4]

An important advantage of forwarding Kademlia is that this method of routing requires a lot less bandwidth than the iterative algorithm. In

[4]Healthy nodes could commit to being able to forward within a (very short) constant time; let's call this the forwarding lag. In the case that a downstream peer disconnects before this forwarding lag passes, then the upstream peer can re-forward the message to an alternative peer, thereby keeping the message passing unbroken. See 2.3.1 for more detail.

the iterative version, known peers are not guaranteed to be online, so finding one that is available adds an additional level of unpredictability.

Sender anonymity

Sender anonymity is a crucial feature of Swarm. It is important that peers further down in the request cascade can never know who the originator of the request was, because requests are relayed from peer-to-peer.

The above rigid formulation of Kademlia routing would suggest that if a node receives a message from a peer and that message and peer have a proximity order of 0, then the recipient would be able to conclude that the peer it received the message from must be the sender. If we allow light node Swarm clients, i.e. clients that due to resource constraints do not keep a full Kademlia saturation but instead have just a local neighbourhood, then even a message from a peer in bin 0 remains of ambiguous origin.

Bin density and multi-order hops

As a consequence of logarithmic distance and uniform node distribution, the population of peers exponentially increases as we move further away from a particular node. This means that unless the number of required connections in a bin doubles as bins increase in distance from the node, shallower bins will always allow more choice of nodes for potential connection. In particular, nodes have a chance to increase the number of connections per bin in such a way that peer addresses maximise density (i.e., in proximity order bin b, the subsequent bits of peer addresses form a balanced binary tree). Such an arrangement is optimal in the sense that for a bin depth of d, nodes are able to relay all messages so that in one hop the proximity order of the destination address will increase by d (see Figure 2.4).

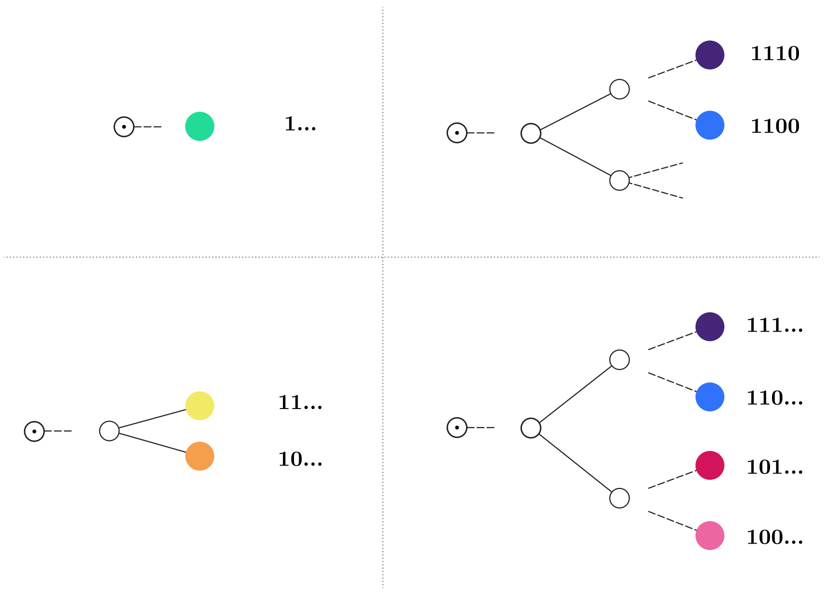


Figure 2.4: Bin density: types of saturation for PO bin 0 for a node with overlay address starting with bit 0. **Top left**: A "thin" bin with a single peer is not resilient to churn and only increases PO by 1 in one hop. **Top right:** At least two peers are needed to maintain Kademlia topology in case of churn; two peers when not balanced cannot guarantee multi-order hops. **Bottom left:** Two peers balanced guarantees an increase of 2 POs in one hop. **Bottom right:** Four peers, when balanced, can guarantee an increase of 3 POs in one hop.

Factoring in underlay proximity

It is expected that as Swarm clients continue to evolve and develop, nodes may factor in throughput when they select peers for connection. All things being equal, nodes physically closer to each other tend to have higher throughput, and therefore will be preferred in the long run. This is how forwarding Kademlia is implicitly aware of the underlay topology (Heep 2010).

2.1.4 Bootstrapping and maintaining Kademlia topology

This section discusses how a stable Kademlia topology can emerge. In particular, it outlines the exact bootstrapping protocol that each node must follow to reach and maintain a saturated Kademlia connectivity. Nodes joining a decentralised network are supposed to be initially naive, potentially initiating connection via only a single known peer with no prior knowledge. For this reason, the bootstrapping process needs to include an initial step that helps naive nodes to begin exchanging information about each other. This discovery process is called the hive protocol.

Bootnodes

Swarm has no distinct node type or operation mode for bootnodes. This means that naive nodes should be able to connect to any node on the network and bootstrap their desired connectivity. In order not to overburden any single node, electing one particular node as an initial connection should be avoided, and the role of being a bootnode for the newly connecting naive nodes should ideally be distributed among participant nodes. This is achieved either with an invite system, or a centralised bootnode service running a public gateway that responds to an API call with the bzz address of a randomly chosen node among online peers.

Once connected to a node in the network, the hive protocol kicks in and the naive node begins to learn about the bzz addresses of other nodes, and thus it can start bootstrapping its connectivity.

Building up connections

Initially, each node begins with zero as their saturation depth. Nodes keep advertising their saturation depth to their connected peers as it changes. When a node A receives an attempt to establish a new connection from a node B, she notifies each of her other peers about B connecting to her only in the case that each peer's proximity order relative to the connecting node A is not lower than that peer's advertised saturation depth. The notification is always sent to a peer that shares a proximity order bin with the new connection. Formally, when y connects to x, x notifies a subset of its connected peers. A peer p belongs to this subset if $PO(x,p) = PO(x,y)$ or $d_p \leq PO(y,p)$. The notification takes the form of a protocol message and includes the full overlay address and underlay address information.[5]

Mature connectivity

After a sufficient number of nodes are connected, a bin becomes saturated and the node's neighbourhood depth can begin to increase. Nodes keep their peers up to date by advertising their current depth if it changes. As their depth increases, nodes will get notified of fewer and fewer peers. Once the node finds all their nearest neighbours and has saturated all the bins, no new peers are to be expected. For this reason, a node can conclude a saturated Kademlia state if it receives

[5]Light nodes that do not wish to relay messages and do not aspire to build up a healthy Kademlia are not included, see Section 2.3.4.

no new peers for some time.[6] Instead of having a hard deadline and a binary state of saturation, we can quantify the certainty of saturation by considering the time elapsed since the arrival of the most recent new peer. Assuming stable connections, eventually each node online will get to know its nearest neighbours and connect to them while keeping each bin up to d non-empty. Therefore each node will converge on the saturated state. To maintain a robust Kademlia topology in the face of changing peer connections, it is crucial to include multiple peers within each proximity order bin. This prevents the node from regressing to a lower saturation state, even when there are no new nodes joining the network.

2.2 Swarm storage

In this section, in 2.2.1, we first show how a network with quasi-permanent connections in a Kademlia topology can support a load balancing, distributed storage of fixed-sized data blobs. In 2.2.1, we detail the generic requirements on chunks and introduce actual chunk types. Finally, in 2.2.5, we turn to redundancy by neighbourhood replication as a first line of defense against node churn.

2.2.1 Distributed immutable store for chunks

In this section, we discuss how networks using Kademlia overlay routing are a suitable basis on which to implement a serverless storage solution using distributed hash tables (DHTs). Then we introduce the DISC[7]

[6]Note that the node does not need to know the total number of nodes in the network. In fact, some time after the node stops receiving new peer addresses, the node can effectively estimate the size of the network: the depth of network is $\log_2(n+1)+d$ where n is the number of remote peers in the nearest neighbourhood and d is the depth of that neighbourhood. It then follows that the total number of nodes in the network can be estimated simply by taking this to the power of 2.

[7]DISC is distributed immutable store for chunks. In earlier work, we have referred to this component as the 'distributed preimage archive' (DPA), however, this phrase became misleading since we now also allow chunks that are not the preimage of their address.

model, Swarm's narrower interpretation of a DHT for storage. This model imposes some requirements on chunks and necessitates 'upload' protocols.

As is customary in Swarm, we provide a few resolutions of this acronym, which summarise the most important features:

— decentralised infrastructure for storage and communication,
— distributed immutable store for chunks,
— data integrity by signature or content address,
— driven by incentives with smart contracts.

From DHT to DISC

Swarm's DISC shares many similarities with widely known distributed hash tables. The most important difference is that Swarm does not keep track of *where* files are to be found, instead it actually *stores pieces of the file itself* directly with the closest node(s). In what follows, we review DHTs, as well as dive into the similarities and differences with DISC in more detail.

Distributed hash tables use an overlay network to implement a key–value container distributed over the nodes (see Figure 2.5). The basic idea is that the keyspace is mapped onto the overlay address space, and the value for a key in the container is to be found with nodes whose addresses are in the proximity of the key. In the simplest case, let us say that this is the single closest node to the key that stores the value. In a network with Kademlia connectivity, any node can route to a node whose address is closest to the key, therefore a *lookup* (i.e. looking up the value belonging to a key) is reduced simply to routing a request.

DHTs used for distributed storage typically associate content identifiers (as keys/addresses) with a changing list of seeders (as values) that can serve that content (IPFS 2014, Crosby and Wallach 2007). However, the same structure can be used directly: in Swarm, it is not information about the location of content that is stored at the node closest to the address, but the content itself (see Figure 2.6).

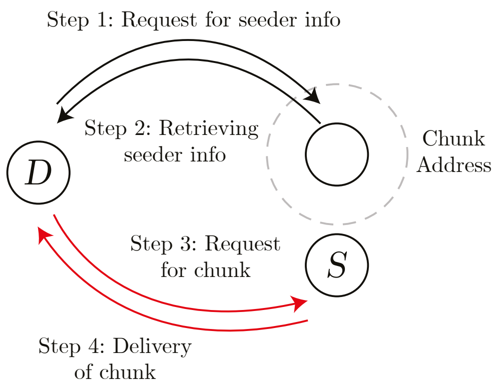

Step 1: Request for seeder info
Step 2: Retrieving seeder info
D
Chunk Address
Step 3: Request for chunk
S
Step 4: Delivery of chunk

Figure 2.5: Distributed hash tables (DHTs) used for storage: node *D* (downloader) uses Kademlia routing in Step 1 to query nodes in the neighbourhood of the chunk address to retrieve seeder info in Step 2. The seeder info is used to contact node *S* (seeder) directly to request the chunk and deliver it in Steps 3 and 4.

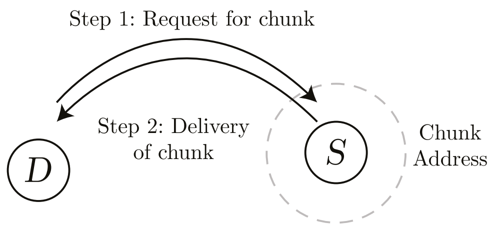


Figure 2.6: Swarm DISC: Distributed Immutable Store for Chunks. In Step 1, downloader node *D* uses Kademlia connectivity to send a request for the chunk to a peer storer node that is closer to the address. This peer then repeats this until node *S* is found that has the chunk. In other words peers relay the request recursively via live peer connections ultimately to the neighbourhood of the chunk address (request forwarding). In Step 2 the chunk is delivered along the same route using the forwarding steps in the opposite direction (response backwarding).

Constraints

The DISC storage model is opinionated about which nodes store what content and this implies the following restrictions:

fixed-size chunks
: Load balancing of content is required among nodes and is realised by splitting content into equal-sized units called chunks (see 2.2.1).

syncing
: There must be a process whereby chunks get to where they are supposed to be stored, no matter which node uploads them (see 2.3.2).

plausible deniability
: Since nodes do not have a say in what they store, measures should be employed that serve as the basis of legal protection for node operators. They need to be able to plausibly deny knowing (or even being able to know) anything about the chunks' contents (see 2.2.4).

garbage collection
: Since nodes commit to store any data close to them, there needs to be a strategy to select which chunks are kept and which are discarded in the presence of storage space constraints.

Chunks

Chunks are the basic storage units used in Swarm's network layer. They are an association of an address with content. Since retrieval in Swarm (2.3.1) assumes that chunks are stored with nodes close to their address, fair and equal load balancing requires that the addresses of chunks should also be uniformly distributed in the address space, and have their content limited and roughly uniform in size.

When chunks are retrieved, the downloader must be able to verify the correctness of the content given the address. Such integrity translates to guaranteeing uniqueness of content associated with an address. In order to protect against frivolous network traffic, a third party of forwarding nodes should be able to verify the integrity of chunks using only local information available to the node.

The deterministic and collision-free nature of addressing implies that chunks are unique as a key–value association: If there exists a chunk with an address, then no other valid chunk can have the same address; this assumption is crucial as it makes the chunk store immutable, i.e. there is no replace/update operation on chunks. Immutability is beneficial in the context of relaying chunks as nodes can negotiate information about the possession of chunks simply by checking their addresses. This plays an important role in the stream protocol (see 2.3.3) and justifies the DISC resolution as a *distributed immutable store for chunks*.

To sum up, chunk addressing needs to fulfill the following requirements:

deterministic
  To enable local validation.
collision-free
  To provide integrity guarantee.
uniformly distributed
  To deliver load balancing.

In the current version of Swarm, we support two types of chunks: content addressed chunks and single owner chunks.

2.2.2 Content addressed chunks

A content addressed chunk is not assumed to be a meaningful storage unit, i.e. they can be just blobs of arbitrary data resulting from splitting a larger data blob, a file. The methods by which files are disassembled into chunks when uploading and then reassembled from chunks when downloading are detailed in 4.1. The data size of a content addressed Swarm chunk is limited to 4 kilobytes. One of the desirable consequences of using this small chunk size is that concurrent retrieval is available even for relatively small files, reducing the latency of downloads.

Binary Merkle tree hash

The canonical content addressed chunk in Swarm is called a binary Merkle tree chunk (BMT chunk). The address of BMT chunks is calculated using the binary Merkle tree hash algorithm (BMT hash). The base

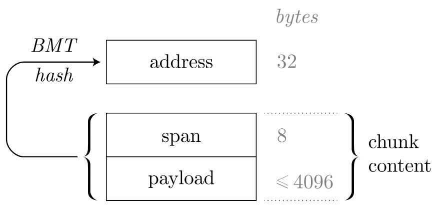


Figure 2.7: Content addressed chunk. An at most 4KB payload with a 64-bit little-endian encoded span prepended to it constitutes the chunk content used in transport. The content address of the chunk is the hash of the byte slice that is the span and the BMT root of the payload concatenated.

hash used in BMT is Keccak256, properties of which such as uniformity, irreversibility, and collision resistance all carry over to the BMT hash algorithm. As a result of uniformity, a random set of chunked content will generate addresses evenly spread in the address space, i.e. imposing storage requirements balanced among nodes.

The BMT chunk address is the hash of the 8-byte span and the root hash of a binary Merkle tree (BMT) built on the 32-byte segments of the underlying data (see Figure 2.8). If the chunk content is less than 4k, the hash is calculated as if the chunk was padded with all zeros up to 4096 bytes.

This structure allows for compact inclusion proofs with a 32-byte resolution. An inclusion proof is a proof that one string is a substring of another string, for instance, that a string is included in a chunk. Inclusion proofs are defined on a data segment of a particular index, see Figure 2.9. Such Merkle proofs are also used as proof of custody when storer nodes provide evidence that they possess a chunk (see 3.4). Together with the Swarm file hash (see 4.1.1), they allow for logarithmic inclusion proofs for files, i.e., proof that a string is found to be part of a file.

2.2.3 Single owner chunks

With single owner chunks, a user can assign arbitrary data to an address and attest chunk integrity with their digital signature. The address is

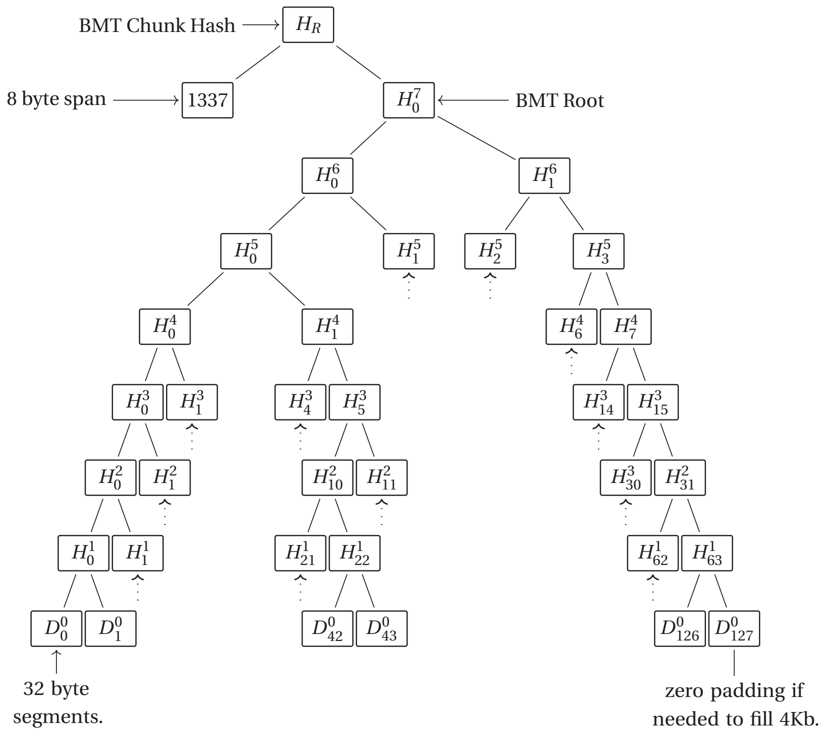


Figure 2.8: Binary Merkle Tree chunk hash in Swarm: the 1337 bytes of chunk data is segmented into 32-byte segments. Zero padding is used to fill up the rest up to 4 kilobytes. Pairs of segments are hashed together using Keccak256 to build up the binary tree. On level 8, the binary Merkle root is prepended with the 8-byte span and hashed to yield the BMT chunk hash.

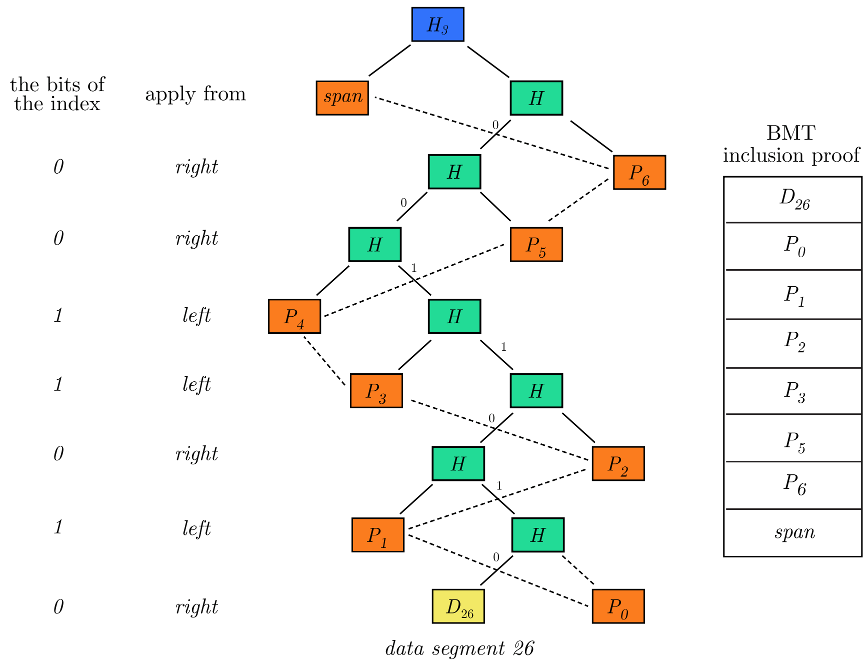


Figure 2.9: Compact segment inclusion proofs for chunks. Assume we need proof for segment 26 of a chunk (yellow). The orange hashes of the BMT are the sister nodes on the path from the data segment up to the root and constitute what needs to be part of a proof. When these are provided together with the root hash and the segment index, the proof can be verified. The side on which proof item i needs to be applied depends on the i-th bit (starting from least significant) of the binary representation of the index. Finally, the span is prepended and the resulting hash should match the chunk root hash.

calculated as the hash of an identifier and an owner. The chunk content is presented in a structure composed of the identifier, the payload, and a signature attesting to the association of identifier and payload (see Figure 2.10).

content
: payload
    - 32 bytes arbitrary identifier
    - 65 bytes $\langle r, s, v\rangle$ representation of an EC signature (32+32+1 bytes),
    - an 8-byte little-endian binary of uint64 chunk span,
    - maximum 4096 bytes of regular chunk data.

address
: Keccak256 hash of identifier + owner account.

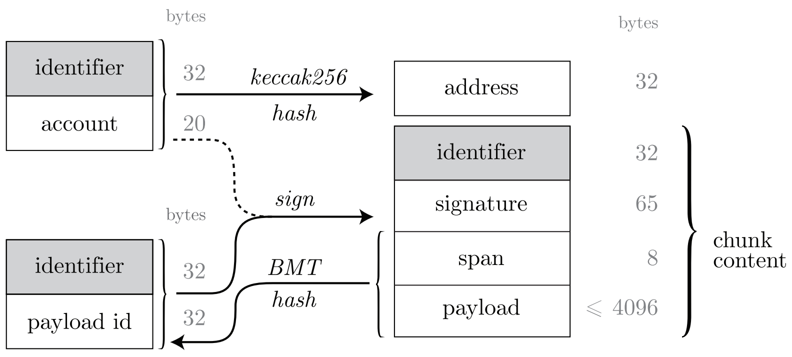


Figure 2.10: Single owner chunk. The chunk content is composed of headers followed by an at most 4KB payload. The last header field is the 8-byte span prepended just like in content addressed chunks. The first two header fields provide single-owner attestation of integrity: an identifier and a signature signing off on the identifier and the BMT hash of span and payload. The address is the hash of the ID and the signer account.

The validity of a single owner chunk is checked with the following process:

1. Deserialise the chunk content into fields for identifier, signature, and payload.

2. Construct the expected plain text composed of the identifier and the BMT hash of the payload.
3. Recover the owner's address from the signature using the plain text.
4. Check the hash of the identifier and the owner (expected address) against the chunk address.

Single owner chunks offer a virtual partitioning of part of the address space into subspaces associated with the single owner. Checking their validity is actually an authentication verifying that the owner has write access to the address with the correct identifier.

As suggested by the span and the length of the payload, a single owner chunk can encapsulate a regular content addressed chunk. Anyone can simply reassign a regular chunk to an address in their subspace designated by the identifier (see also 4.4.4).

It should be noted that the notion of integrity is somewhat weaker for single owner chunks than in the case of content addressed chunks: After all, it is, in principle, possible to assign and sign any payload to an identifier. Nonetheless, given the fact that the chunk can only be created by a single owner (of the private key that the signature requires), it is reasonable to expect uniqueness guarantees because we hope the node will want to comply with application protocols to get the desired result. However, if the owner of the private key signs two different payloads with the same identifier and uploads both chunks to Swarm, the behaviour of the network is unpredictable. Measures can be taken to mitigate this in layer (3) and are discussed later in detail in 4.3.3.

With two types of chunks, integrity is linked to collision-free hash digests, derived from either a single owner and an arbitrary identifier attested by a signature or directly from the content. This justifies the resolution of the DISC acronym as *data integrity through signing or content address.*

2.2.4 Chunk encryption

Chunks should be encrypted by default. Beyond client needs for confidentiality, encryption has two further important roles. (1) Obfuscation of chunk content by encryption provides a degree of plausible deniability; using it across the board makes this defense stronger. (2) The ability to choose arbitrary encryption keys together with the property of uniform distribution offer predictable ways of mining chunks, i.e., generating an encrypted variant of the same content so that the resulting chunk address satisfies certain constraints, e.g. is closer to or farther away from a particular address. This is an important property used in (1) price arbitrage (see 3.1.2) and (2) efficient utilisation of postage stamps (see 3.3).

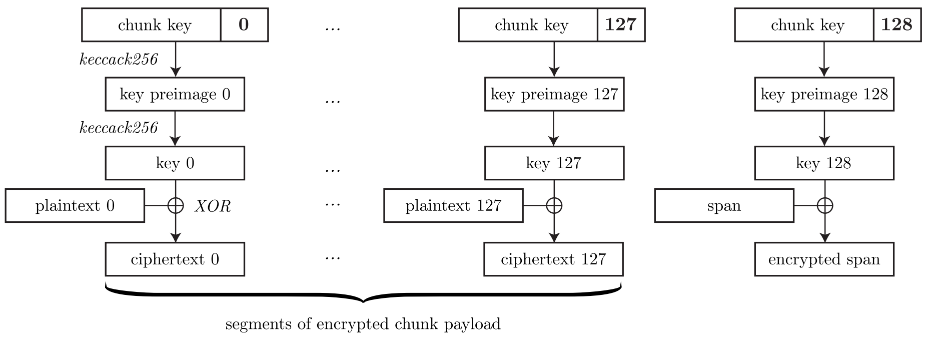


Figure 2.11: Chunk encryption in Swarm. Symmetric encryption with a modified counter-mode block cipher. The plaintext input is the content padded with random bytes to 4 kilobytes. The span bytes are also encrypted as if they were continuations of the payload.

Chunks shorter than 4 kilobytes are padded with random bytes (generated from the chunk encryption seed). The full chunk plaintext is encrypted and decrypted using stream cipher; XOR with a PRNG seeded with the corresponding symmetric key. In order not to increase the attack surface by introducing additional cryptographic primitives, the stream cipher of choice is using Keccak256 in counter mode, i.e. hashing together the key with a counter for each consecutive segment of 32 bytes. In order to allow selective disclosure of individual segments that are part of an encrypted file, yet leak no information about the rest of the file, we add an additional step of hashing to derive the encryption key for a segment within the chunk. This scheme is easy and cheap to implement in the (EVM), lending itself to use in smart contracts containing the plaintext of encrypted Swarm content.

The prepended metadata encoding the chunk span is also encrypted as if it was a continuation of the chunk, i.e. with counter 128. Encrypted chunk content is hashed using the BMT hash digest just as unencrypted ones are. The fact that a chunk is encrypted may be guessed from the span value, but apart from this, in the network layer, encrypted chunks behave in exactly the same way as unencrypted ones.

Single owner chunks can also be encrypted, which simply means that they wrap an encrypted regular chunk. Therefore, their payload and span reflect the chunk content encryption described above, the hash signed with the identifier is the BMT hash of the encrypted span and payload, i.e. the same as that of the wrapped chunk.

2.2.5 Redundancy by local replication

It is important to have a resilient means of requesting data. To achieve this, Swarm implements the approach of defence in depth. In the case that a request fails due to a problem with forwarding, one can retry the request with another peer. Alternatively, to guard against these occurrences, a node can initiate concurrent retrieve requests right away. However, such fallback options are not available if the single last node that stores the chunk drops out from the network. Therefore, redundancy is of major importance to ensure data availability. If the closest node is the only storer of the requested data and it drops out of the network, then there is no way to retrieve the content. This basic scenario is handled by ensuring that each set of nearest neighbours hold replicas of each chunk that is closest to any one of them, duplicating the storage of chunks and therefore providing data redundancy.

Size of nearest neighbourhoods

If the Kademlia connectivity is defined over storer nodes, then in a network with Kademlia topology there exists a depth d such that (1) each proximity order bin less than d contains at least k storer peers, and (2) all storer nodes with proximity order d or higher are actually connected peers. In order to ensure data redundancy, we can add to this definition a criterion that (3) the nearest neighbourhood defined by d must contain at least r peers.

Let us define neighbourhood size $NHS_x(d)$ as the cardinality of the neighbourhood defined by depth d of node x. Then, a node has Kademlia connectivity with redundancy factor r if there exists a depth d such that (1) each proximity order bin lower than d contains at least k storer peers (k is the bin density parameter, see 2.1.3), and (2) all storer nodes with proximity order d or higher are actually connected peers, and (3) $NHS_x(d) \geq r$.

We can then take the highest depth d' such that (1) and (2) are satisfied. Such a d is guaranteed to exist and the hive protocol is always able to bootstrap it. As we decrease d', the number of distinct neighbourhoods grow proportionally, so for any redundancy parameter not greater than the network size $r \leq N = NHS_x(0)$, there will be a highest $0 < d_r \leq d'$ such that $NHS_x(d_r) \geq r$. Therefore, redundant Kademlia connectivity is always achievable.

For a particular redundancy, the area of the fully connected neighbourhood defines an area of responsibility. The proximity order boundary of the area of responsibility defines a radius of responsibility for the node. A storer node is said to be *responsible* for (storing) a chunk if the chunk address falls within the node's radius of responsibility.

It is already instructive at this point to show neighbourhoods and how they are structured, see Figure 2.12.

Redundant retrievability

A chunk is said to have redundant retrievability with degree r if it is retrievable and would remain so even after any r nodes responsible for it leave the network. The naive approach presented so far requiring the single closest node to keep the content can be interpreted as degree zero retrievability. If nodes in their area of responsibility fully replicate their content (see 2.3.3), then every chunk in the Swarm DISC is redundantly

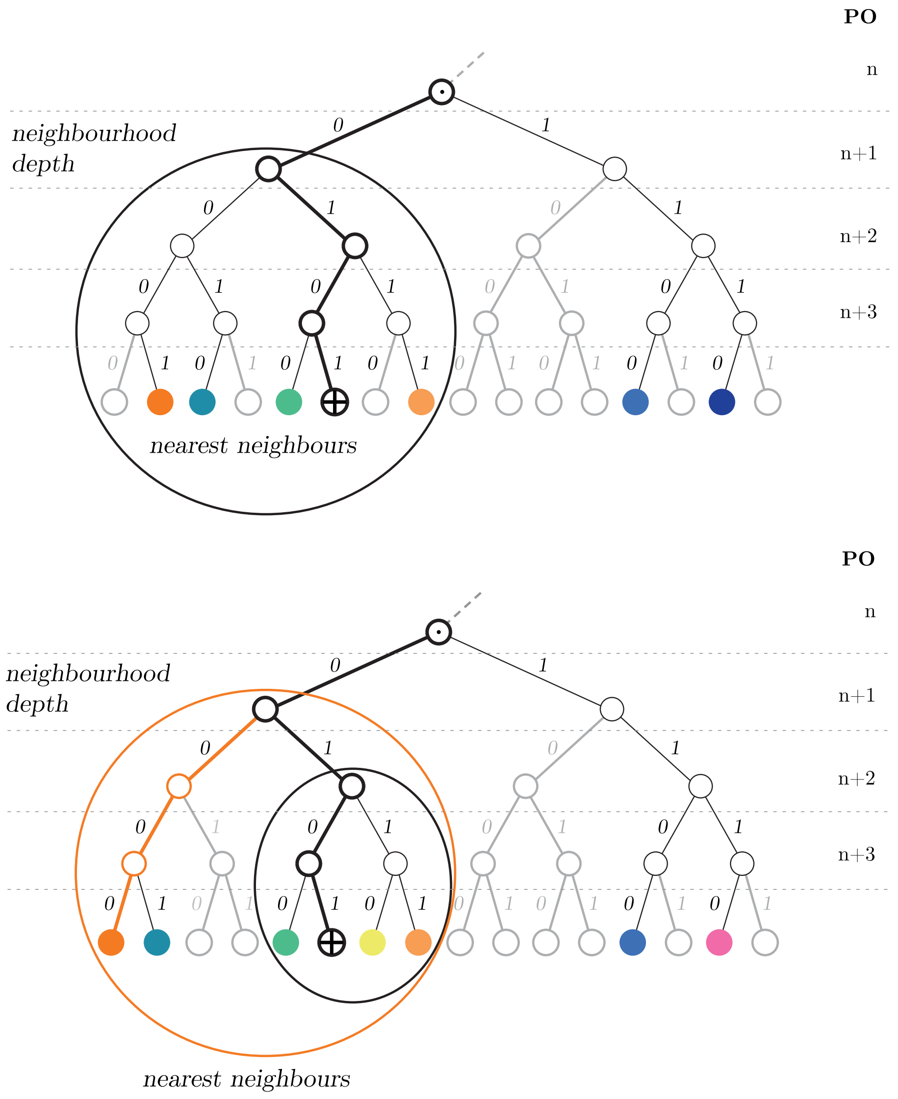


Figure 2.12: Nearest neighbours. **Top**: Each PO defines a neighbourhood, the neighbourhood depth of the node (black circle) is defined as the highest PO such that the neighbourhood has at least R=4 peers (redundancy parameter) and all shallower bins are non-empty. **Bottom**: An asymmetric neighbourhood. Nearest neighbours of the orange node include the black node but not the other way round.

retrievable with degree r. Let us take the node x that is closest to a chunk c. Since it has Kademlia connectivity with redundancy r, there are $r+1$ nodes responsible for the chunk in a neighbourhood fully connected and replicating content. After r responsible nodes drop out, there is just one node remaining which still has the chunk. However, if Kademlia connectivity is maintained as the r nodes leave, this node will continue to be accessible by any other node in the network, and therefore the chunk is still retrievable. Now, for the network to ensure that all chunks remain redundantly retrievable with degree r, the nodes comprising the new neighbourhood formed due to the reorganising of the network must respond by re-syncing their content to satisfy the protocol's replication criteria. This is called the guarantee of eventual consistency.

Resource constraints

Let us assume then that (1) the forwarding strategy that relays requests along stable nodes and (2) the storage strategy that each node in the nearest neighbourhood (of r storer nodes) stores all chunks whose addresses fall within their radius of responsibility. As long as these assumptions hold, each chunk is retrievable even if r storer nodes drop offline simultaneously. As for (2), we still need to assume that every node in the nearest neighbour set can store each chunk. Realistically, however, all nodes have resource limitations. With time, the overall amount of distinct chunks ever uploaded to Swarm will increase indefinitely. Unless the total storage capacity steadily increases, we should expect that the nodes in Swarm are able to store only a subset of chunks. Some nodes will reach the limit of their storage capacity and therefore face the decision whether to stop accepting new chunks via syncing or to make space by deleting some of their existing chunks.

The process that purges chunks from their local storage is called garbage collection. The process that dictates which chunks are chosen for garbage collection is called the garbage collection strategy. For a profit-maximizing node, it holds that it is always best to garbage-collect the chunks that are predicted to be the least profitable in the future and, in order to maximize profit, it is desired for a node to get this prediction right (see 3.3). So, in order to factor in these capacity constraints, we will introduce the notion of chunk value and modify our definitions using the minimum value constraint:

In Swarm's DISC, at all times, there is a chunk value v such that every chunk with a value greater than v is both retrievable and eventually (after syncing) redundantly retrievable with degree r.

This value ideally corresponds to the relative importance of preserving the chunk that uploaders need to indicate. In order for storer nodes to respect it, the value should also align with the profitability of a chunk and is therefore expressed in the pricing of uploads (see 3.3.4).

2.3 Push and pull: chunk retrieval and syncing

In this section, we demonstrate how chunks actually move around in the network: How they are pushed to the storer nodes in the neighbourhood they belong to when they are uploaded, as well as how they are pulled from the storer nodes when they are downloaded.

2.3.1 Retrieval

In a distributed chunk store, we say that a chunk is an accessible chunk if a message is routable between the requester and the node that is closest to the chunk. Sending a retrieve request message to the chunk address will reach this node. Because of eventual consistency, the node closest to the chunk address will store the chunk. Therefore, in a DISC distributed chunk store with healthy Kademlia topology, all chunks are always accessible for every node.

Chunk delivery

For retrieval, accessibility needs to be complemented with a process to have the content delivered back to the requesting node, preferably using only the chunk address. There are at least three alternative ways to achieve this (see Figure 2.13):

direct delivery
: The chunk delivery is sent via a direct underlay connection.

routed delivery

The chunk delivery is sent as message using routing.

backwarding

The chunk delivery response simply follows the route along which the request was forwarded, just backwards all the way to the originator.

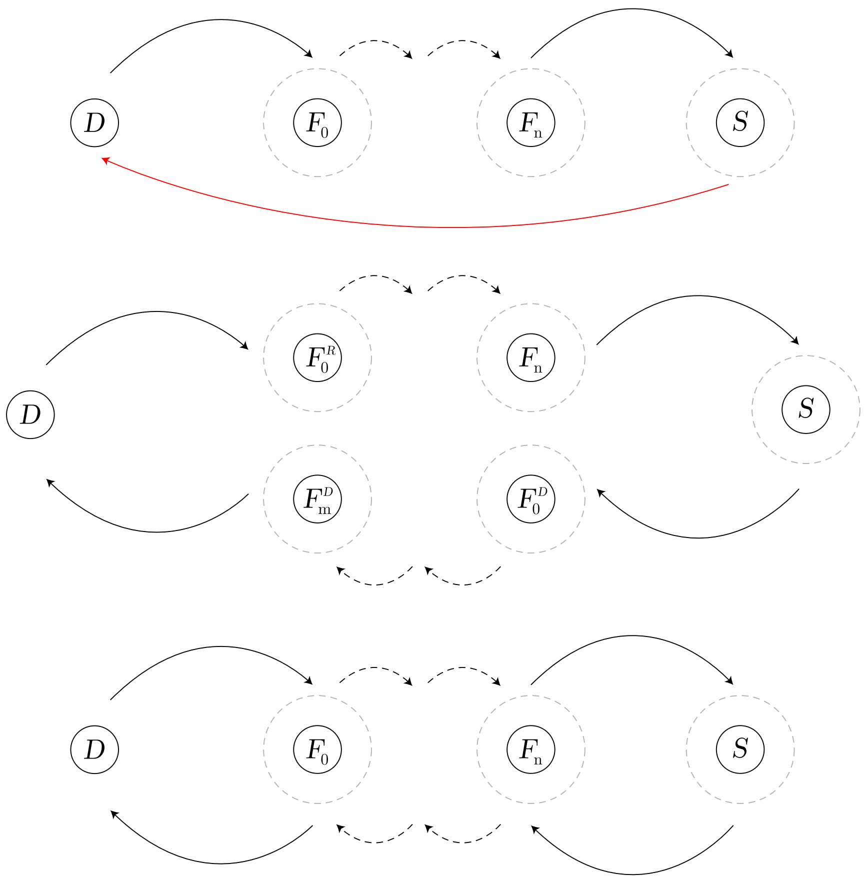


Figure 2.13: Alternative ways to deliver chunks. **Top:** *direct delivery*: via direct underlay connection. **Centre:** *routed delivery*: chunk is sent using Kademlia routing. **Bottom:** backwarding re-uses the exact peers on the path of the request route to relay the delivery response.

Firstly, using the obvious direct delivery, the chunk is delivered in one step via a lower-level network protocol. This requires an ad-hoc connection with the associated improvement in latency traded off for worsened security of privacy.[8] Secondly, using routed delivery, a chunk is delivered back to its requestor using ad-hoc routing as determined from the storer's perspective at the time of sending it. Whether direct or routed, allowing deliveries routed independently of the request route presupposes that the requestor's address is (at least partially) known by the storer and routing nodes. Consequently, these methods disclose information that can identify the requestor. However, with forwarding–backwarding Kademlia this is not necessary: The storer node responds back to their requesting peer with the delivery, while intermediate forwarding nodes remember which of their peers requested what chunk. When the chunk is delivered, they pass it on back to their immediate requestor, and so on until it eventually arrives at the node that originally requested it. In other words, the chunk delivery response simply follows the request route back to the originator (see Figure 2.14). Since it is the reverse of the forwarding, we can playfully call this backwarding. Swarm uses this option, which makes it possible to disclose no requestor identification in any form, and thus Swarm implements completely anonymous retrieval.

Ensuring requestor anonymity by default in the retrieval protocol is a crucial feature that Swarm insists upon. This feature aims to safeguard user privacy and enables censorship-resistant access.

The generic solution of implementing retrieval by backwarding as depicted in Figure 2.15 has further benefits relating to spam protection, scaling and incentivisation, which will be discussed in the remainder of this section.

Protection against unsolicited chunks

In order to remember requests, the forwarding node needs to allocate resources that come with a certain cost (they occupy space in memory). The requests that are not followed by a corresponding delivery should eventually be garbage collected, so there needs to be a defined time

[8]Beeline delivery has some merit, i.e. bandwidth saving and better latency, so we do not completely rule out the possibility of implementing it.

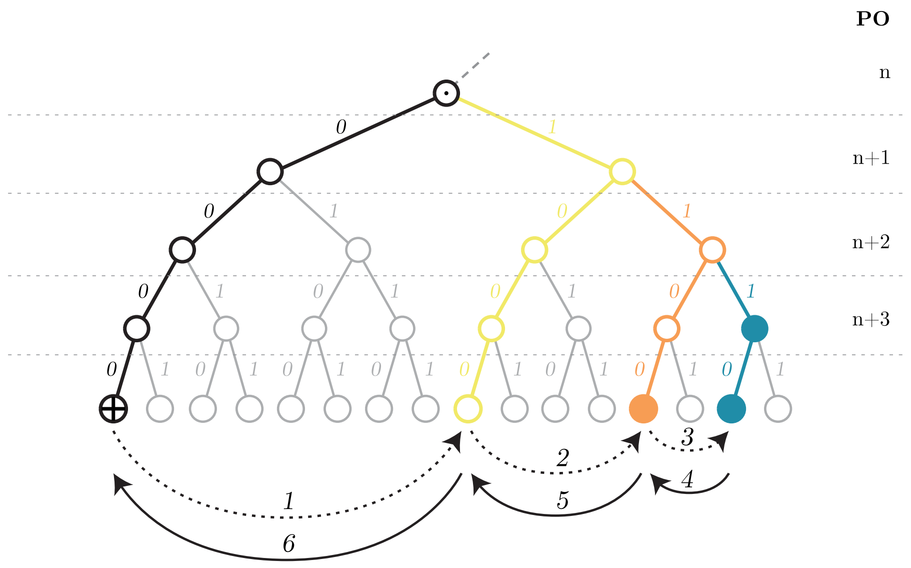


Figure 2.14: Backwarding: pattern for anonymous request–response round-trips in forwarding Kademlia. Here a node with overlay address ...0000... sending a request to target ....1111... to which the closest online node is ...1110... The leading ellipsis represents the prefix shared by the requestor and target and has a length of n bits. The trailing ellipsis represents part of the address that is not relevant for routing as at that depth nodes are already unique. The request uses the usual Kademlia forwarding, but the relaying nodes on the way remember the peer the request came from so that when the response arrives, they can *backward* it (i.e. pass it back) along the same route.

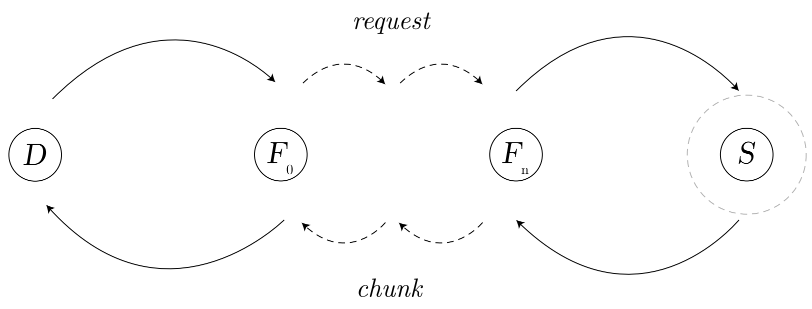


Figure 2.15: Retrieval. Node D (Downloader) sends a retrieve request to the chunk's address. Retrieval uses forwarding Kademlia, so the request is relayed via forwarding nodes F_0, ..., F_n all the way to node S, the storer node closest to the chunk address. The chunk is then delivered by being passed back along the same route to the downloader.

period during which they are active. Downstream peers also need to be informed about the timeout of this request. This makes sense, since the originator of the request will want to attach a time-to-live duration to the request to indicate how long it will wait for a response.

Sending unsolicited chunks is an offence as it can lead to denial of service (DoS). By remembering a request, nodes are able to recognise unsolicited chunk deliveries and penalise the peers sending them. Chunks that are delivered after the request expires will be treated as unsolicited. Since there may be some discrepancy assessing the expiry time between nodes, there needs to be some tolerance for unsolicited chunk deliveries, but if they go above a particular (but still small) percentage of requests forwarded, the offending peer is disconnected and blacklisted. Such local sanctions are the easiest and simplest way to incentivise adherence to the protocol (see 3.2.5).

Re-requesting

There is the potential for a large proportion of Swarm nodes to not be always stably online. Such a high churn situation would be problematic if we used the naive strategy of forwarding requests to any one closer node: If a node on the path were to go offline before delivery is completed, then the request-response round trip is broken, effectively rendering the chunk requested not retrievable. Commitment to pay for a chunk is considered void if the connection to the requested peer is dropped, so there is no harm in re-requesting the chunk from another node.

Timeout vs. not found

Note that in Swarm there is no explicit negative response for chunks not being found. In principle, the node that is closest to the retrieved address can determine the absence of a chunk at that address and could issue a "not found" response. However, this is not desirable for the following reason: While the closest node to a chunk can verify its absence from its expected location in the network, nodes further away from the chunk cannot reliably conclude the same. They lack first-hand verification, and any positive evidence regarding the chunk's retrievability obtained later can be retrospectively plausibly deniable.

All in all, as long as delivery has the potential to create earnings for the storer, the best strategy is to keep a pending request open until it times out and be prepared in case the chunk should appear. There are several ways the chunk could arrive after the request: (1) syncing from existing peers (2) appearance of a new node or (3) if a request precedes upload, e.g. the requestor has already "subscribed" to a single owner address (see 6.3) to decrease latency of retrieval. This is conceptually different from the usual server-client based architectures where it makes sense to expect a resource to be either on the host server or not.

Opportunistic caching

Using backwarding for chunk delivery responses to retrieve requests also enables opportunistic caching, where a forwarding node receives a chunk and the chunk is then saved in case it will be requested again. This mechanism is crucial in ensuring that Swarm scales the storage and distribution of popular content automatically (see 3.1.2).

Incentives

So far, we have shown that by using the retrieval protocol and maintaining Kademlia connectivity, nodes in the network are capable of retrieving chunks. However, since forwarding is expending a scarce resource (bandwidth), without providing the ability to account for this bandwidth use, network reliability will be contingent on the proportion of freeriding and altruism. To address this, in Section 3 we will outline a system of economic incentives that align with the desired behaviour of nodes in the network. When these profit-maximising strategies are employed by node operators, they give rise to emergent behaviour that is beneficial for users of the network as a whole.

2.3.2 Push syncing

In the previous sections, we presented how a network of nodes maintaining a Kademlia overlay topology can be used as a distributed chunk store and how Forwarding Kademlia routing can be used to define a protocol for retrieving chunks. When discussing retrieval, we assumed that chunks are located with the node whose address is closest to theirs. This section describes the protocol responsible for realising this assumption: ensuring delivery of the chunk to its prescribed storer after it has been uploaded to any arbitrary node.

This network protocol, called push syncing, is analogous to chunk retrieval: First, a chunk is relayed to the node closest to the chunk address via the same route as a retrieval request would be, and then in response a statement of custody receipt is passed back along the same path (see Figure 2.16). The statement of custody sent back by the storer to the uploader indicates that the chunk has reached the neighbourhood from which it is universally retrievable. By tracking these responses for each constituent chunk of an upload, uploaders can make sure that their upload is fully retrievable by any node in the network before sharing or publishing the address of their upload. Keeping this count of chunks push-synced and receipts received serves as the back-end for a *progress bar* that can be displayed to the uploader to give feedback of the successful propagation of their data across the network (see 6.1).

Statements of custody are signed by the nodes that claim to be the closest to the address. Similarly to downloaders in the retrieval protocol, the identity of uploaders can also remain hidden, hence forwarding Kademlia can implement anonymous uploads.

Another similarity is that in order to allow backwarding for responses, nodes should remember which peer sent a particular chunk. This record should persist for a short period while the statement of custody responses are expected. When this period ends, the record is removed. A statement of custody not matching a record is considered unsolicited and is allowed only up to a small percentage of all push-sync traffic

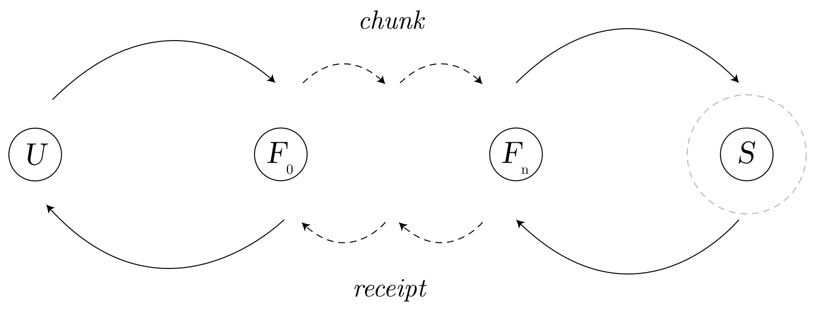


Figure 2.16: Push syncing. Node U (Uploader) push-syncs a chunk to the chunk's address. Push-sync uses forwarding, so the chunk is relayed via forwarding nodes F_0, ..., F_n all the way to node S, the storer node closest to the chunk address (the arrows represent transfer of the chunk via direct peer-to-peer connection). A statement of custody receipt signed by S is then passed back along the same route as an acknowledgment to the uploader.

with a peer. Going above this tolerance threshold is sanctioned with disconnection and blacklisting (see 3.2.5).

In this section, we described how the logistics of chunk uploads can be organised with a network protocol using Forwarding Kademlia routing with response backwarding. However, this solution is not complete until it is secured with aligned incentives: The strategy to follow this protocol should be incentivised and DoS abuse should be disincentivised. These are discussed later in detail in 3.3 and 3.1.3).

2.3.3 Pull syncing

Pull syncing is the protocol that is responsible for the following two properties:

eventual consistency
: Syncing neighbourhoods as and when the topology changes due to churn or new nodes joining.

maximum resource utilisation
: Nodes can pull chunks from their peers to fill up their surplus storage.[9]

Pull syncing is node-centric as opposed to chunk-centric, i.e. it makes sure that a node's storage is filled if needed, as well as syncing chunks within a neighbourhood. When two nodes are connected, they will start syncing both ways so that on each peer connection there is bidirectional chunk traffic. The two directions of syncing are managed by distinct and independent *streams*. In the context of a stream, the consumer of the stream is called downstream peer or client, while the provider is called the upstream peer or server.

When two nodes connect and engage in chunk synchronisation, the upstream peer offers all the chunks it stores locally in a data stream per proximity order bin. To receive chunks closer to the downstream peer than to the upstream peer, a downstream peer can subscribe to the chunk stream of the proximity order bin that the upstream peer belongs to in their Kademlia table. If the peer connection is within the nearest neighbour depth d, the client subscribes to all streams with proximity order bin d or greater. As a result, peers eventually replicate all chunks belonging to their area of responsibility.

A pull syncing server's behaviour is referred to as being that of a stream provider in the stream protocol. Nodes maintain a record of the time when they stored a chunk locally by indexing them with an ascending storage count known as the bin ID. For each proximity order bin, upstream peers offer to stream chunks in descending order of storage timestamp. As a result of syncing streams on each peer connection, a chunk can be synced to a downstream peer from multiple upstream peers. In order to save bandwidth by not sending data chunks to peers

[9]Maximum storage utilisation may not be optimal in terms of the profitability of nodes. Put differently, storer nodes have an optimal storage capacity based on how often content is requested from them. This means that in practice, profit-optimised maximum utilisation of storage capacity requires operators to run multiple node instances.

that already have them, the stream protocol implements a round-trip: Before sending chunks, the upstream peer presents a batch of chunks identified by their address. The downstream peer then responds with indicating which chunks from the offered batch they actually need (see Figure 2.17). Note that the downstream peer determines whether they have the chunk based on the chunk address. Thus, this method critically relies on the chunk integrity assumption discussed in 2.2.1.

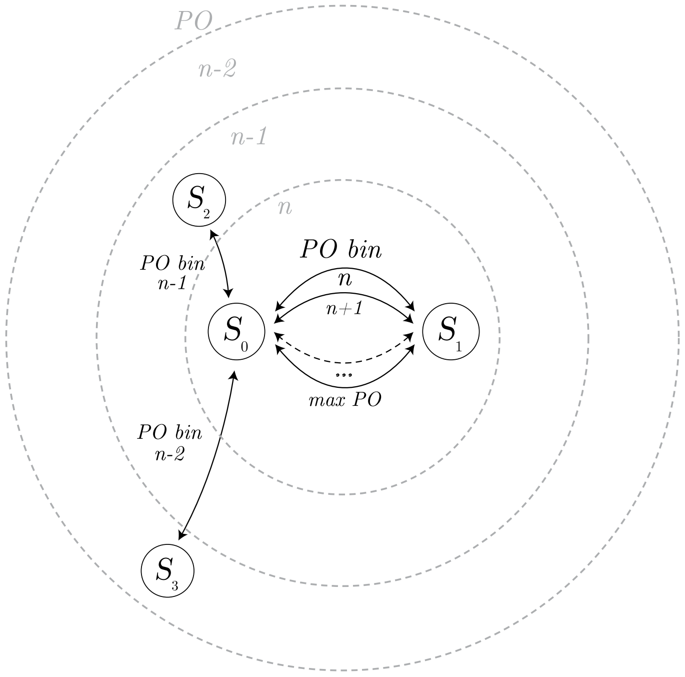


Figure 2.17: Pull syncing. Nodes continuously synchronise their nearest neighbourhood. If they have free capacity, they also pull sync chunks belonging to shallower bins from peers falling outside the neighbourhood depth.

In the context of a peer connection, a client is said to be *synced* if it has synced all the chunks of the upstream peer. Note that due to disk capacity limitations, nodes must impose a value cutoff, and as such, "all chunks" reads as shorthand for "all chunks having a value greater than v" (v is a constant ranking function, the origin of which is discussed later in 3.3.3). In order for a node to promise they store all chunks with value greater than v, it is necessary for all its neighbours to have also stored all chunks greater than value v. In other words, nodes syncing inherit the maximum such value from among their storer peers.

If chunks are synced in the order they are stored, this may not result in the node always having the most profitable (most often requested) chunks. Thus it may be advisable to sync chunks starting with the most popular ones according to upstream peers and finish syncing when storage capacity is reached. In this way, a node's limited storage will be optimised. Syncing and garbage collection are discussed further in 3.3 and 3.3.4.

To conclude this section, we show how the criteria of eventual consistency are met in a healthy Swarm. Chunks found in the local store of any node will become retrievable after being synced to their storers. This is because as long as those as peers in the network pull chunks closer to them than to the upstream peer, each chunk travels a route that would also qualify as valid a forwarding path in the push-sync protocol. If new nodes are added and old nodes drop out, neighbourhoods change, but as long as local redundancy is high enough that churn can not render previously retrievable chunks non-retrievable, neighbourhoods eventually replicate their content and redundancy is restored. Consider the unlikely event that a whole new neighbourhood is formed and the nodes that originally held the content belonging to this neighbourhood end up outside of it, resulting in a temporary unavailability of those chunks. Even in this scenario, as long as there is a chain of nodes running pull-syncing streams on the relevant bins, redundant retrievability is eventually restored.

2.3.4 Light nodes

The concept of a light node refers to a special mode of operation necessitated by poor bandwidth environments, e.g. mobile devices on low throughput networks or devices allowing only transient or low-volume storage.

A node is said to be light by virtue of not participating fully in the usual protocols detailed in the previous sections, i.e. retrieval, push syncing, or pull syncing.

A node that has restricted bandwidth environment or in whatever way has limited capacity to maintain underlay connections is not expected to be able to forward messages conforming to the rules of Kademlia routing. This needs to be communicated to its peers so that they do not relay messages to it.

As all protocols in Swarm are modular, a node may switch on or off any protocol independently (depending on capacity and earnings requirements). To give an example: a node that has no storage space available, but has spare bandwidth, may participate as a forwarding node only. Of course, while switching off protocols is technically feasible, a node must at all times take into account the fact that his peers expect a certain level of service if this is advertised and may not accept that some services are switched off and choose not to interact with that node.

Since forwarding can earn revenue, these nodes may still be incentivised to accept retrieve requests. However, if the light node has Kademlia connectivity above proximity order bin p (i.e. they are connected to all storer nodes within their nearest neighbourhood of r peers at depth d, and there is at least one peer in each of their proximity order bin from p to d), they can advertise this and therefore participate in forwarding.

When they want to retrieve or push chunks, if the chunk address falls into a proximity order bin where there are no peers, they can just pick a peer in another bin. Though this may result in a spurious hop (where the proximity of the message destination to the latest peer does not increase as a result of the relaying), the Kademlia assumption that routing can be completed in logarithmic steps still holds valid.

A node that is advertised as a storer/caching node is expected to store all chunks above a certain value. In order to maintain consistency, they need to synchronise content within their area of responsibility, which requires them to run the pull-sync protocol. The same applies to aspiring storer nodes that come online with available storage and open up to pull-sync streams to fill their storage capacity. In the early stages of this, it does not make sense for a node to sync to other full storer nodes. However, it can still be useful for them to sync with other similar newcomer nodes, especially if storer nodes are maxing out on their bandwidth.

The crucial thing here is that for redundancy and hops to work, light nodes with incomplete, unsaturated Kademlia tables should not be considered by other peers when calculating the level of saturation of the network.

3. Incentives

The Swarm network comprises many independent nodes, running software which implements the Swarm protocol. It is important to realise that even though nodes run the same protocol, the emergent behaviour of the network is not guaranteed by the protocol alone; as nodes are autonomous, they are essentially "free" to react in any way they desire to incoming messages of peers. It is, however possible to make it profitable for a node to react in a way that is beneficial for the desired emergent behaviour of the network, while making it costly to act in a way that is detrimental. Broadly speaking, this is achieved in Swarm by enabling a transfer of value from those nodes who are using the resources of the network (net users) to those who are providing it (net providers).

3.1 Sharing bandwidth

3.1.1 Incentives for serving and relaying

Forwarding Kademlia and repeated dealings

The retrieval of a chunk is ultimately initiated by someone accessing content, and therefore all costs related to this retrieval should be borne by them. While paid retrievals may not sound like a popular idea when today's web is "free", many of the problems with the current web stems from consumers' inability to share the costs of hosting and distribution with content publishers directly. In principle, the retrieval of a chunk can be perceived as a functional unit where the storer acts as a service provider and the requestor as consumer. The provider renders a service

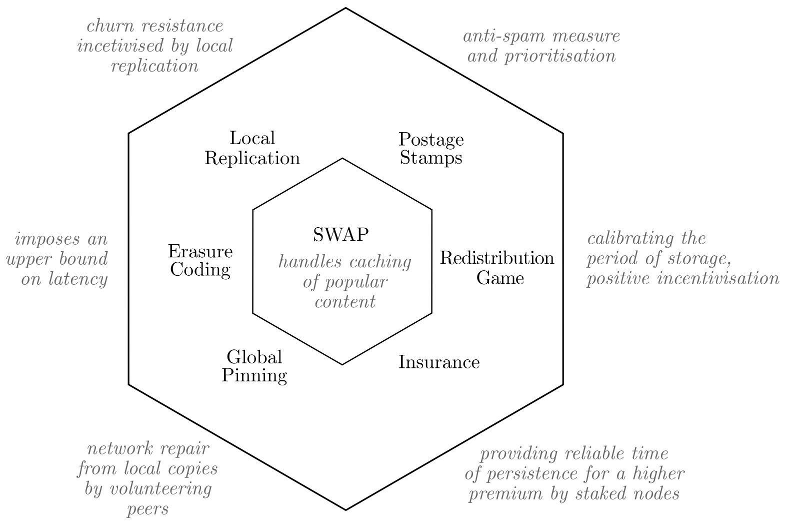

churn resistance incetivised by local replication
anti-spam measure and prioritisation
Local Replication
Postage Stamps
imposes an upper bound on latency
Erasure Coding
SWAP
handles caching of popular content
Redistribution Game
calibrating the period of storage, positive incentivisation
Global Pinning
Insurance
network repair from local copies by volunteering peers
providing reliable time of persistence for a higher premium by staked nodes

Figure 3.1: Incentive design

to the consumer, and in return, the consumer should provide compensation. Such a direct transaction would normally require that transactors are known to each other, so if we are to maintain the anonymity requirement on downloads, we must conceptualise compensation in a novel way.

As we use forwarding Kademlia, chunk retrieval subsumes a series of relaying actions performed by forwarding nodes. Since these are independent actors, it is already necessary to incentivise each act of relaying independently. Importantly, if only instances of relaying matter, then transactors are restricted to connected peers, regardless of the specifics of accounting and compensation (see 3.2.1). Given that the set of ever connected peers forms a quasi-permanent set across sessions, we are able to frame the interaction within the context of repeated dealings. Such a setting always creates extra incentive for the parties involved to play nice. It is reasonable to exercise preference for peers showing an untainted historical record. Moreover, since the set of connected peers is logarithmic in the network size, any book-keeping or blockchain contract that the repeated interaction with a peer might necessitate is kept manageable, offering a scalable solution. Turning the argument around, we could say that keeping balances with a manageable number of peers, as well as the ambiguity of request origination are the very reasons for nodes to have limited connectivity, i.e., that they choose leaner Kademlia bins.

Charging for backwarded response

If accepting a retrieve request already constitutes revenue for forwarding nodes, i.e. an accounting event crediting the downstream peer is triggered before the response is delivered, then it creates a perverse incentive not to forward the requests. Conditioning the request revenue fulfilment on successful retrieval is the natural solution: The accounting event is triggered only when a requested chunk is delivered back to its requestor, see Figure 3.2.

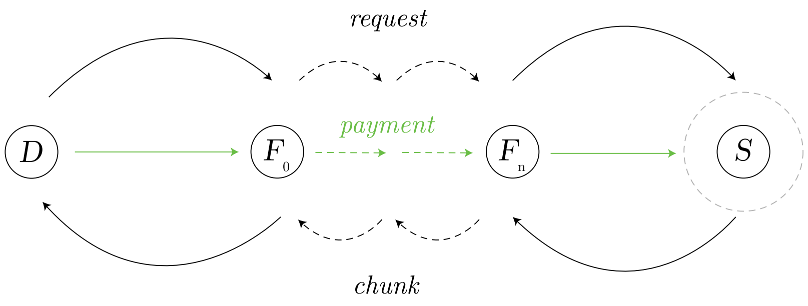


Figure 3.2: Incentivising retrieval. Node D (Downloader) sends a retrieve request to the chunk's address. Retrieval uses forwarding, so the request is relayed via forwarding nodes F_0, ..., F_n all the way to node S, the storer node closest to the chunk address. The chunk is delivered by being passed back along the same route to the downloader. Receiving the chunk response triggers an accounting event.

If, however, there is no cost to a request, then sending many illegitimate requests for non-existing chunks (random addresses) becomes possible. This is easily mitigated by imposing sanctions on peers that send too many requests for chunks that do not exist (see 3.2.5).

Once a node initiates (starts or forwards) a request, it commits to pay for that chunk if it is delivered within the defined time to live (TTL), therefore there is never an incentive to block timely deliveries when the chunk is passed back. This commitment also dissuades nodes from frivolously asking too many peers for a chunk, since, if multiple peers respond with delivery, each must be paid.

3.1.2 Pricing protocol for chunk retrieval

Next, we describe the protocol which nodes use to communicate their price for delivering chunks in the Swarm network. Building on top of this protocol, strategies can then be implemented by nodes who wish to compete in the market with other nodes in terms of quality of service and price.

Price discovery

The main merit of the protocol is that it allows for the mechanisms of price discovery to be based only on local decisions, which is essential for the following reasons: (1) Bandwidth costs are not homogeneous around the world: Allowing nodes to express their cost structure via their price will enable competition on price and quality, ultimately benefiting the end-user. (2) The demand for bandwidth resource is constantly changing due to fluctuations in usage or connectivity. (3) Being able to react directly to changes creates a self-regulating system.

Practically, without this possibility, a node operator might decide to shut down their node when costs go up or, conversely, end-users might overpay for an extended period of time when costs or demand decrease and there is no competitive pressure for nodes to reduce their price accordingly.

Bandwidth is a service that comes with "instant gratification" and therefore immediate acknowledgement and accounting of its cost are justified. Since it is hard to conceive of any externalities or non-linearities in the overall demand and supply of bandwidth, a pricing mechanism which provides for both (1) efficient and immediate signalling and (2) competitive choice with minimal switching and discovery costs is most likely to accommodate strategies that result in a globally optimal resource allocation.

To facilitate this, we introduce a protocol message that can communicate these prices to upstream peers. We can conceptualise this message as an alternative response to a request. Nodes maintain the prices associated with each peer for each proximity order. Therefore, when they issue a retrieve request, they already know the price they commit to pay as long as the downstream peer successfully delivers the valid chunk within the time-to-live period. However, there is no point in restricting the price signal just to responses: If, for whatever reason, a peer decides to change the prices, it is in the interest of both parties to exchange this information even if there is a request to respond to. In order to prevent DoS attacks by flooding upstream peers with price change messages, the rate of price messages is limited. Well-behaved and competitively priced nodes are favoured by their peers; if a node's prices are set too high or their prices exhibit a much higher volatility than others in the network, then peers will be less willing to request chunks from them.[1]

For simplicity of reasoning, we posit that the default price is zero, corresponding to a free service (altruistic strategy).

Differential pricing of proximities

If the price of a chunk is the same at all proximities, then there is no real incentive for nodes to forward requests other than the potential to cache the chunk and earn revenue by reselling it. This option is hard to justify for new chunks, especially if they are in the shallow proximity orders of a node where they are unlikely to be requested. More importantly, if the pricing of chunks is uniform across proximity orders, colluding nodes can generate chunk traffic and pocket exactly as much as they send, virtually a free DoS attack (see Figure 3.3).

To mitigate this attack, the price a requestor pays for a chunk needs to be strictly greater than what the storer node would receive as compensation when a request is routed from requestor to storer. We need to establish a

[1]While this suggests that unreasonable pricing is taken care of by market forces, in order to prevent catastrophic connectivity changes as a result of radical price fluctuations, limiting the rate of change may need to be enforced on the protocol level.

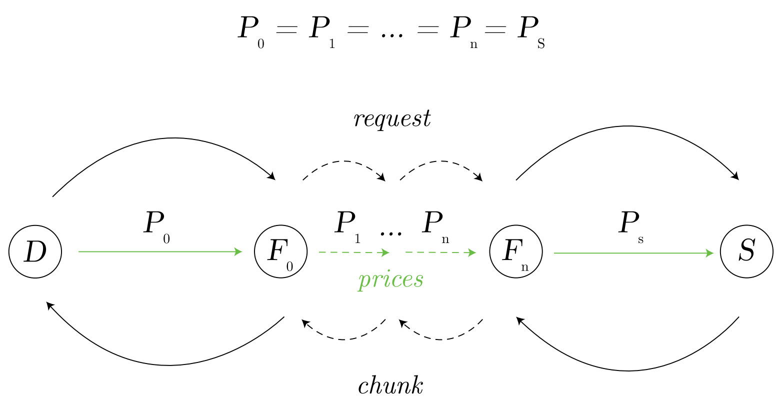


Figure 3.3: Uniform chunk price across proximities would allow a DoS attack. An attacker can create a flow of traffic between two nodes *D* and *S* by sending retrieve requests towards *S* which only *S* can serve. If prices are the same across proximities, such an attack would incur no cost for the attacker.

pricing scheme that rewards forwarding nodes, hence, this necessitates the implementation of differential pricing based on node proximity. If the price of delivery is lower as a node gets further from the chunk, then the request can always be sent that way because the forwarder will pocket the difference and therefore make a profit. This means that an effective differential scheme will converge to a pricing model where delivery costs more if the peer is further from the chunk address, i.e. rewards for chunk deliveries are a decreasing function of proximity.

Due to competitive pressure along the delivery path and in the neighborhood, we expect that the differential a node is applying to the downstream price to converge towards the marginal cost of an instance of forwarding. The downstream price is determined by the bin density of the node. Assuming balanced bins with cardinality 2^n, a node can guarantee to increase the proximity order by n in one hop. At the same time, it also means that they can spread the cost over n proximity bins pushing the overall price down.

Uniformity of price across peers

Take a node A that needs to forward a request for a chunk which falls into A's PO bin n. Notice that all other peers of A in bins $n+1, n+2, \ldots$, just like A also have the chunk in their PO n. If any of these peers, say B, has a price for proximity order n cheaper than A, A can lower its price for PO bin n, forward all increased traffic to B and still pocket the difference, see Figure 3.4. Note that this is not ideal for the network as it introduces a spurious hop in routing, i.e., in relaying without increasing the proximity.

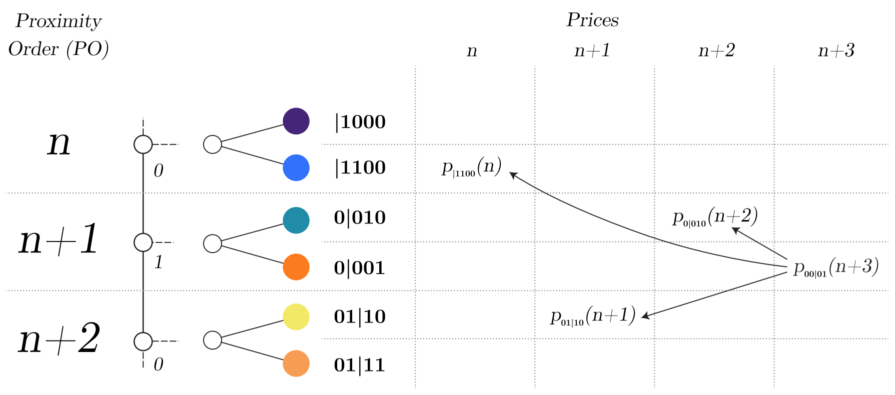


Figure 3.4: Price arbitrage. Nodes keep a price table for prices of every proximity order for each peer. The diagram shows node 0101 trying to forward a retrieve request for 0000. The arrows originate from the closest node, and point to cells where other peers although further from the chunk, offer cheaper to forward. Choosing the cheaper peer will direct traffic away from the overpriced peer and lead to a pressure on both to adjust.

Similarly, peers of A in shallower bins that have lower price than A for their respective bins, e.g., B in bin $n-1$ being cheaper than A in bin n, then A can always forward any request to B and pocket the difference.

Now let's assume that all peers have price tables which are monotonically decreasing as PO decreases. Also assume that shallower bins have higher prices for bins less than n, and all deeper peers in bins higher than n have the same prices for n. Let B, C, D and E be the peers in bin n densely balanced. A wants to forward a chunk to a peer so that the

PO with its target address increases by 3. If peers B and C attempt to collude against A and raise the price of forwarding chunks to bin $n+3$, they are still bound by D and E's price on PO bin $n+2$. In particular, if they are lower than B and C for $n+3$.

Such price discrepancies offer nodes an arbitrage opportunity; the strategy to forward to the cheapest peer will direct traffic away from expensive peers and increase traffic for cheaper ones. As a consequence, prices will adjust.

All else being equal, this price arbitrage strategy will achieve (1) uniform prices for the same proximity order across the network, (2) prices that linearly decrease as a function of proximity (3) nodes can increase connectivity and keep prices lower. In this way, incentivisation is designed so that strategies that are beneficial to individual nodes are also neatly aligned in order to benefit the health of the system as a whole.

Bin density

Charging based on the downstream peer's proximity to the chunk has the important consequence that the net revenue earned from a single act of non-local delivery to a single requestor is a monotonically increasing function of the difference between the chunk's proximity to the node itself and to the peer the request was forwarded to. In other words, the more distance we can cover in one forward request, the more we earn.

This incentive aligns with downloaders' interest to save hops in serving their requests, leading to lower-latency delivery and reduced bandwidth overhead. This scheme incentivises nodes to keep a gap-free balanced set of addresses in their Kademlia bins as deep as possible (see Figure 2.4), i.e, it is better for a node to keep dense Kademlia bins than thin ones.

Nodes that are able to maintain denser bins actually have the same cost as thinner ones, but saving hops will improve latency and make the peer more efficient. This will lead to the peer being preferred over other peers that have the same prices. Increased traffic essentially can also lead to bandwidth contention, which eventually allows the raising of prices.

Note that such arbitrage is more efficient in shallow bins where the number of peers to choose from is higher. This is in major opposition to deep bins in the area of responsibility. If a node does not replicate its neighbourhood's chunks, some of these chunks will need to be requested by the node closer to the address, but further from the node. This will only be possible at a loss. An added incentive for neighbours to replicate their area of responsibility is discussed in 3.4. With the area of responsibility stored however, a node can choose to set their price arbitrarily.

Caching and auto-scaling

Nodes receive a reward every time they serve a chunk, therefore the profitability of a chunk is proportional to its popularity: the more often a chunk is requested, the higher the reward relative to the fixed cost of storage per time unit. When nodes reach storage capacity limits and need to decide which chunks to delete, a rational agent seeking to maximise profit would opt to remove chunks with the lowest profitability. A reasonably[2] good predictor for this is the age of last request. In order to maximise the set of chunks to select from, nodes engage in opportunistic caching of the deliveries they relay as well as the chunks they sync. This results in popular chunks being more widely spread and faster served, transforming the whole of Swarm into an auto-scaled and auto-balanced *content distribution network*.

Non-caching nodes

Any scheme that ensures relaying nodes make a profit creates a positive incentive for forwarding-only non-caching nodes to enter the network. Such nodes are not inherently beneficial to the network as they are creating unnecessary bandwidth overhead. On the one hand, their presence could, in principle, unburden storer nodes from relaying traffic, so using them in shallow bins may not be detrimental. On the other hand, closer

[2]Better metrics for predicting chunk profitability than the age of last request will continue to be identified and developed.

to neighbourhood depth, their peers will favour a caching/storing node to them because of their disadvantage at least for chunks in their hypothetical area of responsibility. Non-caching nodes can also contribute to increase anonymity (see 2.3.1).

3.1.3 Incentivising push-syncing

The push-sync (see 2.3.2) protocol ensures that chunks uploaded into the network arrive at their designated address. In what follows, we will explain how forwarding is incentivised. [3]

Push-syncing is analogous to the retrieval protocol in the sense that their respective message exchange sequences travel the same route. The delivery of the chunk in the push-sync protocol is analogous to a retrieval request and, conversely, the statement of custody receipt in push-sync is analogous to the chunk delivery response in retrieval.

In principle, push-syncing could be left without explicit forwarding incentives. Due to the retrieval protocol, as nodes expect chunks to be found in the neighbourhood of their address, participants in Swarm are at least weakly incentivised to help deliver uploaded chunks to their destination. However, we need to provide the possibility that chunks are uploaded via nodes further from it than the requestor (light nodes or retries). Thus, if push-syncing was free, nodes could generate wasteful amounts of bandwidth.

Requiring payment only for push-sync delivery by downstream peers would put the forwarder in a position to bargain with a storer node regarding the delivery of the chunk. The possession of a chunk is valuable for the prospective storer node because there is also a system of rewards for storage (see 3.4). Based on this, the forwarder node could, in theory, hold onto the chunk unless the storer node pays marginally more than the value of possessing that chunk, factoring in the profit potential due

[3]To complement our solution for bandwidth compensation, further measures are needed for spam protection and storage incentivisation which are discussed later in 3.3 and 3.4, respectively.

to storage incentives. In particular, since forwarders on the route from the uploader are not numerous, any profits generated from a storage reward mechanism might be captured by these forwarding nodes.

Instead, in push-sync, by making the statement of custody receipt a paid message, the roles switch. The forwarder node is no longer in the position to bargain. To understand why, let's consider a scenario where a forwarding node tries to hold on to a chunk to negotiate a price for pushing it to a storer node. In this case, the uploader will not get a statement of custody receipt within the expected time frame. As a result, the uploader will assume that the attempt has failed and re-upload the chunk via a different route. Now, suddenly the original forwarding node is forced to compete with another forwarding node in getting compensation for their bandwidth costs. Since all forwarding nodes are aware of this dynamic, emergent behaviour will produce a series of peers that are willing to forward the chunk to the storer node for a relatively small compensation and the bandwidth costs incurred. This eliminates the need for the original forwarding node to try and bargain with the storer node in the first place: Instead, they can generate a small profit immediately by simply returning the statement of custody receipt.

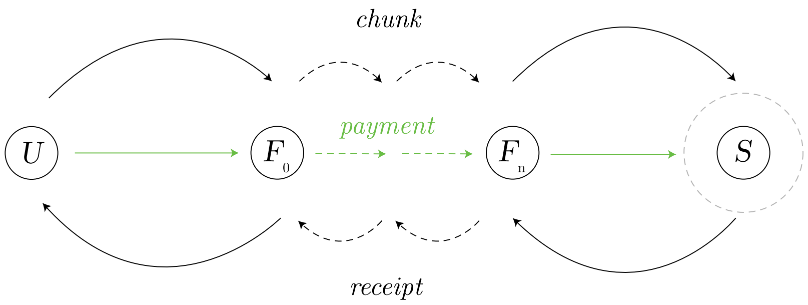


Figure 3.5: Incentives for push-sync protocol. Node U (uploader) sends the chunk towards its address, the closest node to which is node S (storer) via forwarding nodes $F_0, \dots F_n$. The storer node responds with a statement of custody receipt which is passed back to the uploader via the same forwarding nodes $F_n, \dots F_0$. Receiving the statement of custody receipt triggers an accounting event.

This scheme highlights why the incentivisation of the two protocols relies on the same premises: there are many sellers (forwarders) and only one buyer (uploader) for a homogeneous good (the statement of custody receipt). As a result, the price of the service (delivering the chunk to the storer) is determined by the sum of the marginal costs of forwarding for each node along the route. At the same time, the storer node can capture all the profits from the storage compensation scheme.

In this way, we can make sure that (1) storers actually respond with receipts, and (2) have a way to detect timed out or unsolicited receipt responses to protect against DoS, see Figure 3.5.

Similar to the retrieval protocol, the pricing in this scheme is expected to vary based on different proximities (see 3.1.2). Additionally, as the costs of the nodes in the network fluctuate (depending on capacity utilization and node efficiency), the pricing will also be subject to change over time. Given that the compensation is calculated for one chunk and one shorter message (retrieve request and custody receipt) during the accounting process, we can safely conclude that the price structure for forwarding for both protocols is identical. Consequently, a unified pricing scheme for forwarding can be applied to both protocols, as discussed in 3.1.2. What distinguishes push-sync from the retrieval protocol is that, unlike in retrieval where the chunk is delivered back and its integrity can be validated, the accounting event in push-sync is a statement of custody which can be spoofed. Due to the forwarding incentive, nodes may be motivated to withhold forwarding and impersonate a storer node by issuing the statement of custody. This makes it advisable to query (retrieve) a chunk via alternative routes. If such retrieval attempts fail, it may be necessary to try push-syncing chunks through alternative routes.

3.2 Swap: accounting and settlement

This section covers aspects of incentivisation relating to bandwidth sharing. In 3.2.1, we introduce a mechanism to keep track of the data traffic between peers and offer peer-to peer-accounting for message relaying. Subsequently, in 3.2.2, we describe the conditions of compensating for unbalanced services and show how settlement can be achieved. In particular we introduce the concept of a. cheques and the chequebook contract. In 3.2.3, we discuss waivers as an optimisation that allows for additional savings on transaction costs. In 3.2.4 we discuss how an incentivised service of sending in cashing transactions enables zero-cash entry to Swarm and, finally, in 3.2.5 we delve into the fundamental set of sanctions that serve as incentives for nodes to play nice and adhere to the protocols.

3.2.1 Peer to peer accounting

Trón et al. (2016) introduce a protocol for peer-to-peer accounting, called swap. Swap is a tit-for-tat accounting scheme that scales micro-transactions. The scheme allows directly connected peers to swap payments or payment commitments. The system's key characteristics are captured playfully with different mnemonic resolutions of the acronym SWAP:

Swarm accounting protocol
: A scheme used by Swarm for keeping a record of reciprocal sharing of bandwidth.

service wanted and provided
: Allows service exchange.

settle with automated payments
: Send a cheque when payment threshold is exceeded.

send waiver as payment
: Debt can be waived in the value of un-cashed cheques.

start without a penny
: Zero-cash entry is supported by unidirectional swap.

Service for service

swap allows service for service exchange between connected peers. When there is equal consumption with low variance over time, bidirectional services can be accounted for without the need for any payments. Data relaying is an example of such a service, making Swap well-suited for implementing bandwidth incentives in content delivery or mesh networks.

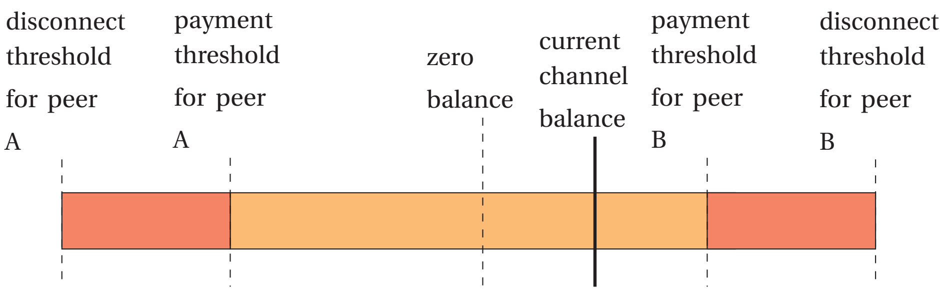

disconnect threshold for peer A
payment threshold for peer A
zero balance
current channel balance
payment threshold for peer B
disconnect threshold for peer B

Figure 3.6: Swap balance and swap thresholds. Zero balance in the middle indicates the equal consumption and provision of services. The current channel balance represents the difference in uncompensated service provision: If the balance is to the right of zero, it tilts in favour of A with peer B being in debt, whereas to the left, the balance tilts in favour of B with A being in debt. The orange interval represents loss tolerance. When the balance exceeds the payment threshold, the party in debt sends a cheque to its peer. If it reaches the disconnect threshold, the peer in debt is disconnected.

Settling with payments

In situations where there is high variance or unequal consumption of services, the balance will eventually tilt significantly toward one peer. In such cases, the indebted party issues a payment to the creditor to restore the nominal balance to zero. This process is automatic and justifies the concept of swap as *settle (the balance) with automated payments* (see Figure 3.6). These payments can be in the form of commitments rather than immediate transactions.

Payment thresholds

To quantify what counts as "significant tilt", the swap protocol requires peers to advertise a payment threshold as part of the handshake: When their relative debt to their peer goes above this threshold, they send a message containing a payment to their peer. It is reasonable for any node to send a message when the debt reaches this level, as there is also a disconnect threshold in place. The disconnect threshold can be set freely by any peer, but it is recommended to choose a value that takes into account the usual variance in accounting balances between the two peers. This can be done by considering the difference between the payment threshold and the disconnect threshold.

Atomicity

Sending the cheque and updating the balance on the receiving side cannot be made an atomic operation without substantial added complexity. For instance, a client could crash between receiving and processing the message, so even if the sending returns with no error, the sending peer can not be sure the payment was received, this can result in discrepancies in accounting on both sides. The tolerance expressed by the difference between the two thresholds ($\mathit{DisconnectThreshold} - \mathit{PaymentThreshold}$) guards against this, i.e. if the occurrence of such crashes is infrequent and happens with roughly equal probability for both peers, the resulting minor discrepancies are filtered out. This mechanism protects nodes from facing sanctions.

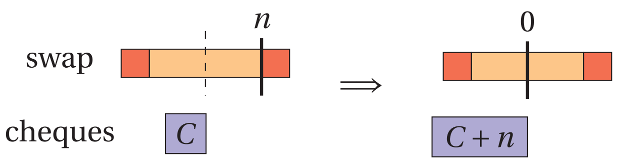


Figure 3.7: Peer B's swap balance (with respect to A) reaches the payment threshold (left), B sends a cheque to peer A. B keeps the cheque and restores the swap balance to zero.

3.2.2 Cheques as off-chain commitments to pay

One of the major challenges with conducting direct on-chain payments in a blockchain network is the high transaction costs associated with processing each transaction by every participating node. It is, however, possible to create a payment without presenting this payment on-chain. Such payments are called second-layer payment strategies. One such strategy is deferring payments and processing them in bulk. In exchange for reduced cost, the beneficiary must be willing to incur a higher risk of settlement failure. We argue that this is perfectly acceptable in the case of bandwidth incentivisation in Swarm, where peers will engage in repeated dealings.

The chequebook contract

A simple smart contract called the chequebook contract, introduced in Trón et al. (2016), allows the beneficiary to determine the timing of payments. This contract acts as a wallet that can process cheques issued by its owner. Similar to traditional financial transactions, the issuer signs a *cheque* specifying the *beneficiary*, *date*, and *amount*, providing it to the recipient as a token of promise to pay at a later date. The smart contract plays the role of the bank. When the recipient wishes to get paid, they "cash the cheque" by submitting it to the smart contract. The contract, after validating the signature, date and the amount specified on the cheque, transfers the amount to the beneficiary's account (see Figure 3.8). Analogous to the person taking the cheque to the bank to cash it, anyone can send a digital cheque in a transaction to the owner's chequebook account, initiating the transfer.

The swap protocol specifies that when the *payment threshold* is exceeded, a cheque is sent over by the creditor peer. Such cheques can be immediately cashed by sending them to the issuer's chequebook contract. Alternatively, cheques can also be held, which effectively serves as a form of lending on credit, enabling parties to save on transaction costs.

The amount deposited in the chequebook (global balance) serves as collateral for the cheques and is pooled over the beneficiaries of all outstanding cheques. In this simplest form, the chequebook provides the same guarantees as real-world cheques: None. Since funds can be freely moved out of the chequebook wallet at any time, solvency at the time of cashing can never be guaranteed: If the chequebook's balance is less than the amount specified in a submitted cheque, the cheque will bounce. This is the trade-off between transaction costs and risk of settlement failure.

While, strictly speaking, there are no guarantees for solvency, nor is there an explicit punitive measure in the case of insolvency, a bounced cheque can negatively impact the issuer's reputation as the chequebook contract records such incidents. On the premise that cheques are swapped in the context of repeating dealings, peers will refrain from issuing cheques beyond their balance. In other words, a node's interest in keeping a good reputation with their peers serves as a sufficient incentive to maintain its solvency.

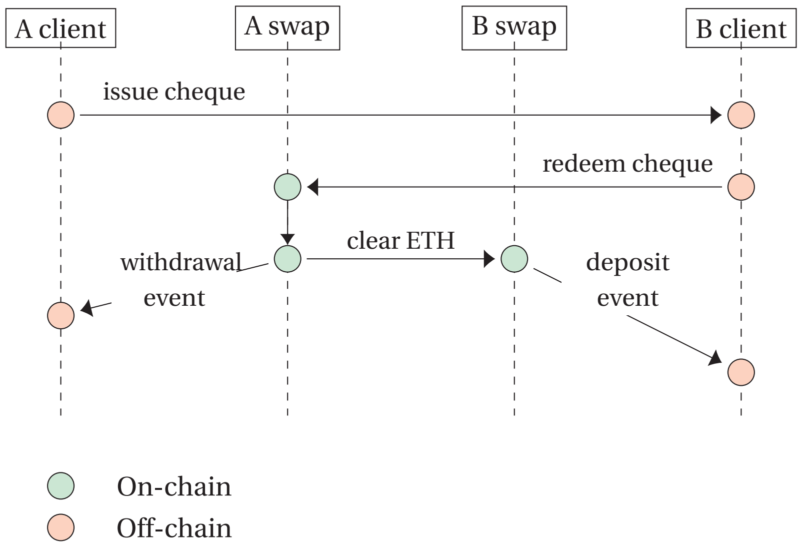


Figure 3.8: The basic interaction sequence for swap chequebooks

Double cashing

Since these digital cheques are files and can therefore be copied, it is crucial to implement measures to prevent the cashing of the same cheque multiple times. Such "double cashing" can be prevented by assigning each cheque given to a particular beneficiary a serial number which the contract will store when the cheque is cashed. The chequebook contract can then rely on the serial number to make sure cheques are cashed in sequential order, thus needing to store only a single serial number per beneficiary.

Alternatively, to address repeated payments to the same beneficiary, the cheques can contain the *cumulative* total amount ever credited to that beneficiary. The contract maintains a record of the total amount that has been cashed out for each beneficiary, and when a new cheque is submitted, the contract compares the amount on the cheque to the stored total. Cheques with an amount equal to or less than the stored total are ignored, while cheques with a higher total will result in the transfer of the difference to the beneficiary.

This simple trick also makes it possible to cash cheques in bulk because only the most recent "last cheque" needs to be processed, leading to a significant reduction of transaction costs.

Cashing without Ether

Not all peers in Swarm are expected to have the Ether needed to pay for the transaction costs to cash out a cheque. The chequebook allows third parties to cash cheques. The sender of the transaction is incentivised with a reward for the service performed.

3.2.3 Waivers

If the imbalance in the swap channel is due to high variance rather than unequal consumption, after a period of accumulating cheques, the channel balance starts tilting in the opposite direction. Normally, it is now up to the other party to issue cheques to its peer, resulting in uncashed cheques accumulating on both sides. To allow for further savings in transaction costs, it might be desirable to be able to offset these cheques against each other.

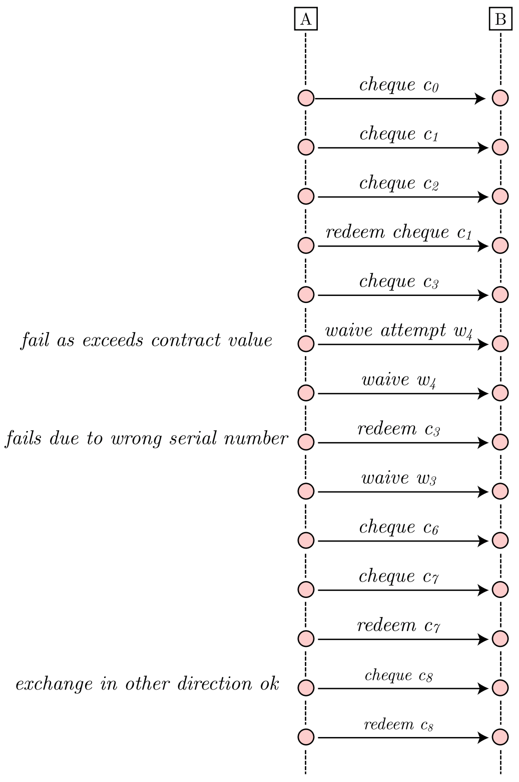
Such a process is possible, but it requires certain important changes within the chequebook contract. In particular, cashing cheques can no longer be immediate and must incur a security delay, a concept familiar from other payment channel implementations (Poon and Dryja 2015, Ferrante 2017, McDonald 2017, Tremback and Hess 2015).

Let us imagine a system analogous to cheques being returned to the issuer. Assume peer *A* issued cheques to *B* and the balance was brought back to zero. Later, the balance tilts in *A*'s favour, but the cheques from *A* to *B* have not been cashed. In the traditional financial world, *B* could either simply return the last cheque to *A* or provably destroy it. In our case, it is not so simple; we need some other mechanism by which *B commits not to cash* that particular cheque. Such a commitment could take several forms; it could be implemented by *B* signing a message allowing *A* to issue a new 'last cheque' with a lower cumulative total amount than before, or perhaps *B* could issue a form of 'negative' cheque for A's chequebook, effectively offsetting the amount as if a cheque with the same amount had been paid.

These implementations share the characteristics of not allowing the instantaneous cashing of cheques in the chequebook. Upon receiving a cheque-cashing request, the contract must wait to allow the other party to submit potentially missing information about cancelled cheques or reduced totals. To accommodate (semi-)bidirectional payments using a single chequebook, we introduce the following modifications:

- All cheques from user A to user B must contain a serial number.
- Each new cheque issued by A to B must have a serial number higher than the previous one.
- A's chequebook contract records the serial number of the last cheque that B cashed.
- During the cashing delay, any valid cheque with a higher serial number supersedes any previously submitted cheques, regardless of their face value.
- Any submitted cheque which decreases the payout of the previously submitted cheque is only valid if it is signed by the beneficiary.

With these rules in place, it is easy to see how cheque cancellation would work. Let's consider the scenario where user *A* has issued cheques $c_0 \ldots c_n$ with cumulative totals $t_0 \ldots t_n$ to user *B*. Suppose that the last cheque *B* cashed was c_i. The chequebook contract has recorded that *B*



	A → B	serial number	amount due	contract value	cumulative value
	cheque c_0	*0*	*6*	*6*	*6*
	cheque c_1	*1*	*9*	*15*	*15*
	cheque c_2	*2*	*13*	*28*	*28*
	redeem cheque c_1	*1*	*15*	*19*	*28*
	cheque c_3	*3*	*14*	*33*	*42*
fail as exceeds contract value	*waive attempt w_4*	*4*	*100*	*33*	*42*
	waive w_4	*4*	*7*	*26*	*42*
fails due to wrong serial number	*redeem c_3*	*3*	*42*	*26*	*42*
	waive w_3	*5*	*26*	*0*	*2*
	cheque c_6	*6*	*11*	*11*	*52*
	cheque c_7	*7*	*15*	*26*	*68*
	redeem c_7	*7*	*68*	*0*	*68*
exchange in other direction ok	*cheque c_8*	*0*			
	redeem c_8	*1*			

Figure 3.9: Example sequence of mixed cheques and waivers exchange

has received a payout of t_i and that the last cheque cashed had serial number i.

Let us further suppose that the balance starts tilting in A's favour by some amount x. If B had already cashed cheque c_n, then B would be required to issue a cheque of her own using B's chequebook as the source and naming A as the beneficiary. However, since cheques $c_{i+1} \dots c_n$ are still uncashed, B can instead send to A a cheque with A's chequebook as the source, B as the beneficiary, with serial number $n+1$ and cumulative total $t_{n+1} = t_n - x$. Due to the rules enumerated above, A will accept this as an equivalent payment of amount x from B. In this scenario, instead of sending a cheque to A, B waives part of their earlier entitlement. This justifies the concept of SWAP as *send waiver as payment*.

This process can be repeated multiple times until the cumulative total is brought back to t_i. At this point, all outstanding debt has effectively been cancelled, and any further payments must be made in the form of a proper cheque from B's chequebook to A (see Figure 3.9).

3.2.4 Zero cash entry

Swap accounting can also work in a one-directional manner. When a party enters the system with zero liquid capital (a newcomer) but connects to a peer with funds (an insider), the newcomer can begin to provide a service (and not use any) in order to earn a positive swap balance.

If the insider has a chequebook, they are able to simply pay the newcomer with a cheque. However, this has a caveat: The newcomer will be able to earn cheques for the services provided but will not have the means to cash them. Cashing cheques requires sending a transaction to the blockchain, and therefore requires gas, unless the node can convince one of its peers to execute the transaction on its behalf. To facilitate this, nodes are able to sign off on a structure that they want to be sent, and then extend the Swap contract with a preprocessing step that triggers payment to the newcomer, covering the transaction's gas cost plus a service fee for the sender of the transaction. The newcomer's cheque may be cashed by any insider (see Figure 3.10). This feature justifies the concept of SWAP as *start without a penny, send with a peer.*

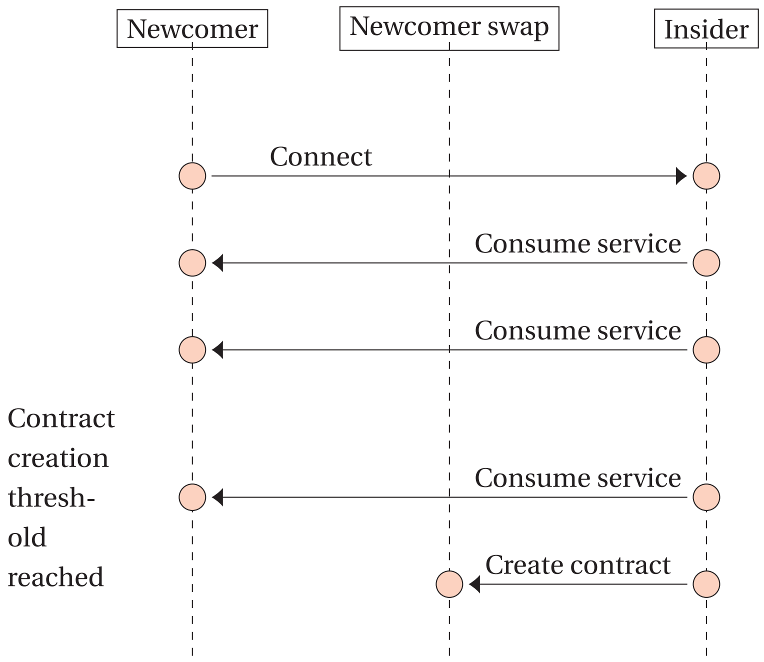


Figure 3.10: Bootstrapping or how to launch as a swap capable node consuming and providing a service and earn money.

The possibility to earn small amounts of money without starting capital is crucial, as it provides a way for new users to get access to Swarm without the need to purchase the token. This benefit extends to the Ethereum ecosystem in general: using Swarm, anybody can earn small amounts of money to start paying the gas to fuel their dapps, without the need to go through a painful process of acquiring tokens prior to onboarding.

3.2.5 Sanctions and blacklisting

This section complements the SWAP scheme with additional incentives and protection against foul play.

Protocol breach

In a peer-to-peer trustless setting, implementing nuanced sanctions against undesired peer behaviour can be challenging. However, when the basic rules of interaction are violated, the node that detects it can simply disconnect from that peer. In order to avoid deadlocks due to attempted reconnection, the sanctions imposed on transgressive nodes also include recording the peer's address into a blacklist. This simple measure is enough to provide a clear disincentive to nodes seeking to exploit the protocol.

Excessive frivolity

Both retrieval and push-sync protocols have an incentive structure where only the response to a request generates income. Although this creates a strong incentive to play ball, it may also be necessary to take measures to ensure that nodes are not able to spam the network with frivolous requests that have no associated cost. In the case of push-syncing, it is especially important not to allow chunks to expunge others at no cost. This will form the topic of a later section where we introduce postage stamps (see 3.3).

In the case of pull-sync retrieval, the potential attack consists of requesting non-existing chunks and causing downstream peers to initiate a lot of network traffic, as well as some memory consumption, due to requests being persisted during the time-to-live period. Surely, there is a possibility that a requestor may unknowingly request non-existing chunks, and what is more, the requested chunk could have been be garbage-collected in the network, in which case, the requestor may have acted in good faith.

To mitigate this, each node maintains a record of the number of retrieve requests from each of its peers and then updates the relative frequency of failed requests, i.e. requests that have timed out even though the node in question had forwarded it. If the proportion of failed requests to successful requests exceeds a certain threshold, sanctions are imposed on the peer: it is disconnected and blacklisted.

By remembering the requests they have forwarded, nodes can distinguish legitimate responses from a potential DoS attack: for retrieval, if the chunk delivered does not fulfil an open request, it is considered unsolicited; for push-sync, if a statement of custody response does not match an existing entry for forwarded chunk, it is considered unsolicited.

Timeouts are crucial here. After the time-to-live period for a request has passed, the record of the open request can be removed. Any response received after this point is considered unsolicited, as it is indistinguishable from messages that were never requested.

To account for slight discrepancies in time measurement, once again a small percentage of illegitimate messages are tolerated from a peer before they are disconnected and blacklisted.

Quality of service

Beyond the rate of unsolicited messages, nodes can cause grievances on other ways, such as by setting high prices, having low network throughput, or long response latencies. Similarly to excessively frivolous requests, there is no need for a distinction between malicious attacks or sub-optimal (poor quality, overpriced) service provided in good faith. As a result, mitigating quality of service issues is discussed in the context of peer selection strategies in forwarding and connectivity.

Blacklisting

Blacklisting is a strategy that complements disconnection as a measure against peers. It is supposed to extend our judgment expressed in the act of disconnection that the peer is unfit for business. Blacklists serve as a reference when accepting incoming connections as well as in the peer suggestion strategy of the connectivity driver. On the one hand, blacklisting can save the node from being deadlocked in a cycle of malicious peers trying to reconnect. On the other hand, care must be taken not to blacklist peers acting in good faith, as this could negatively impact network connectivity.

3.3 Postage stamps

A postage stamp is a verifiable proof of payment associated with a chunk witnessed by the signature of its owner. It serves two purposes: preventing frivolous uploads by imposing an advance cost, and indicating the relative importance of a chunk by ascribing a specific amount of BZZ to it. Storer nodes can then use this information to prioritise which chunks to retain and serve, as well as which ones to garbage-collect in case of limited capacity.

In this section, we first introduce the concept of a postage batch, which allows for the bulk purchase of stamps (3.3.1). In 3.3.2, we explain how limited issuance is represented and enforced. In 3.3.3, we introduce the notion of a reserve and outline the rules governing how storer nodes can maximise its utilisation. We conclude in 3.3.4 with exploring the relationship between reserved capacity, effective demand, and the number of nodes and their impact on the data availability.

3.3.1 Purchasing upload capacity

Uploaders can acquire postage stamps in bulk by purchasing a postage batch from the postage smart contract on the Ethereum blockchain. The creation of a postage batch involves initiating a transaction to the batch creation endpoint of a contract, along with an amount of BZZ tokens and transaction data that specifies some parameters. As the transaction is processed, the postage contract registers a new batch entry with the following pieces of information:

batch identifier
A randomly generated ID that serves as a reference for this batch.

batch depth
Base 2 logarithm of the issuance volume, i.e., the number of chunks that can be stamped using this batch.

owner address
The Ethereum address of the owner entitled to issue stamps, as per the transaction data sent along with the creation or the transaction sender if not specified.

per-chunk balance
: The total amount sent along with the transaction divided by the issuance volume.

mutability
: A boolean flag indicating whether the storage slots of the batch can be reassigned to another chunk with a stamp if its timestamp is older.

uniformity depth
: the base 2 logarithm of the number of equal-sized buckets the storage slots are arranged in.

The postage contract provides endpoints to users to modify the per-chunk balance of batches. This allows users to add funds to extend the validity period of the stamps issued by the batch (*top-up*) or add volume to decrease it (*dilute*). While anyone can choose to top up the balance of a batch at a later date, only the owner has the authority to dilute it.[4]

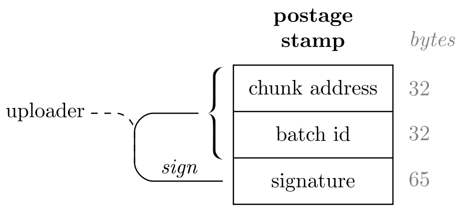


Figure 3.11: Postage stamp is a data structure comprised of the postage contract batch id, storage slot index, timestamp the chunk address and a witness signature attesting to the association of these four. Uploaders and forwarders must attach a valid postage stamp to every chunk uploaded.

Owners issue postage stamps in order to attach them to chunks. Each batch has a number of storage slots effectively arranged into a number of equal-sized buckets. Issuing a stamp means to assign a chunk to a storage slot. A stamp is a data structure comprising the following fields (see Figure 3.11):

[4]As a planned feature, the remaining balance of a batch can be reassigned to a new batch, resulting in the immediate expiry of the original.

chunk address
: The address of the chunk the stamp is attached to.

batch identifier
: The ID referencing the issuing batch (generated at its creation).

storage slot
: A bucket index referencing one of the equal-sized buckets of the batch, and a within-bucket index referencing the storage slot the chunk is assigned to.

timestamp
: The time the chunk is stamped.

witness
: The batch owner's signature attesting to link between the storage slot and the chunk.

A postage stamp's validity can be checked by verifying that it scores all true on the following five attributes:

authentic
: The batch identifier is registered in the postage contract's storage.

alive
: The referenced batch has not yet exhausted its balance.

authorised
: The postage stamp is signed by the address specified as the owner of the batch.

available
: The referenced storage slot is within valid range based on the batch depth, and, in the case of an immutable batch, has no duplicates.

aligned
: The referenced storage slot has the bucket specified and it aligns with the chunk address stamped.

All this can be easily checked by nodes in Swarm only using information available on the public blockchain (read-only endpoints of the postage contract). When a chunk is uploaded, the validity of the attached postage stamp is verified by forwarders along the push-syncing route (see Figure 3.12).

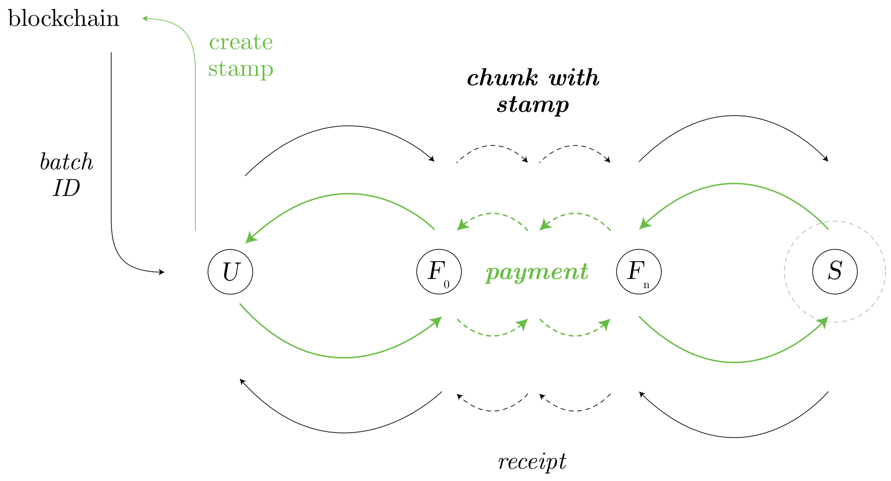


Figure 3.12: Postage stamps are purchased in bulk on the blockchain and attached to chunks at upload. They are passed along the push-syncing route together and their validity is checked by forwarders at each hop.

The normalised per-chunk balance of a batch is calculated as the batch inpayment divided by the batch size in chunk storage slots. The chunk balance is interpreted as an amount pre-committed to be spent on storage. The balance decreases with time as if *storage rent* was paid for each block at the price dictated by the price oracle contract.

This system of prepayment for storage eliminates the need to speculate on the future price of storage or fluctuations in currency exchange rates. At the cost of decreased certainty about the expiration date, one gains resilience against price volatility. On top of this, uploaders can enjoy the luxury of non-engagement by tying up more of the batch balance; while it serves as collateral against price increase, if that does not happen the funds can still be used up (for storing).

3.3.2 Limited issuance

Purchasing a postage batch effectively entitles the owner to issue a fixed amount of postage stamps against the batch ID called the issuance volume or batch size. It is restricted to the powers of 2 and is specified using the base 2 logarithm of the amount which is called batch depth.

The storage slots within a batch are arranged into buckets, and each slot is assigned an index within its respective bucket. The number of buckets is restricted to the powers of 2 and is specified using its base 2 logarithm called uniformity depth. To ensure the size limitation of a batch with batch depth d and uniformity depth u, the following conditions must be met:

— the bucket index ranges from 0 to $2^u - 1$.
— the within-bucket index ranges from 0 to $2^{d-u} - 1$.
— there are no duplicate indexes.

While the first two criteria are easily verifiable by any third party, the last one is not. In order for index collisions to be detectable by individual storer nodes, the uniformity depth must be large enough to fall within the nodes' area of responsibility. As long as this condition is maintained, all chunks in the same bucket are guaranteed to land in the same neighbourhood, and, as a result, duplicate assignments can be locally detected by nodes (see Figure 3.13).

In order to keep their stamps collision-free, uploaders need to maintain counters for how many stamps they have issued for each bucket within a batch and ensure that the number does not exceed the maximum bucket size.

In general, the most efficient utilisation of a batch is by filling each bucket to its capacity. Continued non-uniformity (i.e., *targeted issuance*) leads to underutilised batches, and therefore a higher unit price for uploading and storing each chunk. This feature has the desired side effect that it imposes an upfront cost to non-uniform uploads: the more concentrated the distribution of chunks in an upload, the more unused storage slots in the postage batch. In this way, we ensure that targeted denial-of-service attacks against a neighbourhood (i.e., uploading a disproportionate number of chunks in a particular address range) is costly since the *inert cost* (due to the degree of under-utilisation of the batch) is exponential in the depth of the skew.

Beyond DoS protection, postage stamps can serve as a *fiduciary signal* indicating how much it is worth for a user to persist a chunk in Swarm.

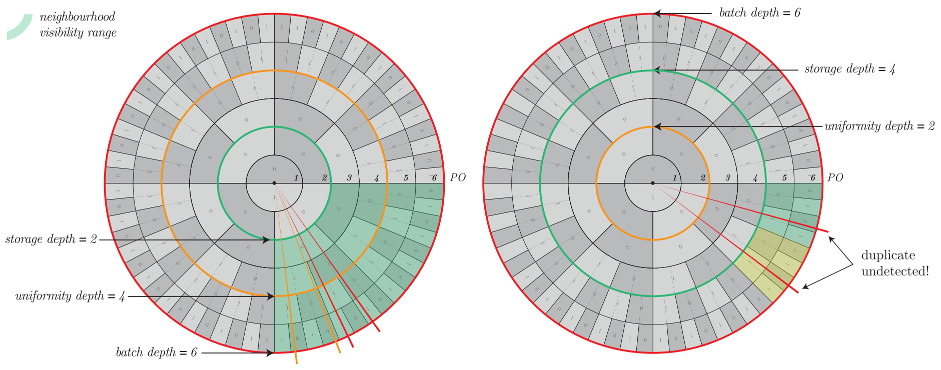


Figure 3.13: Batches come with 2^u equal-sized buckets (u is uniformity depth, marked by the orange circle) each containing an equal number of storage slots (2^{d-u}) adding up to batch capacity of 2^d chunks (d is batch depth, marked by the red circle). The storage slots are indexed and each index is associated with a chunk via the stamp signature. Storer nodes can locally detect postage stamp over-issuance as long as the buckets are deeper than their storage depth (green circle), as in the diagram on the left. In this case, they will receive all the chunks that are correctly assigned to the relevant bucket (orange radii) and correctly identify collisions (red radii) by forbidding indexes that are either out of range ($\geq 2^{d-u}$) or multiply assigned. In contrast, the diagram on the right shows that it is not possible for a node with a storage depth of 4 to identify duplicates for a batch with $u = 2$.

In particular, the per-chunk balance of batches can provide the differential a priori bias, determining which chunks should be protected from garbage collection when there is no evidence available to predict their profitability from swap.

3.3.3 Rules of the reserve

The reserve refers to a fixed size of storage space dedicated to storing the chunks within a node's area of responsibility. Chunks within the reserve are protected against garbage collection as long as they have valid postage stamps. When batches expire, i.e., their balance is fully depleted, the chunks they stamped are no longer protected from eviction. Their eviction from the reserve frees up some space that can accommodate new or more distant chunks belonging to valid batches.

From the point of view of incentives, chunks within the same proximity order and the same batch are considered equivalent. When it comes to eviction due to batch expiry, these equivalence classes, called batch bins, are handled as a single unit: the chunks in a batch bin are evicted from the reserve and inserted into the cache in one atomic operation.

Assuming a global oracle for the unit price of rent and a fixed reserve capacity prescribed for nodes, the content of the reserve is coordinated according to a set of constraints on batch bins called the rules of the reserve:

1. if a batch bin of a certain PO is reserved, then all batch bins at closer proximity orders (higher PO) are also reserved.
2. if a batch bin is reserved at a certain proximity order (PO), then all batch bins at the same PO belonging to batches with a higher per-chunk balance are also reserved.
3. the reserve should not exceed capacity.
4. the reserve should be maximally utilised, i.e, it cannot be extended while still adhering to rules 1-3.

The first rule means the reserve is closed upwards for PO, which encodes a global preference for storing chunks that are closer to the node's address. This is incentivised by routing: keeping the closest chunks, a node will maximise the number of receipts it can issue and the number of retrieve requests it can respond to. Additionally, storing closer chunks ensures wider coverage within the neighbourhood, even when the neighbourhood no longer provides the desired redundancy.

The second rule expresses the constraint that the reserve for a PO is upward closed for per-chunk balance. This constraint reflects a secondary preference among chunks of the same proximity, favouring those that are stamped using a batch with higher per-chunk balance. This is incentivised by the differential absolute profit that chunks promise: due to the constraint that balances are not revocable, chunks with higher balances expire later and therefore provide greater absolute profit to storers compared to chunks with earlier expiration dates, despite both paying the same rent during their period of validity.[5]

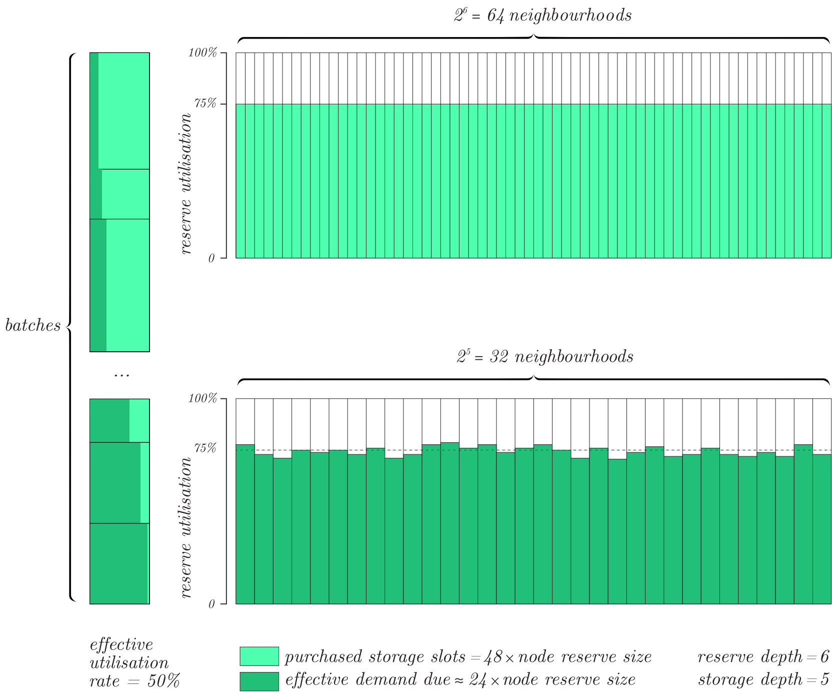


Figure 3.14: The total size of all batches with non-zero balance on the blockchain (left) indicates the potential demand for chunk storage. The lower bound on neighbourhood depth to store this capacity is the reserve depth (top right). The storage depth represents the effective volume of chunks uploaded and stored in a neighbourhood's reserve (bottom right). The difference between them is a result of partial batch utilisation. The uniformity of the volume of chunks across neighbourhoods is incentivised by the efficient utilisation of postage batches.

[5] Note that even if there was no scheme for redistributing postage revenue and the inpayments are frozen/burnt, this strategy is still mildly incentivised in as much as it is aligned with the interests of token-holders: batches with higher balance exert more deflationary force on the token (per chunk, i.e, the unit of invested resource) by keeping their balance frozen, which is expected to realise in a proportional price increase.

When a new chunk arrives in Swarm through pull-sync, push-sync, or upload, the validity of the attached postage stamp is verified. If the PO of the chunk is lower than the batch depth, the node inserts the chunk into the garbage collection index, indicating that it can be subject to garbage collection. On the other hand, if the PO is equal to or greater than the batch depth, the chunk is considered to be in the reserve. If the reserve size exceeds the designated capacity, a number of batch bins are identified whose combined size is sufficient to cover the excess. These batch bins will be *evicted* from the reserve, reducing its size to meet the capacity requirement.

3.3.4 Reserve depth, storage depth, neighbourhood depth

Reserve depth

The potential demand for chunks to be stored in the DISC is quantified by the total number of storage slots in valid batches. This is calculated as the sum of the sizes of all non-expired batches. Since the batches and their balances are recorded in the postage contract, the reserved size of the DISC is agreed upon through consensus.[6]

The reserve depth is determined by taking the base 2 logarithm of the DISC reserve size and rounding it up to the nearest integer. It represents the shallowest PO at which disjoint neighbourhoods are collectively able to accommodate the volume of data corresponding to the total number of paid chunks. This assumes that nodes within the neighbourhood have a fixed prescribed storage capacity to store their share of the reserve.

The reserve depth also serves as the *safe lower bound* for pull-syncing, i.e, the farthest bin a neighbourhood needs to synchronise to guarantee storing the reserve. Conversely, if any neighbourhood marked by reserve

[6]The volume is best explicitly maintained by the contract by adding the size of newly created batches and deducting the sizes of expired batches. The DISC reserve size is updated each time a batch is created or topped up, and expired batches are removed during each redistribution round, executed as part of the process triggered by the claim transaction.

depth has no nodes in it, the swarm is not working correctly, i.e., chunks with valid stamps are not being protected from getting lost. See Figure 3.15.

Storage depth

The effective demand for chunks to be stored in the DISC corresponds to the total number of chunks actually uploaded. While each chunk in the reserve is associated with a valid postage batch and assigned to a storage slot, it is possible for a postage batch to have unassigned storage slots. As a result, the number of chunks actually stored in the DISC may be less than the DISC reserve size.

The effective area of responsibility is marked by the proximity order of the farthest batch bin in the reserve, assuming the node complies with the rules of the reserve.

A node's storage depth is defined as the shallowest *complete* bin, i.e., the lowest PO at which a compliant reserve stores all batch bins. Unless the farthest bin in the node's reserve is complete, the storage depth equals the reserve's edge PO plus one.

The storage depth is the *optimal lower bound* for pull-syncing, i.e, it indicates the farthest bin the node needs to synchronise with its neighbours to achieve maximum reserve utilisation.[7] Maximum reserve utilisation should be incentivised as part of the storage incentives.

The gap between actual storage depth and the reserve depth exists because of the bulk purchase of stamps. Since entire batches of stamps reserve storage slots that are assigned to chunks only at later times when they are actually uploaded, the batch *utilisation rate* can be substantially less than 1. Storage depth and reserve depth will be the same only when all batches are fully utilised.

[7]The nodes will have full connectivity up to the shallowest bin that they are pull syncing. This choice is incentivised by the risk of having two disjoint connected sets of pull-syncing nodes resulting in non-consensual reserve. As a consequence, we can say that storage depth is an upper bound on the depth of full connectivity.

Neighbourhood depth

Swarm has a requirement on local replication, which states that each neighbourhood designated by the storage depth should contain a minimum of four nodes. If neighbourhoods were made of one node, then the outage of that one node would make the chunks in the node's area of responsibility not retrievable. With two nodes in a neighbourhood, we significantly improve resilience against ad-hoc outages, but because of connectivity latencies a two-peer neighbourhood may still result in an unstable user experience. The ideal scenario is to have four nodes per full connectivity neighbourhood, which prompts the following definition: neighbourhood depth for a particular node is the highest PO d such that the address range designated by the d-bit-long prefix of the node's overlay contains at least 3 other peers.

Figure 3.15 details the potential relative orders of the three depths and their consequences on the health, efficiency, and redundancy of the swarm.

3.4 Fair redistribution

The system of positive[8] storage incentives in Swarm aims to redistribute to storage providers the BZZ tokens that uploaders deposited within the postage contract.[9] The overall balance on the contract covers the reward pot which represents the cumulative storage rent across all postage batches for a particular period. The storage rent must be redistributed to storage providers in a way that guarantees that their earnings are proportional to their contribution, weighing in storage space, quality of service, and length of commitment.

[8]The concept of *positive incentives* refers to a scheme whereby providers of a service are entitled to reward but there is no loss involved if they discontinue their service or are not online.

[9]As explained earlier, uploaders pay in an unwithdrawable amount to the postage contract which serves as the balance to pay storage rent. In exchange they obtain the right to issue a fixed number of postage stamps which they attach to chunks they want the network to store.

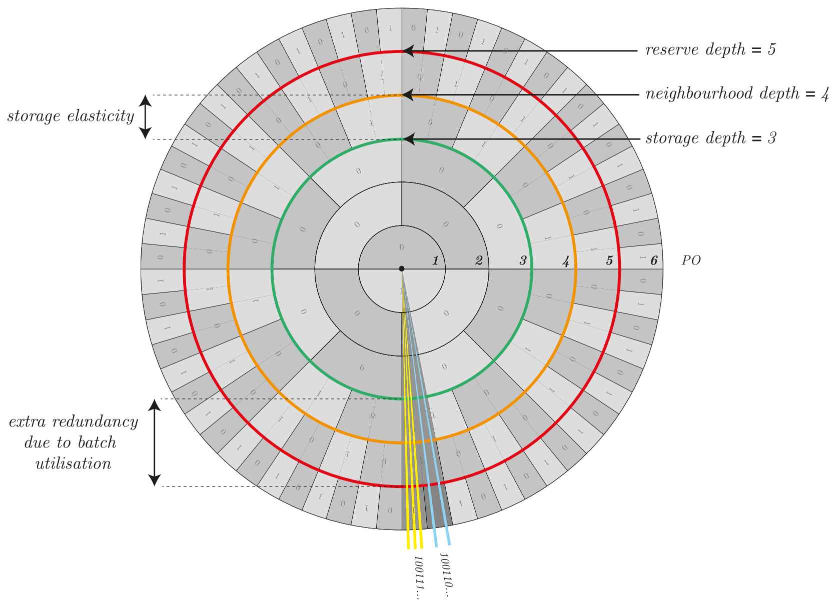


Figure 3.15: The 3 depths (reserve, storage, and neighbourhood) express the order of magnitude of reserved capacity (potential demand, red circle), uploaded chunks (effective demand, green circle), and the number of nodes (effective supply, orange circle), respectively. Their possible orderings reflect various scenarios that have distinct impacts on data availability. Storage depth cannot be greater than the reserve depth. A gap between the storage depth and the reserve depth quantifies the average batch utilisation rate. The gap between the storage depth and a deeper neighbourhood depth quantifies the elasticity of the storage: the difference expresses how many times the effective volume can double before redundancy falls below the required level. While such oversupply may be anticipatory of growth in demand, if the neighbourhood depth remains deeper than the storage depth long term, it may indicate excessive profits. The opposite order indicates undersupply (redundancy below the desired level).

The procedure for redistribution is best conceived of as a game orchestrated by a suite of smart contracts on the blockchain. Nodes earn the right to play through participation in storing and syncing chunks, and the winners can claim their rewards by initiating a transaction with the game contract.

In section 3.4.1, we formulate the idea of redistribution in terms of probabilistic outpayments to allow an easy proof of fairness. We then proceed to outline the mechanics of the redistribution game in 3.4.2. Sections 3.4.3 and 3.4.4 explain how we enforce maximum utilisation of dedicated storage for persisting relevant content redundantly. We conclude in 3.4.5 by discussing how to interpret certain aspects of the game as price signals that render the network self-regulating through automatic price discovery.

3.4.1 Neighbourhoods, uniformity and probabilistic outpayments

In this section, we argue that the efficient use of postage batches incentivises a balanced chunk distribution which, in turn, gives rise to uniform storage depth across neighbourhoods. We then explain how this enables a fair system of redistribution using probabilistic outpayments.

Assuming an oracle that sets the unit price of storage, it becomes possible to calculate the storage rent due for a specific period of time for a given batch. The number of rent units for a batch is the result of multiplying the size of the batch by the number of blocks in the specified period. The price of rent is calculated from the number of rent units multiplied by the unit price.[10] The total storage rent cumulated over all batches for the period between two outpayments constitutes the *reward pot* for the round.

Instead of dividing the reward pot among neighbourhoods regularly, the entire reward pot can be transferred to (representative nodes in) one target neighbourhood in each round. This probabilistic outpayment scheme ensures fairness among neighbourhoods, as long as the probability of selecting a neighbourhood as the target corresponds to its relative contribution to the overall network storage. Given a constant prescribed reserve capacity and replication of the reserve content by

[10] If this theoretical amount is less than the the current balance of the batch, then the batch is expired and the effective rent is only the remaining balance.

nodes within a neighbourhood, each neighbourhood, defined by storage depth, contributes equally to the network.

In Section 3.3, we mentioned that uploaders have a strong incentive to use their postage batch in a way that the chunks they stamp with it are uniformly distributed across the address space. This being true of all batches creates a situation that chunks are uniformly distributed across the DISC. In particular, the sets of chunks sharing a common prefix are expected to be roughly equal in size. Therefore we expect nodes to fill their prescribed reserve capacity with chunks at the same proximity order, irrespective of their location in the address space, i.e., the storage depth is uniform across nodes and therefore across neighbourhoods.[11] With neighbourhoods at equal depth, uniform sampling of neighbourhoods can be modelled by choosing the neighbourhood which contains an anchor (called the *the neighbourhood selection anchor*) randomly dropped in the address space (see Figure 3.16).

3.4.2 The mechanics of the redistribution game

The collaborative effort among peers to store data redundantly for the network's benefit is underpinned by a Schelling game aimed at proving that the peers agree on the chunks they need to store and they do, in fact, store them. The redistribution game is orchestrated by the game contract, one of the building blocks of the system of 4 smart contracts which collectively drive the swarm storage incentive system (see Figure 3.17):

Postage contract
: serving as the batch store to sell postage batches to uploaders, keeping track of batch balances, batch expiry, storage rent, and the reward pot itself.

Game contract
: orchestrates the redistribution rounds interacting with potential

[11] Differences do occur due to variance but over many rounds, deviation from the mean is meant to be independent of the location.

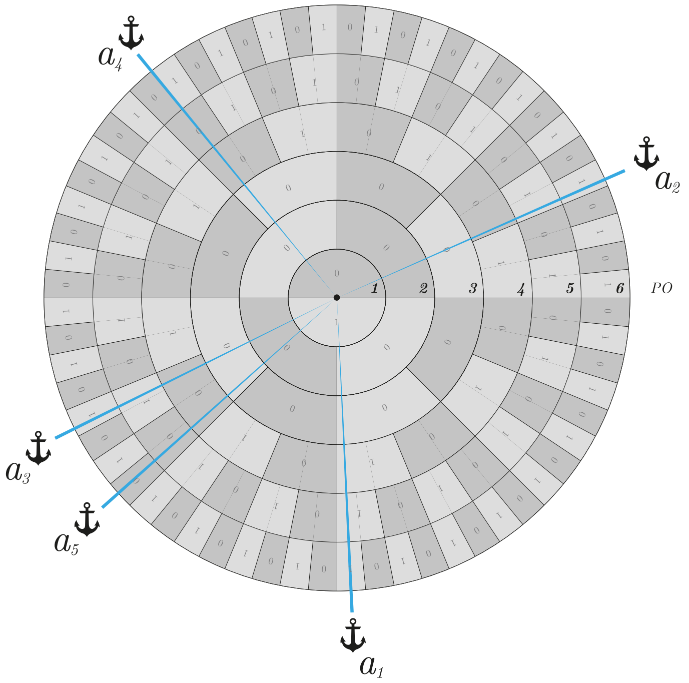


Figure 3.16: Neighbourhood selection and pot redistribution. The winning locality is selected by the neighbourhood selection anchor. Neighbourhoods that contain the anchor within their storage depth are invited to submit an application by committing to a consensual reserve sample.

winners accepting commit, reveal, and claim transactions from storage providers in selected neighbourhoods.

Staking contract

manages a stake registry, maintaining committed stake and stake balance for nodes based on their overlay; enables freezing and slashing of stake, as well as withdrawal of surplus balance for stakers.

Price oracle

maintains the unit price of storage rent, accepts signals from the game contract to dynamically adjust according to supply and demand, and provides current price oracle service for the other three contracts.

The game is structured as a sequence of *rounds*. Each round lasts for a fixed number of blocks and recurs periodically. A round consists of

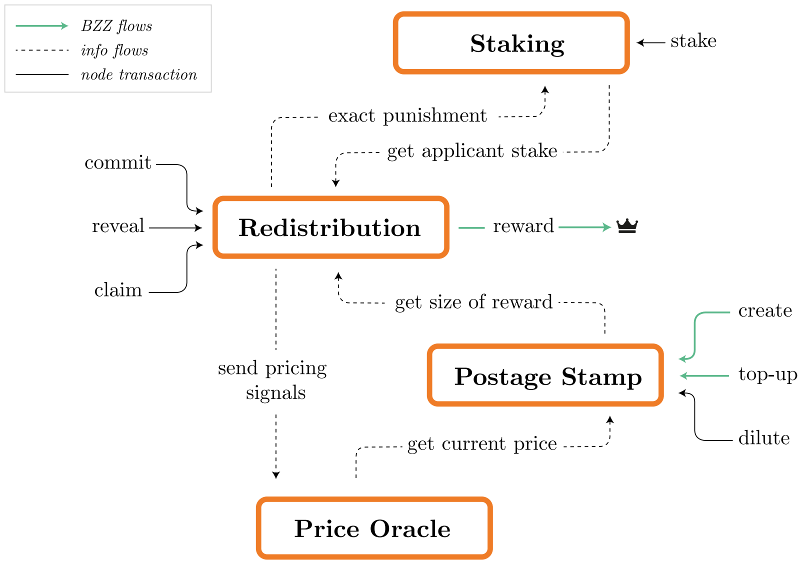


Figure 3.17: Interaction of smart contracts for swarm storage incentives. The figure shows with the dotted line the information flow between the four contracts comprising the storage incentive smart contract suite as well as the public transaction types they accept.

3 phases: *commit*, *reveal*, and *claim*.[12] The phases are named after the type of transaction the smart contract expects during that particular phase and that nodes from the selected neighbourhood need to submit.[13] See Figure 3.18

Once the reveal phase is over, the neighbourhood selection anchor becomes known. Nodes that have the anchor within their respective neighbourhoods[14] are eligible to participate in the following round (see Figure 3.16).

[12]The commit and reveal phases are one quarter of the round length while the claim phase is one half.

[13]Both commit and reveal are simple and cheap transactions. The only expensive transaction is claim but that only the winner needs to submit.

[14]If storage depth is less than the anchor's proximity order relative to the overlay address.

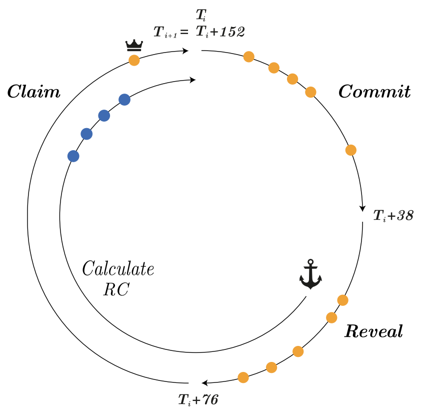


Figure 3.18: Phases of a round of the redistribution game. The figure displays the timeline of the repeating rounds of the redistribution game with its phases. In the context of smart contract interaction, logically starting with the commit phase, followed by reveal and claim. From the point of view of client node engagement starting with the end of the reveal phase with the neighbourhood selection anchor revealed, those in the selected neighbourhood start calculating their reserve sample only to submit it by the end of the next commit phase. If they are selected as an honest node and as a winner, they submit their proof of entitlement in a claim transaction.

The storer nodes within a neighbourhood are assumed to have consensus over the chunks that make up their reserve and provide evidence, known as proof of entitlement, to the blockchain (discussed below in detail in 3.4.4). In such a game, the Nash-optimal strategy for each node is to follow the protocols and coordinate with others to ensure that all neighbouring peers arrive at the same proof of entitlement based on the shared information. Since the proof of entitlement needs to be consensual but unstealable,[15] a commit/reveal scheme must be used.

During the commit phase, nodes within a neighbourhood will apply by submitting the reserve commitment obfuscated with an arbitrary

[15]Any explicit communication between independent nodes about this reserve before the end of the commit phase constitutes risk in that it may leak the proof to a node not doing storage work. Therefore nodes are incentivised to keep the proof a secret. Making these proofs unstealable helps detect opportunistic peers that pose as storers but do not provide adequate storage.

key (that they later reveal). The smart contract receiving the commit transaction verifies that the node is staked, i.e., the registry of the staking contract contains an entry for the node's overlay with a stake value that is higher than the minimum required stake.

During the reveal phase, nodes that had previously committed to a reserve now reveal their commitment by submitting a transaction containing their reserve commitments, storage depth, overlay address, and the key they used to obfuscate the commit. Upon receiving the reveal transaction, the contract verifies that the revealed data, when serialised, does indeed hash to their commitment. It is also checked if the node belongs to the neighbourhood designated by the neighbourhood selection anchor, i.e., is within the storage depth provided in the reveal.

In the claim phase, the winner node is required to submit a claim transaction.[16] First, in order to determine the outcome of the Schelling game, one reveal is selected from the reveals submitted during the reveal phase.[17] The selected reveal represents the truth; the set of applications that agree with the selected one represent the honest peers of the neighbourhood, the ones who disagree are considered liars, while those committers that did not reveal or revealed invalid data are classified as saboteurs. Honesty is incentivised by the fact that liars and saboteurs get punished. In what follows we introduce staking that is needed for both the selection processes and the punitive measure.

3.4.3 Staking

Neighbours with shared storage

In order to provide robust protection against accidental node churn, i.e., to ensure the retrievability of chunks from a neighbourhood in the face of some nodes being offline, the swarm requires a number of indepen-

[16]Every node in the selected neighbourhood needs to perform the corresponding calculations to determine whether or not they are the winner.

[17]This is relevant only if the depth and/or the commitment are non-uniform across applicants.

dent storers in each neighbourhood to physically replicate content. If payout was given to each node that shows proof of entitlement, operators could exploit the system by creating spurious nodes for the sole purpose of applying for the reward. Although measures can be implemented to enforce that these spurious nodes must be operating on the network, operators may still opt to run several nodes yet share their storage on a single hardware. The incentive system must ensure that storage providers do not adopt this strategy. To this end, we introduce staking.

Stakes serve as weights used by the contract to determine the true reserve commitment (truth selection) and to identify the winner among honest nodes (winner selection). The probability of winning is determined by peers' relative stakes, making stake an additive factor. Consequently, operators' profits depend solely on their total stake within the neighbourhood. Given the costs associated with running a node, operators will have no motivation to divide their stake among multiple nodes sharing the same storage hardware.

Committed stake and stake balance

When registering in the staking contract, stakers commit to a stake denominated in rent units called committed stake. The committed stake amount must have a lower bound.[18] The amount sent with the transaction is recorded and serves as collateral called stake balance. Stakes can be created or topped up at any time, but the update time and amount are recorded. Participation is limited to peers whose stake has not changed recently, ensuring that stakes cannot be altered after learning about the selected neighbourhood. When querying the stake of a node, the contract returns the absolute committed stake in BZZ. This value is calculated as taking either (1) the committed stake in rent

[18]A large number of staked nodes could cause the claim transaction to fail due to the gas cost required for iterating over them. This presents a potential attack where the adversary registers stakes for numerous nodes and commits for all of them. Such an attack is made prohibitively costly by imposing a minimum stake requirement.

units multiplied by the unit price of rent or (2) the entire stake balance, whichever is smaller.

Stakes must be transferable between overlay addresses to facilitate neighbourhood hopping in case the distribution of stake per neighbourhood is unbalanced.

Withdrawability of surplus stake balance

The committed stake allows operators to indicate their profit margin together with their time preference for realising that profit. However, since the profit is only transparent once the relative stakes within the neighbourhood are known, it may take a while for nodes to discover their optimal stake.

If the BZZ token price increases and the unit price of rent drops, the entry for the node in the stake registry will show an excess balance. This surplus can be withdrawn at any time, allowing stakers to realise their profit from BZZ appreciation.[19]

3.4.4 Neighbourhood consensus over the reserve

Peers applying for the round must reach a consensus on which chunks belong to their respective reserves. At a minimum, applicants must agree on their area of responsibility, which can be derived from their storage depth and their overlay address. The consensus over the reserve content is verified through the identity of a reserve sample. The sample consists of the first k chunks in the reserve using an ordering based on a modified hash of the chunks. The modified chunk hash is obtained using the chunk contents and a *salt* specific to the round.[20] It is impossible

[19]In case the token price goes up substantially, the stake balance can become significantly more valuable than what nodes could ever expect to earn. If the stake balance was not at all withdrawable, participation would be disincentivised due to the fear of losing the potential gains in the event of BZZ token appreciation.

[20]This modified hash is the BMT hash of the chunk data using Keccak-256 prefixed with the reserve sample salt as a base hash. The ordering is the ascending integer order reading the 32-byte modified hash as a big-endian encoded 256-bit integer.

for any node to construct this set unless they store all (or a substantial number of the) valid chunks, together with their data, at or after the time the salt is revealed.

Recency and sampling

The reserve sample must exclude very recent chunks to prevent malicious uploaders from bombarding nodes in the neighbourhood with a non-identical set of chunks that are going to be sampled, thereby disrupting the consensus about the reserve. One way to guard against this attack is to save each chunk together with its time of storage[21] in the local database. Pairwise synchronisation of chunks between neighbouring nodes, using the pull-sync protocol, respects this ordering by time of storage. We require that live syncing, i.e., the syncing of chunks received after the peer connection has been started, has a latency no longer than a predefined constant duration called maximum syncing latency (or *max sync lag* for short). Peer connections that exceed this syncing latency are not considered legitimate storer nodes according to the protocol. This restriction ensures that malicious nodes cannot back-date new chunks beyond the maximum sync lag without losing their storer status.

In order to reach consensus, it is important to ensure that all chunks received by any node in the neighbourhood not later than l are distributed to every node of the neighbourhood before the claim phase. If we set the value of l to be 2 times the allowed sync lag, then every chunk landing first with a node has time to arrive at each node to be safely included in a consensual sample.[22]

[21] Using the timestamp within the postage stamp alone, to define the minimum age, on would not solve the consensus problem, since chunks with old postage stamps could be circulated towards the end of sampling and lead to disagreements between neighbours.

[22] Instead of actually monitoring neighbour connections and abstaining from committing to a sample in case of excessive lag, one can just choose a small enough sample size.

Storage depth and honest neighbourhood size

In order to decide which reveal represents the truth for the current round, one submission out of all reveals is selected randomly, with a probability proportional to the amount of stake the revealer has. More precisely: based on the amount of stake per neighbourhood size, i.e., stake density. The reserve sample hash and the reported storage depth thus revealed are considered the truth for the current round.

Now we can understand why nodes will report actual storage depth correctly. If a node chooses to play with a larger neighbourhood than the neighbours, it will be selected more often than the others. However, as the committed storage depth decreases as compared to peers, the node's stake is counted with an exponentially deflated value relative to the peers reporting a deeper storage radius, making such an attack costly.

Overreporting storage depth is possible as long as the the node falls into this narrower proximity of the neighbourhood selection anchor. Therefore, a systematic exploit requires the malicious actor to control a staked node in each sub-neighbourhood of the true honest neighbourhood. Additionally, the winners need to provide evidence that the set of chunks within their storage depth indeed fills their reserve. The actual integer values of the transformed chunk addresses in the sample contain information regarding the size of the original sampled set. By requiring the size of the sampled set to fall within the expected range (with sufficient certainty), a constraint is imposed on the upper bound of the values of the sample. This construct is called proof of density.

Note that the sample-based density proof can be spoofed if the attacker mines content filtering chunks in such a way that the transformed chunk addresses form a dense enough sample, and then uses its own postage batches to stamp them. To enhance security against such attacks, additional measures can be implemented. One approach is to require a commitment to the entire set of postage stamps and prove custody of a sufficient quantity through a randomised sample. By imposing this requirement, fraudulent claimants not only need to generate the content, but also must have enough storage slots to fake the sample. This would require the attacker to purchase postage batches in the magnitude of the entire network or keep track of and store the actual postage stamps existing in the network. The former imposes a prohibitive cost on the attacker, whereas in the latter case, the malicious claimant must bear the risk of depending on honest neighbours for the post-hoc retrieval of the witness chunk data needed for the proof of entitlement.

Skipped rounds and rollover

If no claim is made in a particular round, the funds in the pot simply carry over and increase the outpayment for the next round of the redistribution. This policy is by far the easiest to implement, resulting in the lowest gas expenditures.[23]

The eight rules of entitlement

Here we summarise the eight rules of validating a claim, which involve committing and revealing a reserve commitment, as well as submitting evidence as proof of entitlement; see also Table 3.1):

REPLICATION
: Since liars get frozen, which means they are excluded from the game for a certain period due to revealing a reserve commitment hash or storage depth different from the winner, nodes within a neighbourhood are incentivised to replicate their reserve by synchronising the chunks they store using the pull-sync protocol.

REDUNDANCY
: The stake serves as weights in determining the probability of a node within a neighbourhood being selected as winner. As a result, there is no advantage in submitting multiple claims. Operators running multiple nodes in one neighbourhood (sharing storage) do not gain any advantage compared to running a single node with the same

[23]One might argue for reimbursing honest nodes for their transaction costs. Thereby, nodes with really small stakes can still participate and in general nodes are less exposed to variance in the probabilistic outpayments.

total stake. Assuming that this disincentive to proliferate is effective, staking can be considered a guarantee for true redundancy.

RESPONSIBILITY
: At the time of revealing, it is verified whether the neighbourhood selection anchor falls within the node's radius of responsibility, i.e., if it belongs to the range of addresses covered by the node, where the proximity of those addresses to the node's overlay address is not less than their reported storage depth.

RELEVANCE
: Using a witness proof with the reserve commitment hash as the root, we provide evidence that an arbitrarily chosen segment in the reserve sample packed address chunk corresponds to the address of a witness chunk. A valid postage stamp signed off on this witness chunk address is presented, indicating that storing this chunk in the reserve is relevant to someone (and has been paid for).

RETENTION
: A segment inclusion proof is provided as evidence that the chunk data has been preserved with complete integrity.

RECENCY
: The salt used for the transformed reserve sample is derived from the random noncs of the current round, proving that the RS must have been compiled recently. The witness and segment indexes are derived from the next game's random seed, ensuring that no compressed or partial retention of chunk data would have been sufficient at the time of compilation and commitment.

RETRIEVABILITY
: The chunk's retrievability is demonstrated through proximity-based routing, indicating that its address belongs to the range of addresses covered by the neighbourhood. The chunk's proximity order to the node's overlay address is not less than its reported storage depth.

RESOURCES
: Resource retention verifies the volume of resources constituting the reserve by estimating the sampled set size using the density of chunks and postage stamps.

proof of	construct used	attacks mitigated
REPLICATION	Shelling-game over reserve sample	non-syncing, laggy syncing
REDUNDANCY	share of reward proportional to stake	shared storage, over-application
RESPONSIBILITY	proximity to anchor	depth/neighbourhood misreporting
RELEVANCE	scarcity of postage stamps	generated data
RETENTION	segment inclusion proof	non-storage, partial storage
RECENCY	round-specific salt for reserve sample	create proof once and forget data
RETRIEVABILITY	proximity of chunk	depth over-reporting
RESOURCES	density-based reserve size estimation	targeted chunk generation (mining)

Table 3.1: r8: proofs used as evidence for entitlement to reward.

3.4.5 Pricing and network dynamics

In this section, we first contextualise the redistribution scheme within the framework of self-sustainability and offer a simple solution for price discovery.

For Swarm to be a truly self-sustaining system, the unit price of storage rent needs to be set in a way that is responsive to supply and demand. Ideally, the price is automatically adjusted based on reliable signals, resulting in dynamic self-regulation. The guiding insight here is that the information provided by storer nodes during the redistribution game also serves as a price signal. In other words, the redistribution game serves as a decentralised price oracle.

Splitting and merging of neighbourhoods

The storage depth represents the proximity radius within which the neighbourhood's storer nodes keep all chunks with valid postage stamps and fill their reserve.

If the volume of newly issued storage slots from recently purchased batches (*ingress rate*) and the volume of expired storage slots (*outgress rate*) balance out, the storage depth remains constant. However, let's consider what happens when the volume of reserved chunks increases. As the client's reserve capacity is fixed, over time, nodes are able to fill their capacity with chunks that are closer to them by at most one proximity order compared to the previously farthest chunks. This results in an increase in their storage depth. Specifically, when the volume of reserved chunks doubles, the storage depth increases by one.

In order to store this excess data under the same redundancy constraints, the network needs double the number of nodes. If all else is equal, double the network-wide reserve, double the postage revenue and therefore double the overall pot that gets redistributed. When neighbourhoods split as they are absorbing the new volume, they simultaneously release the chunks in the PO bin of their old depth, i.e., the chunks now stored by their sister nodes.

Utilisation rate is an organic way to introduce pressure against fully maximising a node's reserve with critical content and allows for early detection of capacity pressure. This provides a sufficient safety buffer for the triggered incentives to take effect. For instance, if utilisation rate is 1/8, the storage depth is up to 3 POs shallower than the reserve depth.[24] Now the ingress can be really high and bring the reserve depth down to the storage depth. When a narrowing gap between the potential (reserved) and actual (observed) utilisation of the DISC is detected, any changes in incentives will have the buffer to take effect without the target redundancy being threatened.

Number of honest nodes as price signal

Since the storage capacity is maxed out, the ratio of supply and demand is directly seen in the number of honest nodes playing the Schelling game.

[24]The narrative of this scenario is that uploaders with underutilised batches subsidise extra redundancy for everyone.

We make the assumption that nodes staying in the network for a longer period indicate their profitability. For a stable swarm, neighbourhoods only need a minimum of 4 (balanced) nodes. Assuming equal stake (or more precisely, assuming that relative stake equalises the profitability of node operators) if there are n nodes in a neighbourhood, their long-term profit is equally shared, this amount is optimised if there are exactly four nodes ($n = 4$). However, there can be more nodes in a neighbourhood, as opportunistic operators may anticipate a neighbourhood split due to capacity demand and start their nodes accordingly. As these nodes stay in, the same long-term winnings of the neighbourhood get distributed among more nodes than optimal. However, the fact that nodes tolerate this implies that the reward is too much (the price is too high), and the network can tolerate a decreasing price.

On the other hand, if the number of honest revealers is lower than the neighbourhood redundancy requirement, it signals a capacity shortage and therefore requires an increase in storage rent.

Parameterisation of the price oracle

The rule for updating the price from one round to the next is that the current price is multiplied by a value m which depends on the number of honest revealers in the round. Mathematically, $p_{t+1} = mp_t$, where p_t is the price in round t (and p_{t+1} is then the price in the following round). We define the multiplier m in terms of the number of honest revealers r and a stability parameter σ that governs how quickly the price should increase or decrease, all other things equal.

In particular, we choose $m = 2^{\sigma(4-r)}$, and therefore we have $p_{t+1} = 2^{\sigma(4-r)}p_t$. This expresses how the deviation $4 - r$ of the number of revealers from the optimal value of 4 maps to an exponential change in price. The stability parameter σ determines the generic smoothness of price changes across rounds, indicating how many rounds it takes for the rent price to double in case of a consistent signal of the lowest degree of undersupply (or halve in case of a consistent oversupply). Figure 3.19 illustrates how the price model works.

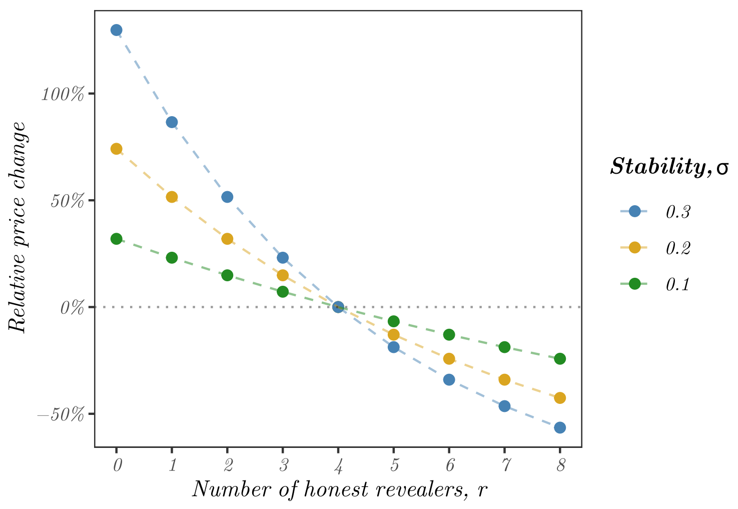


Figure 3.19: Adaptive pricing. The relative change in price (y-axis), mathematically expressed as the price in the next round divided by the price this round minus one ($p_{t+1}/p_t - 1$), is displayed against the number of honest revealers r in the current round (x-axis). This is done so for three different values of the stability parameter σ (colours). The points are the actual price change values; the connecting dashed lines are for visual aid only. The dotted horizontal line marks the point where no price change occurs. Price change is exactly zero for any σ when the number of honest revealers is four. Otherwise, larger values of σ lead to larger relative price changes as the number of honest revealers is varied.

Two minor adjustments are applied to this simple model. First, r is capped at a maximum value $r_{\max}$ (chosen to be 8 in our case). That is, r should actually be interpreted as the minimum of the number of honest revealers and $r_{\max}$. Second, the price is never allowed to drop below a predetermined minimum $p_{\min}$. That is, if the price were to drop from one round to the next and reach a value below the predetermined minimum $p_{\min}$, the price will be held steady at $p_{\min}$ instead.

3.5 Insurance: negative incentives

The storage incentives presented so far refer to the ability of a system to encourage the preservation of content through monetary rewards given to storers. This was achieved using an on-chain game which instrumented the fair redistribution of postage payments to storers, thereby providing positive incentivisation at a collective level. Such a system, however, is suspect to the tragedy of the commons problem in that disappearing content (any particular chunk missing) will have no negative consequence to storers (any one storer node punished). The lack of individual accountability renders the storage incentivisation limited as a security measure against data loss. Introducing competitive insurance, on the other hand, adds an additional layer of negative incentives, compelling storers to be very precise in their commitments to ensure reliability for users. Particular attention is required in the design of the incentive system to make sure that failure to store every last bit promised is not only unprofitable but outright catastrophic to the insurer.

3.5.1 Punitive measures

Unlike in the case of bandwidth incentives where retrievals are immediately accounted and settled, long-term storage guarantees are promissory in nature and it can only be decided if the promise has been kept at the end of its validity. Merely losing reputation is not sufficient as a deterrent against foul play in these instances: since new nodes must be allowed to provide services right away, cheaters could just resort to new identities and keep selling (empty) storage promises.

We need the threat of punitive measures to ensure compliance with storage promises. These can be achieved through a *deposit system*. Nodes wanting to sell promissory storage receipts should have a stake verified and locked-in at the time of making their promise. This implies that nodes need to register in advance, agreeing to a contract and placing a security deposit. Once registered, a node may sell storage promises covering the time period for which their funds are locked. While their registration is active, if they are found to have lost a chunk that was covered by their promise, they stand to lose their deposit.

Let us start from some reasonable guiding principles:

— Owners need to express their risk preference when submitting to storage.

- Storers need to express their risk preference when committing to storage.
- There needs to be a reasonable market mechanism to match demand and supply.
- There needs to be guarantees for the owner that its content is securely stored.
- There needs to be a litigation system where storers can be charged for not keeping their promise.

Owners' risk preferences consist of the time period covered as well as a preference for the *degrees of reliability*. These preferences should be specified on a per-chunk basis and they should be completely flexible at the protocol level.

Satisfying storers' risk preferences means that they have ways to express their certainty of preserving what they store and factor that in their pricing. Some nodes may not wish to provide long-term storage guarantees, while others may be unable to commit large deposits. This differentiates nodes in their competition for service provision.

A *market mechanism* means there is flexible *price negotiation* or discovery or automatic feedback loops that tend to respond to changes in supply and demand.

In what follows we will elaborate on a class of incentive schemes we call "swap, swear, and swindle" due to the basic components:

swap
: Nodes maintain a quasi-permanent, long-term contact with their registered peers. Along these connections, peers exchange chunks and receipts, triggering swap accounting (see 3.2.1).

swear
: Nodes registered on the Swarm network are held accountable and stand to lose their deposit if they are found to violate the rules of the swarm in an on-chain litigation process.

swindle
: Nodes monitor other nodes to check if they comply with their

promise by submitting challenges according to a process of litigation.

3.5.2 Contracts through receipts

A litigation procedure necessitates that there are contractual agreements between parties, ultimately linking an owner, who pays for securing future availability of content, and a storer, who gets rewarded for preserving it and making it immediately accessible at any point in the future. The incentive structure needs to make sure that litigation is used only as a last resort.

The most straightforward approach to manage storage deals is through direct contracts between the owner and the storer. This can be implemented by having storers return signed receipts of chunks they accept to store. Owners then pay for the receipts either directly or via escrow. In the latter case, the storer is only awarded the locked funds if they are able to provide proof of storage. This procedure is analogous to the postage stamp lottery process. Insurance can be bought in the form of specially marked postage stamps. Statements of custody receipts can close the loop and represent a contract between the uploader and the storer. Outpayments conditional on proofs of custody can be implemented the same way as the lottery.

Even if the consumer attempting to access the chunk was not a party to the agreement to store and provide the requested content, failure to deliver the stored content is subject to penalties. Litigation is therefore expected to be available to third parties who wish to retrieve content.

If the pairing of chunks and receipts is public and accessible, then consumers/downloaders (not only creators/uploaders) of the content are able to litigate in case a chunk is found to be missing.

Registration

Before a node can sell promises of long-term storage, it must first register via a contract on the blockchain we call the SWEAR (Secure Ways of Ensuring ARchival or Swarm Enforcement And Registration) contract.

The SWEAR contract allows nodes to register their public key to become accountable participants in the swarm. Registration involves sending the deposit to the SWEAR contract, which serves as collateral in case the terms that registered nodes "swear" to keep are violated (i.e. nodes do not keep their promise to store). The *registration* is valid only for a set period, at the end of which a Swarm node is eligible to reclaim their deposit. Users of Swarm should be able to count on the loss of deposit as a disincentive against foul play for as long as enrolled status is granted. Because of this the deposit must not be refunded before the registration expires. The expiry of the insurance period should therefore include a final phase during which the node is not allowed to issue new receipts but can still be challenged.

When a registered insurer node receives a request to store a chunk that is closest to them, it can acknowledge the request with a signed receipt. It is these signed receipts that are used to enforce penalties for loss of content. Because of the locked collateral backing them, the receipts can be viewed as secured promises for storing and serving a particular chunk.

3.5.3 Submitting a challenge

If a node fails to observe the rules of the Swarm they swear to keep, enforcement of punitive measures must be preceded by a litigation procedure. The implementation of this process is called SWINDLE (Secured With INsurance Deposit Litigation and Escrow).

When a user attempts to retrieve insured content and fails to find a chunk, they can report the loss by submitting a challenge. This scenario is the typical context for starting litigation. This is analogous to a court case in which the issuers of the receipts are the defendants who are guilty until proven innocent. Similarly to a court procedure, public litigation on the blockchain should be a last resort when the rules have been abused despite the deterrents and positive incentives.

The challenge takes the form of a transaction sent to the SWINDLE contract, in which the challenger presents the receipt(s) for the lost chunk. Any node is allowed to send a challenge for a chunk as long as they have a valid receipt for it (although it may not have necessarily been issued to them). The same transaction also sends a deposit covering the price of the upload of a chunk. The validity of the challenge as well as its refutation need to be easily verifiable by the contract. The contract verifies if the receipt is valid, i.e. 1) authentic, 2) active and 3) funded, by checking the following conditions:

authentic
: The receipt was signed with the public key of a registered node.

active
: The expiry date of the receipt has not passed.

funded
: Sufficient funds are sent alongside it to compensate the peer for uploading the chunk in case of a refuted challenge.

The last point above is designed to disincentivise frivolous litigation, i.e. bombarding the blockchain with bogus challenges and potentially causing a DoS attack.

The contract comes with an accessor for checking that a given node is challenged (potentially liable for penalty), so the challenged nodes can be notified that they must present the chunk in a timely fashion. The challenge remains open for a fixed amount of time, the end of which essentially sets the deadline for refuting the challenge.

Upon verifying the format of the refutation, the contract checks its validity by checking the hash of the chunk payload against the hash that is litigated or validating the proof of custody.

If a challenge is refuted within the period the challenge is open, the deposit of the accused node remains untouched. The cost of uploading the chunk must be reimbursed to the uploader from the challenger's deposit. To prevent DoS attacks, this deposit should actually be substantially higher than the upload cost in any case (e.g. a small integer multiple of the corresponding gas price). After successful refutation the challenge is cleared from the blockchain state.

This challenge scheme serves as the simplest method (1) for defendants to refute a challenge and (2) make the disputed data available to nodes that require it.

3.5.4 Successful challenge and enforcement

If the deadline passes without successful refutation of the challenge, then the charge is regarded as proven and the case enters into the enforcement stage. Nodes that are proven guilty of losing a chunk lose their deposit. Enforcement is guaranteed to be successful by the fact that deposits are kept locked up in the SWEAR contract.

If, on litigation, it turns out that a chunk (that was covered by a receipt) was lost, the deposit must be at least partly *burned.* Note that this is necessary because, if penalties were paid out as compensation to holders of receipts of lost chunks, it would provide an avenue of early exit for a registered node by "losing" bogus chunks that had been deposited by colluding users. Since users of Swarm are interested in their information being reliably stored, their primary incentive for keeping the receipts is to keep the swarm motivated to do so, not the potential for compensation in the case they do not. If deposits are substantial, we can get away with paying out compensation for initiating litigation, however we must have the majority (say 95%) of the deposit burned in order to make sure this easy exit route remains closed.

Punishment can entail *suspension*, meaning a node found guilty is no longer considered a registered Swarm node. Such a node is only able to resume selling storage receipts once they create a new identity and put up a deposit once again.[25]

[25]Note that the stored chunks are in the proximity of the address, so having to create a new identity will also imply expending extra bandwidth to replenish storage. This is an extra pain inflicted on offending nodes.

Incentivising promissory services

Delayed payments without locked funds leave storers vulnerable to non-payment. Advance payments (i.e. payments settled at the time of contracting, not after the storage period ends) on the other hand, leave the buyers vulnerable to cheating. Without limiting the total value of receipts a node can sell, a malicious node can collect more than their deposit and disappear. Having forfeited their deposit, they still walk away with a profit even though they broke their promise. Given a network size and a relatively steady demand for insured storage, the deposit could be set sufficiently high so this attack is no longer economical.

Locking the entire amount eliminates the storer's distrust due to potential insolvency of the insured party. When paying for insurance, the funds should cover the total price of storing a chunk for the entire storage period. This amount is locked and is released in installments contingent on the condition that the node provides a proof of custody. On the other hand, since payment is delayed it is no longer possible to collect funds before the work is complete, which eliminates a collect-and-run attack entirely.

3.6 Summary

In the first two chapters of the architecture part of the book, we introduced the core of Swarm: the peer-to peer-network layer described in Chapter 2 implements a distributed immutable storage for chunks, which is complemented by the incentive system described in the subsequent chapter. The resulting base layer system provides:

— permissionless participation and access,
— zero-cash entry for node operators,
— maximum resource utilisation,
— load-balanced distribution of data,
— scalability,
— censorship-resistance and privacy for storage and retrieval,
— auto-scaling popular content,
— basic plausible deniability and confidentiality,

- churn-resistance and eventual consistency in a dynamic network with node dropouts,
- sustainability without intervention due to built-in economic incentives,
- robust private peer-to-peer accounting,
- incentivised bandwidth sharing,
- off-chain micro-commitments with on-chain settlement,
- DoS resistance and spam protection,
- positive (i.e., motivated by reward) incentives for storage,
- negative (i.e., discouraged through threat of punitive measures) incentives against data loss.

— 4. Building on the DISC —

This chapter builds on the distributed chunk store and introduces data structures and processes that enable higher-level functionality, offering a rich experience handling data. In particular, we show how chunks can be organised to represent files (4.1.1) and how files can be organised to represent collections (4.1.2). We also introduce key–value maps (4.1.4) and briefly discuss the potential of arbitrary functional data structures. We then shift our attention to presenting our solution for providing confidentiality and access control (4.2).

In 4.3, we introduce Swarm feeds, which are designed to represent a wide variety of sequential data, such as versioning updates of mutable resources or indexing messages for real-time data exchange: offering a system of persisted pull messaging. To implement push notifications of all kinds, 4.4 introduces the novel concept of Trojan chunks that allow messages to be disguised as chunks and directed to their intended recipient in the swarm. We explain how Trojan chunks and feeds can be combined to form a fully-fledged communication system with robust privacy features.

4.1 Data structures

In the first two chapters, we made the assumption that data is structured in the form of chunks, i.e. fixed-size data blobs. However, in this section, we will present the algorithms and structures that enable the representation of data of arbitrary length. We will introduce Swarm manifests, which form the basis of representing collections, indexes, and routing tables, allowing Swarm to host websites and offer URL-based addressing.

4.1.1 Files and the Swarm hash

In this section, we introduce the concept of the *Swarm hash*, which provides a mechanism for combining chunks to represent larger sets of structured data, such as files. The idea behind the Swarm hashing algorithm is that chunks can be arranged in a Merkle tree. In this structure, leaf nodes correspond to chunks from consecutive segments of input data, while intermediate nodes correspond to chunks that are composed of the chunk references of their children. These combined chunks are packaged together to form another chunk, as illustrated in Figure 4.1.

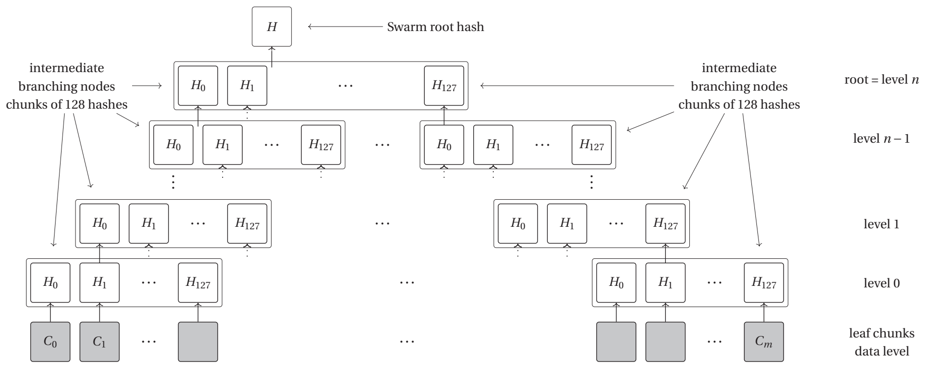


Figure 4.1: Swarm hash: data input is segmented to 4-kilobyte chunks (gray), that are BMT hashed. Their hashes are packaged into intermediate chunks starting on level 0, all the way until a single chunk remains on level n.

Branching factor and reference size

The branching factor of the tree is calculated as the chunk size divided by the reference size. For unencrypted content, the chunk reference is simply the BMT hash of the chunk, which is 32 bytes, so the branching factor is just 4096/32 = 128. A group of chunks referenced under an intermediate node is referred to as a batch. If the content is encrypted, the chunk reference consists of the concatenation of the chunk hash and the decryption key. Both are 32 bytes long, so an encrypted chunk reference will be 64 bytes, and therefore the branching factor is 64.

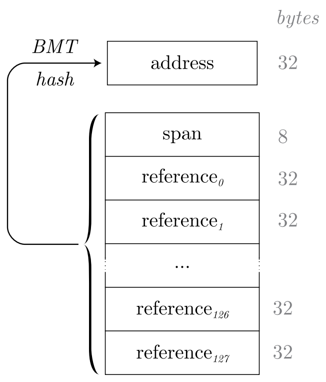


Figure 4.2: Intermediate chunk. It encapsulates references to its children.

As a result, a single chunk can represent an intermediate node in the Swarm hash tree, in which case its content can be segmented to references, allowing retrieval of their children. These child nodes themselves may be intermediate chunks, as illustrated in Figure 4.2. By recursively unpacking these from the root chunk downwards, we can eventually obtain a sequence of data chunks.

Chunk span and integrity of depth

The length of data subsumed under an intermediate chunk is called the chunk span. In order to be able to tell if a chunk is a data chunk or not, the chunk span is prepended to the chunk data in a 64-bit little-endian binary representation. When calculating the BMT hash of a chunk, this span constitutes the metadata that needs to be added to the BMT root and hashed together, resulting in the chunk address. When assembling a file starting from a hash, it is possible to tell if a chunk is a data chunk or an intermediate chunk simply by looking at the span. If the span is larger than 4K, the chunk is an intermediate chunk and its content needs to be interpreted as a series of hashes of its children; otherwise it is a data chunk.

In theory, if the length of the file is already known, spans of intermediate chunks are unnecessary since we could calculate the number of intermediate levels required for the tree. However, using spans disallows reinstating the intermediate levels as data layers. In this way, we impose *integrity of the depth*.

Appending and resuming aborted uploads

The Swarm hash has the interesting property that any data span corresponding to an intermediate chunk is also a file and can therefore be referenced as if the intermediate chunk was its root hash. This property is significant because it enables appending to a file while retaining a historical reference to the earlier state, without duplicating chunks, except for the incomplete right edge of the Merkle tree. Appending data to a file is particularly useful for scenarios such as resuming uploads after a crash partway through uploading big files.

Random access

Note that all chunks in a file, except for the right edge, are completely filled. Given that chunks have a fixed size, it is possible to calculate the path to a specific chunk and the offset to search within that chunk for any arbitrary data offset ahead of time. Because of this, *random access to files* is supported right away (see Figure 4.3).

Compact inclusion proofs for files

Suppose we were to prove the inclusion of a substring in a file at a particular offset. We have observed that the offset, when applied to the data, follows a deterministic path traversing the Swarm hash. Since a substring inclusion proof simply reduces to a series of proofs of data segment paths, the chunk addresses are a result of a BMT hash, where the base segments are 32 bytes long. This means that in intermediate chunks, BMT base segments align with the addresses of their children. As a consequence, proving that a child of an intermediate chunk at a particular span offset is equivalent to giving a segment inclusion proof on the child hash. Therefore, substring inclusion in files can be proved with

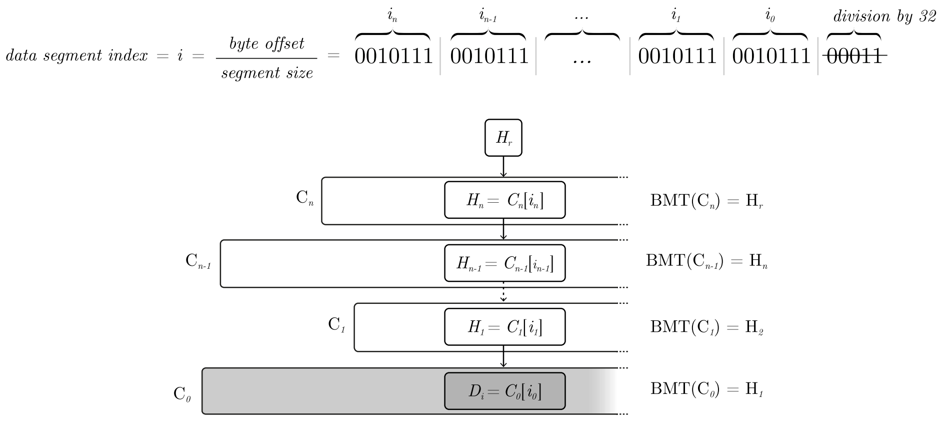


Figure 4.3: Random access at arbitrary offset with Swarm hash. The arbitrary offset informs us how to traverse the Swarm hash tree.

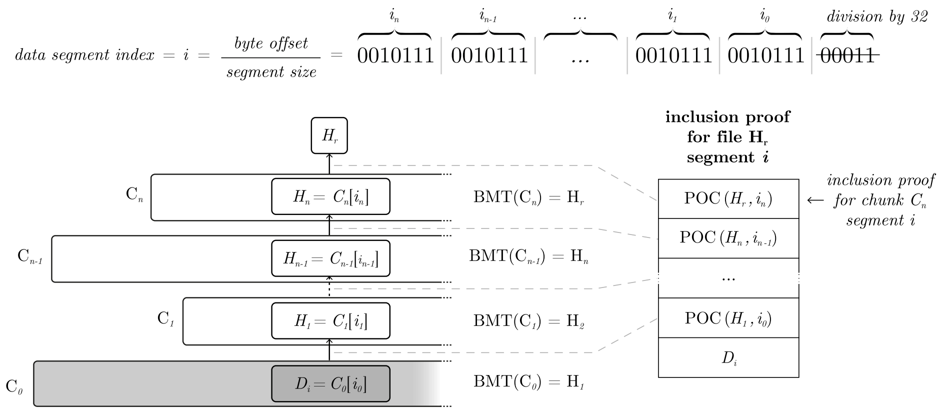


Figure 4.4: Compact inclusion proofs for files. If we need to prove inclusion of segment i, after division by 32 (within-segment position), we follow groups of 7 bits to find the respective segment of the intermediate node.

a sequence of BMT inclusion proofs where the length of the sequence corresponds to the depth of the Swarm hash tree (see Figure 4.4).

Note that such inclusion proofs are possible even in the case of encrypted data. This is because the decryption key for a segment position can be selectively disclosed without revealing any information that could compromise the encryption of other parts in the chunk.

In this section, we have presented the Swarm hash, a data structure over chunks that represents files, which supports the following functionalities:

random access
: The file can be read from any arbitrary offset with no extra cost.

append
: Supports appending without duplication.

length-preserving edits
: Supports length-preserving edits without the duplication of unmodified parts.

compact inclusion proofs
: Allow inclusion proofs with resolution of 32 bytes in space logarithmic in file size.

4.1.2 Collections and manifests

The Swarm manifest serves as a framework that defines a mapping between arbitrary paths and files to represent collections. It includes metadata associated with the collection and its objects (files). A manifest entry contains a reference to a file or, more precisely, a reference to the Swarm root chunk of the representation of file (see 4.1.1) and also specifies the media mime type of the file to ensure that browsers can appropriately handle it. A manifest can be thought of as (1) a routing table, (2) a directory tree, or (3) an index, which makes it possible for Swarm to implement (1) web sites, (2) file-system directories, or (3) key–value stores (see 4.1.4), respectively. The use of manifests is essential for URL-based addressing within Swarm (see 4.1.3).

Manifests are represented as a compacted trie[1] in which individual trie nodes are serialised as chunks. The paths are associated with a manifest entry that specifies at least the *reference*. The reference may point to an embedded manifest if the path is a common prefix of more than one path in the collection, thereby implementing branching in the trie, as depicted in Figure 4.5.

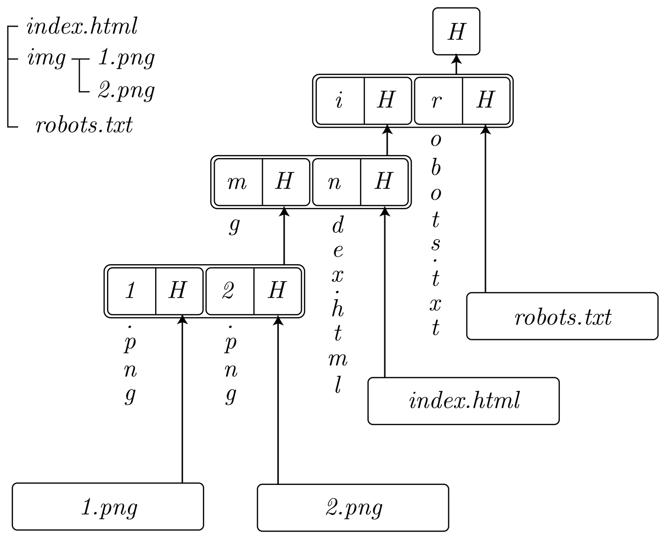


Figure 4.5: Manifest structure. Nodes represent a generic trie node: it contains the forks which describe continuations sharing a prefix. Forks are indexed by the next byte of the key, whose value contains the Swarm reference to the child node as well as the longest prefix (compaction).

A manifest entry is essentially a reference that provides information about a file or directory. The metadata pertains to the following areas of concern:

— Parameters for the downloader component, responsible for assembling chunks into a byte stream. This includes access control information, erasure coding parameters, and the publisher needed for chunk recovery.

[1]See `https://en.wikipedia.org/wiki/Trie`

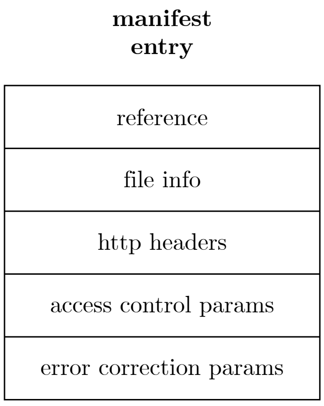


Figure 4.6: Manifest entry is a data structure that contains the reference to a file including metadata about a file or directory pertaining to the assembler, access control, and HTTP headers.

— Information relevant to client-side rendering, handled by the browser. This may include content type headers, or generically HTTP headers, that are picked up by the local swarm client's API and set in the response header when the file is retrieved.
— File information mapped to the file system during downloading, such as file permissions.

The high-level API for manifests offers functionality for uploading and downloading files and directories. It also provides an interface for adding documents to a collection on a path and deleting a document from a collection. Note that deletion here only means that a new manifest is created in which the path in question is omitted. There is no other notion of deletion in Swarm, i.e. the referenced value in the deleted manifest entry still remains in Swarm. Swarm exposes the manifest API via the *bzz URL scheme.*

4.1.3 URL-based addressing and name resolution

Earlier, we introduced the low-level network component of Swarm as a distributed immutable store of chunks (DISC, see 2.2.1). In the previous two sections, we discussed how files (4.1.1) and collections (4.1.2) can be represented in Swarm and identified using chunk references. Manifests provide a way to index individual documents in a collection, enabling them to serve as representations of websites hosted in Swarm. The root manifests serve as the entry-points to virtually hosted sites on Swarm and are therefore analogous to hosting servers. In the current web, domain names resolve to the IP addresses of host servers, and URL paths (of static sites) are mapped to entries in the directory tree based on their path relative to the document root set for the host. Analogously, in Swarm, domain names resolve to references to the root manifests, and URL paths are mapped to manifest entries based on their path.

When the HTTP API serves a URL, the following steps are performed:

domain name resolution
Swarm resolves the host part to a reference to a root manifest,

manifest traversal
recursively traverse embedded manifests along the path matching the URL path to arrive at a manifest entry,

serving the file
the file referenced in the manifest entry is retrieved and rendered in the browser with headers (notably content type) obtained from the metadata of manifest entry.

Swarm supports domain name resolution using the Ethereum Name Service (ENS). ENS is the system that, analogously to the DNS of the old web, translates human-readable names into system-specific identifiers, i.e., references in the case of Swarm. In order to use ENS, a Swarm node needs to be connected to an EVM-based blockchain that supports the Ethereum API (ETH mainnet, Ropsten, ETC, etc). Users of ENS can register a domain name on the blockchain and set it to resolve to a reference, most commonly the content hash of a public (unencrypted) manifest root. In the case that this manifest represents a directory containing the assets of a website, the default path for the hash may be set to be the desired root HTML page. When an ENS name is navigated to using a Swarm-enabled browser or gateway, Swarm will simply render the root HTML page and serve the rest of the assets provided in the relative path. Swarm facilitates easy website hosting, while also providing an interface to older pre-existing browsers and offering a decentralised improvement over the traditional DNS system.

4.1.4 Maps and key–value stores

This section describes two methods for implementing a simple distributed key–value store in Swarm. Both rely solely on tools and APIs which have been already introduced.

The first technique involves using manifests: Paths represent keys and the reference in the manifest entry with the particular path point to the value. This approach benefits from a full API enabling insert, update and remove through the bzz manifest API. Since manifests are structured as a compacted trie, this key–value store is scalable. Index metadata requires storage logarithmic to the number of key–value pairs. Lookup requires logarithmic bandwidth. The data structure allows for iteration that respects key order.

Single owner chunks also provide a way to define a key–value store.

The second technique simply posits that the index of the single owner chunk be constructed as a concatenation of the hash of the database name and the key. This structure only provides insert, without update or remove. Both insert and lookup are constant space and bandwidth. However, lookup is not safe against false negatives, i.e., if the chunk that represents the key–value pair is not found, this does not mean it has never been created (e.g. it may have been garbage collected). Thus, the single owner chunk based key–value store is best used as (1) a bounded cache of recomputable values, (2) mapping between representations such as a translation between a Swarm hash and a Keccak256 hash as used in the Ethereum blockchain state trie nodes, or (3) conventional relational links, such as likes, upvotes, and comments on social media posts.

4.2 Access control

This section first addresses the confidentiality of content using encryption. Encryption becomes especially useful once users are granted the ability to manage others' access to restricted content. This encompasses scenarios such as managing private shared content and granting authorisation for members to access specific areas of a web application. In this way, we provide a robust and simple API to manage access control, something that is traditionally handled through centralised gatekeeping which is subject to frequent and disastrous security breaches.

4.2.1 Encryption

This section focuses on achieving confidentiality in a distributed public data storage. We explore how to fulfill the natural requirement for many use cases to store private information while ensuring that it remains accessible only to specific authorised parties using Swarm.

It is clear that the pseudo-confidentiality provided by the server-based access control predominantly used in current web applications is inadequate. In Swarm, nodes are expected to share the chunks with each other, in fact, storers of chunks are incentivised to serve them to anyone who requests them. This decentralised architecture makes it infeasible for nodes to act as the gatekeepers trusted with controlling access to the data. Moreover, since any node in the network could potentially be a storer, the confidentiality solution must not reveal any information that could distinguish a private chunk from random data. As a consequence of this, the only way to prevent unauthorized parties from accessing private chunks is through encryption. In Swarm, if a requestor is authorized to access a chunk, they must possess a decryption key that allows them to decrypt the chunk. Unauthorized parties, on the other hand, must not have access to the decryption key. Incidentally, this mechanism also serves as the basis for plausible deniability.

Encryption at the chunk level is described in 2.2.4. It has the desirable property of being virtually independent of the chunk store layer, using the exact same underlying infrastructure for storing and retrieving chunks as unencrypted content. The only difference between accessing private and public data is the presence of a decryption/encryption key in the chunk references and the associated minor cryptographic computational overhead.

The storage API's raw `GET` endpoint allows both encrypted and unencrypted chunk references. Decryption is triggered if the chunk reference is double size; consisting of the address of the encrypted chunk and a decryption key. Using the address, the encrypted chunk is retrieved, stored, and decrypted using the supplied decryption key. The API responds with the resulting plaintext.

The storage API's `POST` endpoint expects users to indicate if they want to have encryption on the upload or not. In both cases, the chunk will be stored and push-synced to the network, but if encryption is desired, the encrypted chunk needs to be created first. If no further context is given, a random encryption key is generated which is used as a seed to generate random padding to fill the chunk up to a complete 4096 bytes if needed, and finally this plaintext is encrypted with the key. In the case of encryption, the API `POST` call returns the Swarm reference, which consists of the Swarm hash as the chunk address and the encryption key.

In order to guarantee the uniqueness of encryption keys as well as to ease the load on the OS's entropy pool, it is recommended (but not required) to generate the key as the MAC of the plaintext using a (semi-) permanent random key stored in memory. This key can be permanent and generated using `scrypt` (Percival 2009) with a password provided upon startup. Instead of the plaintext, a namespace and path of the manifest entry can be used as context. Using a key derivation function in this way has the consequence that chunk encryption will be deterministic as long as the context is the same: If we exchange one byte of a file and encrypt it with the same context, all data chunks of the file except the one that was modified will end up being encrypted exactly as the original. Encryption is therefore deduplication-friendly.

4.2.2 Managing access

This section describes the process the client needs to follow in order to obtain the full reference to the encrypted content. This protocol relies on basic meta-information, which is simply encoded as plaintext metadata and explicitly included in the root manifest entry for a document. This level of access, known as root access, does not require special privileges.

In contrast, granted access is a type of selective access that necessitates both root access and access credentials, i.e. an authorised private key or passphrase. Granted access allows different levels of privileges for accessing the content by multiple parties sharing the same root access. This approach allows for updating the content without changing access credentials. Granted access is implemented using an additional layer of encryption on references.

The symmetric encryption of the reference is called the encrypted reference, and the symmetric key used in this layer is called the access key.

In the case of granted access, the root access meta-information contains both the encrypted reference and the additional information required for obtaining the access key using the access credentials. Once the access key is acquired, the reference to the content is obtained by decrypting the encrypted reference with the access key. The resulting full reference consists of the address root chunk and the decryption key for the root chunk. The requested data can then be retrieved and decrypted using the standard method.

The access key can be obtained from a variety of sources, three of which we will define.

First, a session key is derived from the provided credentials. In the case of granting access to a single party, the session key is used directly as the access key, as depicted in Figure 4.7. However, in the case of multiple parties, an additional mechanism is used to transform the session key into the access key.

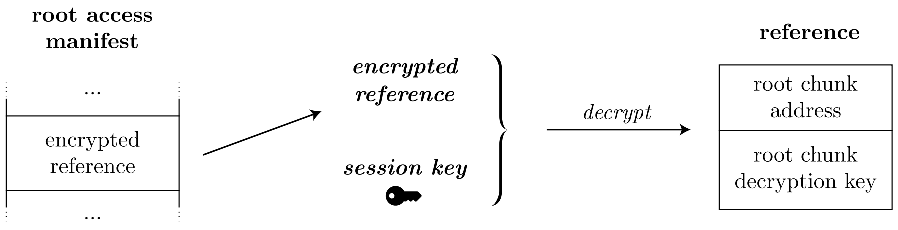


Figure 4.7: Access key as session key for single party access.

Passphrase

The simplest credential for deriving a session key is a *passphrase*. The session key is obtained from a passphrase using `scrypt` with parameters that are specified within the root access meta-information. The output of scrypt is a 32-byte key that may be directly used for Swarm encryption and decryption algorithms.

In typical use cases, the passphrase is distributed by an off-band means with adequate security measures, or exchanged in person. Any user knowing the passphrase from which the key was derived will be able to access the content.

Asymmetric derivation

A more sophisticated credential is a *private key*, identical to those used throughout Ethereum for accessing accounts, i.e. an elliptic curve using secp256k1. In order to obtain the session key, an elliptic curve Diffie-Hellman (ECDH) key agreement must be performed between the content publisher and the grantee. The resulting shared secret is hashed together with a salt. The content publisher's public key as well as the salt are included among metadata in the root access manifest. Based on the standard assumptions of ECDH, this session key can only be computed by the publisher and the grantee and no-one else. Once again, when access is granted to a single public key, the session key derived this way can be directly used as the access key for the decryption of the encrypted reference. Figure 4.8 summarises the use of credentials to derive the session key.

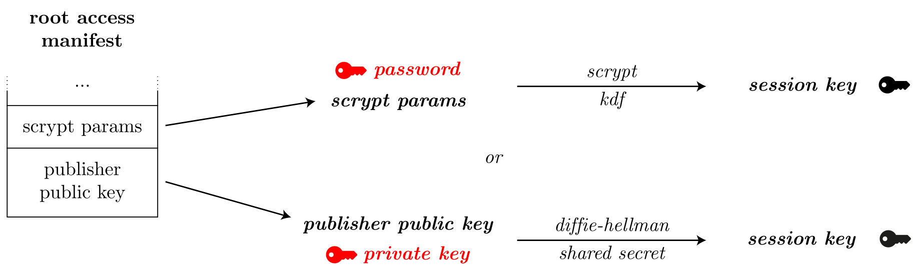


Figure 4.8: Credentials to derive session key.

4.2.3 Selective access to multiple parties

In order to manage access by multiple parties to the same content, an additional layer is introduced to obtain the access key from the session key. In this variant, grantees can be authenticated using either type of credentials, however, the session key derived as described above is not directly used as the access key for decrypting the reference. Instead, two keys are derived from the session key: a lookup key and an access key decryption key. These keys are obtained by hashing the session key with two different constants (0 and 1, respectively).

When granting access, the publisher needs to generate a global access key to encrypt the full reference, and then encrypts it with the access key decryption keys for each grantee. Thereafter, a lookup table is created, mapping each grantee's lookup key to their encrypted access key. Then, for each lookup key, the access key is encrypted with the corresponding access key decryption key.

This lookup table is implemented as an access control trie (ACT) in Swarm manifest format. The paths in the ACT correspond to the lookup keys and manifest entries containing the ciphertext of the encrypted access keys as metadata attribute values. The ACT manifest is an independent resource referenced by a URL, which is included among the root access metadata to indicate whether or not an ACT is to be used.

When accessing content, the user follows these steps: they retrieve the root access meta data, identify the ACT resource, and then calculate their session key using either their passphrase and the scrypt parameters or the publisher public key, their private key, and a salt. From the session key, they can derive the lookup key by hashing it with 0, and then retrieve the manifest entry from the ACT. For this, they will need to know the root of the ACT manifest and then use the lookup key as the URL path. If the entry exists, the user obtains the value of the access key attribute in the form of a ciphertext that is decrypted with a key derived by hashing the session key with the constant 1. The resulting access key can then be used to decrypt the encrypted reference included in the root access manifest, as seen in Figure 4.9. Once the manifest root is unlocked, all references contain the decryption key.

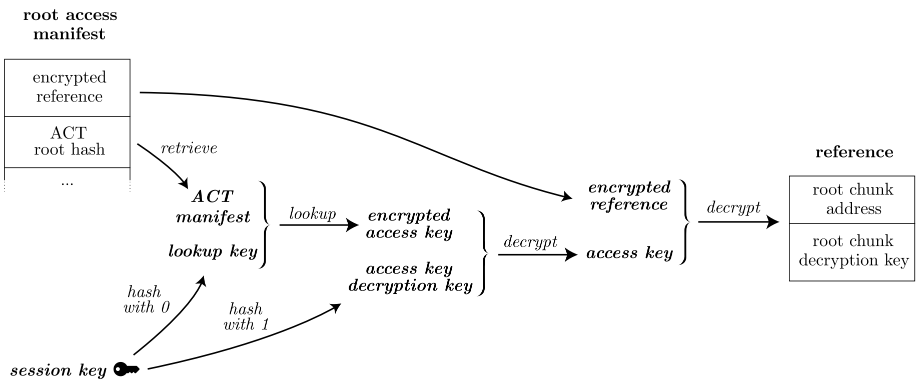


Figure 4.9: Access control for multiple grantees involves an additional layer to get from the session key to the access key. Each user must lookup the global access key specifically encrypted to them. Both the key to look up and the key for decrypting the access key are derived from the session key, which, in turn, requires their credentials.

This access control scheme offers several desirable properties:

- Checking and looking up one's own access is logarithmic in the size of the ACT.
- The size of the ACT merely provides an upper bound on the number of grantees, without disclosing any information beyond this upper bound about the set of grantees to third parties. Even those included in the ACT can only learn that they are grantees, but ob-

tain no information about other grantees beyond an upper bound on their number.

— Granting access to an additional key requires extending the ACT by a single entry, which is logarithmic in the size of the ACT.
— Revoking access requires changing the access key and therefore the rebuilding of the ACT. Note that this also requires that the publisher retain a record of the public keys of grantees after the initial creation of the ACT.

4.2.4 Access hierarchy

In the simplest case, the access key is a symmetric key. However, this is just a special case of the more flexible solution, where the access key consists of a symmetric key and a key derivation path by which it is derived from a root key. In this case, a derivation path may also be included in addition to the encrypted reference. Any party with an access key whose derivation is a prefix to the derivation path of the reference can decrypt the reference by deriving its key using their own key and the rest of the reference's derivation path.

This allows for a tree-like hierarchy of roles, possibly reflecting an organisational structure. As long as role changes are "promotions", i.e. they result in increased privileges, modifying a single ACT entry for each role change is sufficient.

4.3 Feeds: mutability in an immutable store

Feeds are a unique feature of Swarm that constitute the primary use case for single owner chunks. They have a wide range of applications, including versioning revisions of a mutable resource, indexing sequential updates to a topic, publishing parts to streams, or posting consecutive messages in communication channels. Feeds implement persisted pull-messaging and can also be interpreted as a pub-sub system.

In Section 4.3.1, we introduce how feeds are composed of single owner chunks with an indexing scheme, the choice of which we discuss in 4.3.2. We then delve into the importance of feed integrity and methods for verifying and enforcing it in 4.3.3. Section 4.3.4 describes epoch-based feeds which provide a search mechanism for feeds that receive sporadic updates. Finally, in 4.3.5, we demonstrate how feeds can be used as an outbox for sending and receiving subsequent messages within a communication channel.

4.3.1 Feed chunks

A feed chunk is a single owner chunk with the associated constraint that the identifier is composed of the hash of a feed topic and a feed index. The topic is a 32-byte arbitrary byte array, typically the Keccak256 hash of one or more human-readable strings specifying the topic and optionally the subtopic of the feed (see Figure 4.10 for a visual representation).

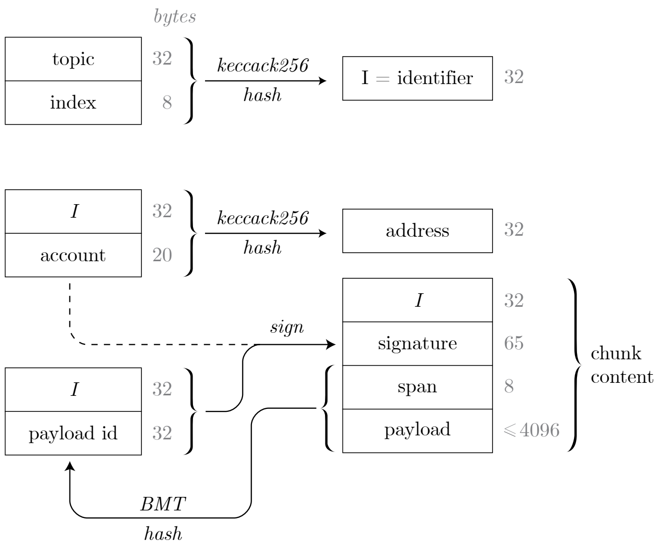


Figure 4.10: Feed chunks are single owner chunks where the identifier is the hash of the topic and an index. Indexes are deterministic sequences calculated according to an indexing scheme. Subsequent indexes for the same topic represent identifiers for feed updates.

The index of a feed can take various forms, defining some of the potential types of feeds. The ones discussed in this section are: (1) simple feeds that use incremental integers as their index (4.3.2); (2) epoch-based feeds that use an epoch ID (4.3.4); and (3) private channel feeds that use nonces generated through a double ratchet key chain. (4.3.5). The common characteristic among all these feed types is that both the publisher (owner) and the consumer must be aware of the indexing scheme in order to interact with the feed effectively.

Publishers have exclusive ownership of the feed chunks and are the only ones authorised to post updates to their feed. Posting an update requires (1) constructing the identifier from the topic and the correct index, and (2) signing the identifier concatenated with the hash of the arbitrary content of the update. Since the identifier designates an address in the owner's subspace of addresses, this signature effectively assigns the payload to this address (see 2.2.3). In this way, all items published on a particular feed can be verified to have been created solely by the owner of the corresponding private key.

On the consumer side, users can retrieve a feed by specifying the chunk address. Retrieving a specific update requires the consumer to construct the address from the owner's public key and the identifier. To calculate the identifier, the user needs two pieces of information: the topic and the appropriate index, for which they need to know the indexing scheme.

Feeds enable Swarm users to represent a sequence of content updates. The content of each update serves as the payload, which the feed owner signs against the identifier. The payload can be a swarm reference, allowing users to retrieve the associated data.

4.3.2 Indexing schemes

Different types of feeds require different indexing schemes and different lookup strategies. In the following sections, we introduce a few largely independent dimensions in which feeds can be categorised and which appear relevant in making a choice.

The actual indexing scheme used, or even the presence of one (i.e. if the single-owner chunk is a feed chunk at all), is left unrevealed in the structure of a feed chunk, as this information is not needed for the validation of a chunk by forwarding nodes. Including the subtype explicitly in the structure would only result in unnecessary information leakage.

Update semantics

Updates of a feed can be categorised into three subtypes, each with distinct semantics.

Feeds that represent *revisions* of the same semantic entity are called mutable resource updates. These resources mutate because the underlying semantic entity undergoes changes, such as updates to your CV or the expansion of a resource description, like the Wikipedia entry about a Roman emperor. Users will typically be interested in the latest update of such resources, with past versions having only historical significance. As the term 'revision' suggests, the interpretation of an update in the case of mutable resources is *substitutive*.

The second subtype of feeds, known as series updates, represents a series of content linked by a common thread, theme, or author. In a series, each update is considered as an *alternative* and independent instantiation or episode that unfolds in a chronological order, such as include social media status updates, a person's blog posts, or blocks of a blockchain. Series updates present a cohesive narrative or progression of information, allowing users to engage with the content in a sequential and interconnected manner.

Finally, there are partitions expressed as feeds, where updates are meant to be *accumulative*: subsequent updates are sequentially added to earlier ones. A common example is a video stream that consists of multiple parts. Partition feeds mainly differ from series in that the individual feed updates are not meaningful or interpretable on their own. Instead, the temporal sequence of updates may represent a processing order that corresponds to some serialisation of the structure of the resource rather than reflecting temporal succession. When accessing a partition feed, it may be necessary to accumulate all the parts in order to ensure the integrity of the represented resource. This means that each update builds on the previous ones, resulting in a comprehensive representation of the entire resource.

If subsequent updates of a feed include a reference to a data structure that indexes the previous updates (e.g. a key–value store using the timestamp for the update or simply the root hash of the concatenation of update content), then the lookup strategy in for all three feed types reduces to retrieving the latest update.

Update frequency

Feeds that are updated over time may be categorised into several types. Some are sporadic feeds with irregular asynchronicities, i.e. updates that can have unpredictable gaps. Another type is periodic feeds, where updates are published at regularly recurring intervals.

Additionally, we will discuss real-time feeds, where the update frequencies may not follow a regular pattern but instead vary within the temporal span of real-time human interaction, i.e. they are punctuated by intervals in the second to minute range.

Subscriptions

Feeds can be interpreted as pub/sub systems that offer persistence, enabling asynchronous pulls. In what follows, we analyse how the choice of indexing scheme affects the implementation of subscriptions to feeds as pub/sub.

In order to cater for subscribers of a feed, the updates need to be tracked. When we have knowledge of the latest update, we can employ periodic polling to fetch subsequent updates. If the feed is periodic, one can start polling after a known period. Alternatively, if the feed updates are frequent enough (at most a 1-digit integer orders of magnitude rarer than the desired polling frequency), then polling is also feasible. However, if the feed is sporadic and updates occur unpredictably, polling may not be practical. In such scenarios, alternative methods like push notifications (see 4.4.1 and 4.4.4) become preferable for ensuring timely updates.

If we have missed out on polling for a period of time due to being offline, or just created the subscription, we can also rely on push notifications or use a lookup strategy to retrieve the necessary updates.

Looking up partitions poses no difficulty as each update needs to be fetched and accumulated. In this case, the strategy of just iterating over the successive indexes cannot be improved. For periodic feeds, we can just calculate the index for a given time, hence asynchronous access is efficient and trivial. However, looking up the latest version of a sporadically updated feed requires some search and hence benefits from epoch-based indexing.

Aggregate indexing

A set of sporadic feeds can be turned into a periodic one using feed aggregation. Imagine, for example, a multi-user forum like Reddit, where each registered participant would publish comments on a post using sporadic feeds. In this scenario, would be impractical for each user to monitor the comment feed of every other user and search through their sporadic feeds for updates in order to retrieve all the comments on the thread. A more efficient approach is to just do it once though for all users. Indexers do exactly that: they aggregate everyone's comments into an index, a data structure whose root can then be published as a periodic feed, see Figure 4.11. The frequency of updates can be chosen to provide a real-time feed experience; even if the rate of change does not justify it, i.e. some updates may be redundant, the cost amortises over all users who use the aggregate feed, making it economically sustainable.

A service of this kind can be offered with arbitrary levels of security, yet trustlessly, without relying on reputation. Using consensual data structures for the aggregation, incorrect indexes can be proven using affordable and concise inclusion proofs (see 4.1.1) and therefore any challenges related to correctness can be evaluated on chain. Providers face the risk of losing their deposit if a challenge remains unrefuted, which acts as a strong incentive for them to uphold a high standard of service quality.

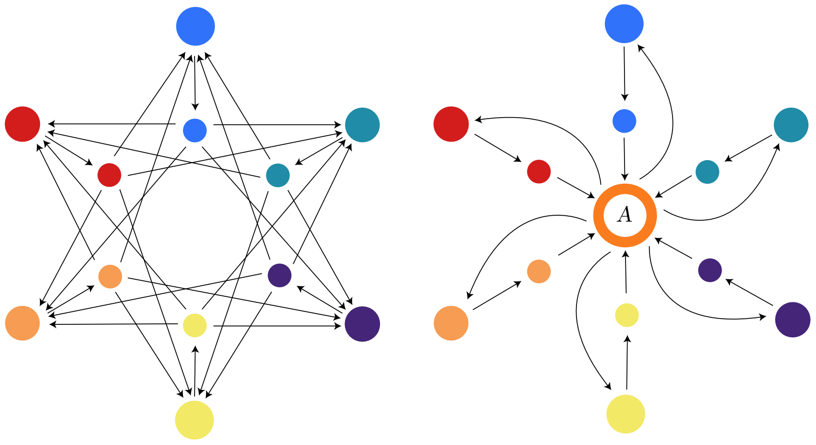


Figure 4.11: Feed aggregation serves to merge information from several source feeds in order to save consumers from duplicate work. **Left:** 6 nodes involved in group communication (discussing a post, having real time chat, or asynchronous email thread). Each node publishes their contributions as outbox feed updates (small coloured circles). Each participant polls the other's epoch-based feeds, duplicating work with the lookup. **Right:** the 6 nodes now register as sources with an aggregator which polls the nodes' feed and creates indices that aggregate the sources into one data structure which each participant can then pull.

4.3.3 Integrity

We consider a feed to have *integrity* when each of its updates is unambiguous. Formally, this means that for each index, the respective feed identifier is only ever assigned to a single payload. Incidentally, this also implies that the corresponding feed chunk has integrity. As discussed in 2.2.3, this is a prerequisite for consistent retrieval. If the payloads of the successive updates are imagined as blocks of a blockchain, then the criterion of integrity requires feed owners to avoid creating forks in their chain.

In fact, the integrity of a feed can only be guaranteed by the owner. However, it is important to consider whether the integrity can be effectively checked or enforced. Owners can commit to the integrity of their feeds by staking a deposit on the blockchain, which they stand to lose if they are found to double sign on an update. While this may provide a strong disincentive to fork a feed in the long run, it alone does not offer sufficient guarantees to consumers of the feed with respect to integrity. Because of this, we must design indexing schemes that actively enforce the desired integrity standards.

Authoritative version history

Mutable resource update feeds track versions pretty much the same way as the Ethereum Name Service does. When a version is consolidated, such as a website update, the owner wants to register the content address of the current version. In order to guarantee that there is no dispute over history, the payload needs to incorporate the hash of the previous payload. This requirement implies that the payload must be a composite structure. However, if the goal is to have a payload consisting of solely a manifest or manifest entry so that it can be rooted to a URL path or directly displayed, this is not possible. Additionally, if in cases where the feed content is not a payload hash, ENS registers a payload hash despite the absence of the corresponding chunk in Swarm, thus violating the semantics of ENS.

An indexing scheme that incorporates the previous payload hash into the subsequent index operates in a similar manner to a blockchain. It expresses the owner's unambiguous commitment to a particular history and requires any consumer who reads and uses it to acknowledge and accept that history. Looking up such feeds is only possible by retrieving each update since the last known one. The address refers to the update chunk, so registering the update address both guarantees historic integrity and preserves ENS semantics so that the registered address is just a Swarm reference to a chunk. Such feeds establish an authoritative version history, i.e. they provide a secure audit trail of the revisions made to a mutable resource.

Real-time integrity check

A deterministically indexed feed provides the ability to perform a real-time integrity check. In the context of feeds that represent blockchains (ledgers/side-chains), integrity refers to having a non-forking and unique chain commitment. The ability to enforce this in real-time allows fast and secure definitions of transaction finality.

We illustrate this with an example of an off-chain p2p payment network where each node's locked-up funds are allocated to a fixed set of creditors (see more detail in Trón et al. 2019a). The creditors of a node need to verify the accuracy of the reallocations, i.e. that the total increases are covered by countersigned decreases. If a debitor keeps publishing a deposit allocation table for an exhaustive list of creditors, by issuing two alternatives to targeted creditors, the debitors will be able to orchestrate a double spend. Conversely, if there is certainty in the uniqueness of this allocation table, the creditor can confidently conclude finality.

We claim that using Swarm feeds, this uniqueness constraint can be verified in real-time.

The key insight is that it is impossible to meaningfully control the responses to a single owner chunk request: Even if an attacker has control over the entire neighbourhood of the chunk address, there is no systematic way to respond with particular versions to particular requestors.[2] This is due to the inherent ambiguity of the originator of the request in the forwarding Kademlia protocol. Let us imagine that the attacker, using some sophisticated traffic analysis, has the chance of $1/n$ (asymptotic ceiling) to identify the originator and give a differential response. By sending multiple requests from random addresses, however, one can test integrity and consider a consistent response a requirement for concluding finality. The probability that the attacker can give a consistent differential response to a creditor testing with k independent requests is $1/n^k$. With linear bandwidth cost in k, we can achieve exponential degrees of certainty about the uniqueness of an update. If a creditor observes consistency in the responses, it can conclude that there is no alternative allocation table.

By requiring the allocation tables to be disseminated as feed updates, we can leverage the advantages of permissionlessness, availability, and anonymity to enforce feed integrity. If the feed is a blockchain-like ledger, a real-time integrity check translates to fork finality.

4.3.4 Epoch-based indexing

In order to use single owner chunks to implement sporadic feeds with flexible update frequency, we introduce epoch-based feeds as an indexing scheme. In this scheme, the identifier of a single owner chunk incorporates anchors related to the time of publishing. In order to be able to find the latest update, we introduce an adaptive lookup algorithm.

Epoch grid

An epoch is a defined time period starting at a specific point in time, known as the epoch base time, and lasts for a specific duration. The

[2]If the chunks are uploaded using the same route, the chunk that comes later will be rejected as already known. If the two chunks originate from different addresses in the network, they might both end up in their local neighbourhood. This scenario will result in inconsistent retrievals depending on which node the request ends up with.

lengths of these periods are expressed as powers of 2 in seconds, ranging from the shortest period of $2^0 = 1$ second to the longest period of 2^{31} seconds.

An epoch grid is the arrangement of epochs, where each row represents an alternative partitioning of time into various disjoint epochs of the same length. Rows, also known as levels, are indexed by the logarithm of the epoch length putting level 0 with 1 second epoch length at the bottom by convention, see Figure 4.12.

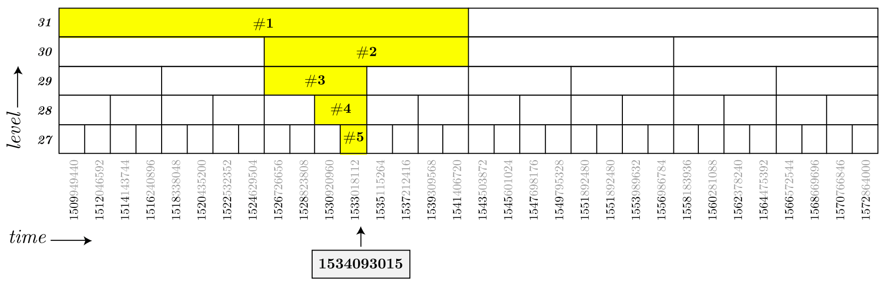


Figure 4.12: Epoch grid showing the first few updates of an epoch-based feed. Epochs occupied are marked in yellow and are numbered to reflect the order of updates they represent.

When representing a epoch-based feed in an epoch grid, each update is assigned to a specific epoch within the grid based on its timestamp. In particular, an update is mapped to the longest free epoch that includes the timestamp. This structure gives the series of updates a contiguous structure, which allows for easy search. The contiguity requirement implies that by knowing the epoch of the previous update, the subsequent update can be mapped to a specific epoch without ambiguity.

To identify a specific epoch within the epoch grid, we need to know both the epoch base time and the level. This pair is called the epoch reference. To calculate the epoch base time for any given instant in time t at a particular level l, the l least significant bits of t are dropped. The level requires one byte, and the epoch base time (using Linux seconds) 4 bytes, so the epoch reference can be serialised in 5 bytes. It is worth noting that the epoch reference of the initial update of any epoch-based feed is always the same.

Mapping epochs to feed update chunks

The serialised epoch reference serves as the feed index for mapping feed updates to feed chunks. The topic of the feed hashed together with the index results in the feed identifier used in constructing the single owner chunk that expresses the feed chunk.

To determine the appropriate epoch for storing a subsequent update, the publisher needs to know the location of the previous update. If the publisher does not keep track of this information, they can use the lookup algorithm to find their most recent update.

Lookup algorithm

When consumers retrieve feeds, their objectives typically revolve around looking up the state of the feed at a particular time (historical lookup) or to retrieving the latest update.

If historical lookups based on a *target* time are required, the update can incorporate a data structure that maps timestamps to corresponding states. In such cases, finding any update later than the target can be used to deterministically look up the state at an earlier time.

If no such index is available, historical lookups need to find the shortest filled epoch whose timestamp is earlier than the target.

To select the best starting epoch from which to walk our grid, we have to assume the worst case scenario, which is that the resource has never been updated since the last time we saw it. If we don't know when the resource was last updated, we assume it to be 0.

We can guess a start level as the position of the first non-zero bit of $\mathit{lastUpdate} \veebar \mathit{NOW}$ counting from the left. The bigger the time difference between the last update time and the current time, the higher the level will be.

4.3.5 Real-time data exchange

Feeds can be used to represent a communication channel, i.e. the outgoing messages of a persona. This type of feed, called an outbox feed can be created to provide email-like communication or instant messaging, or even the two combined. For email-like asynchronicities, epoch-based indexing can be used, while deterministic sequence indexing is more suitable for instant messaging. In group chat or group email, confidentiality is managed through an access control trie over the data structure, which indexes each party's contribution to the thread. Communication clients can retrieve the feeds of each group member relating to a particular thread and merge their timelines for rendering.

Even forums could be implemented with such an outbox mechanism described above. However, as the number of registered participants increases, aggregating all outboxes on the client side may become impractical. In such cases, index aggregators or other schemes may be necessary to crowdsource the combination of the data.

Two-way private channels

Private two-party communication can also be implemented using outbox feeds, see Figure 4.13. The parameters of such feeds are established during the initial key exchange or registration protocol (see 4.4.2), ensuring that the parties consent on the indexing scheme as well as the encryption used.

For real-time instant messaging using a series feed, it is important to have an indexing scheme that supports deterministic continuations for at least a few updates ahead. This enables sending retrieve requests for upcoming updates in advance, i.e. during or even prior to processing the previous messages. When these retrieve requests arrive at the nodes closest to the requested update address, it is expected that the chunk will not be available since the other party will not have sent them yet. However, even these storer nodes are incentivised to keep retrieve requests alive until they expire (as discussed in 2.3.1). This means that up until the end of their time-to-live setting (30 seconds), the requests will

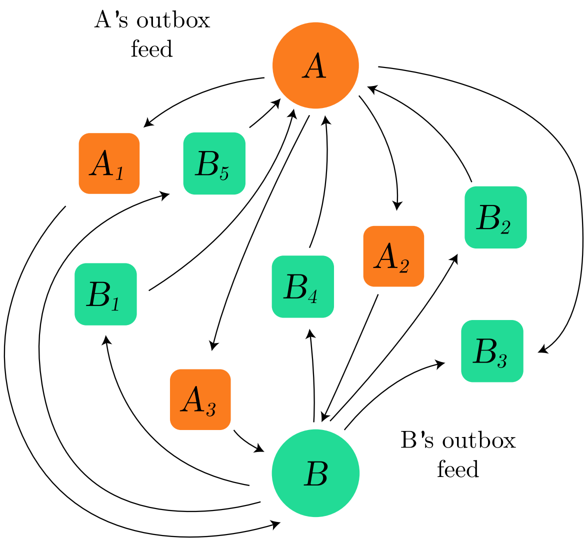
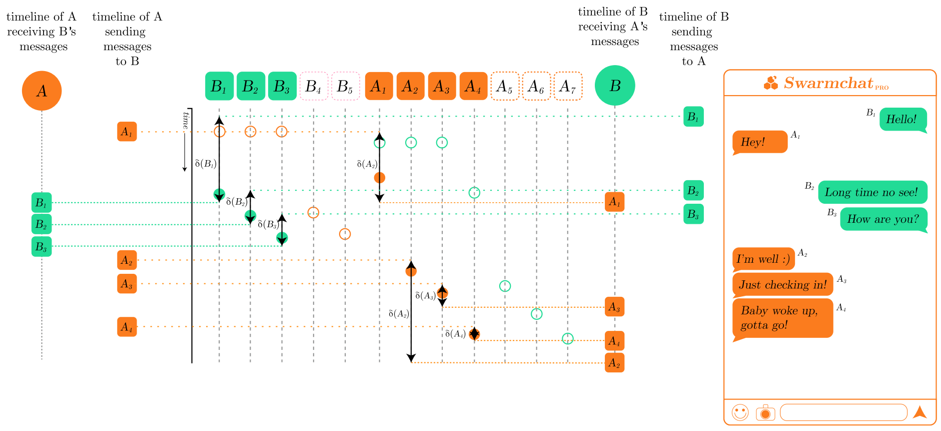


Figure 4.13: Swarm feeds as outboxes for private communication. Outbox feeds represent consecutive messages from a party in a conversation. The indexing scheme can follow a key management system with strong privacy which obfuscates the communication channel itself and renders interception attacks prohibitively expensive.

function as subscriptions: the arrival of the update chunk triggers the delivery response to the open request as if it was the notification sent to the subscriber. This reduces the expected message latency to less than twice the average time of one-way forwarding paths, see Figure 4.14.


timeline of A receiving B's messages
timeline of A sending messages to B
timeline of B receiving A's messages
timeline of B sending messages to A
A
B
B_1 B_2 B_3 B_4 B_5 A_1 A_2 A_3 A_4 A_5 A_6 A_7
time
$\delta(B_1)$
$\delta(B_2)$
$\delta(B_3)$
$\delta(A_1)$
$\delta(A_2)$
$\delta(A_3)$
$\delta(A_4)$
Swarmchat PRO

B_1 Hello!

Hey! A_1

B_2 Long time no see!

B_3 How are you?

I'm well :) A_2

Just checking in! A_3

Baby woke up, gotta go! A_4

Figure 4.14: Advance requests for future updates. The diagram shows the timeline of events during instant messaging between two parties A and B, using outbox feeds. The columns represent the neighbourhood locations of the feed update addresses. The circles show the time of protocol messages arriving: colors indicate the origin of data, empty circles are retrieve requests, and full circles are push-sync deliveries arriving at the respective neighbourhood. Note that the outbox addresses are deterministic 3 messages ahead, allowing retrieve requests to be sent before the corresponding updates arrive.
Importantly, the latency between one party sending a message m and the other receiving it is shown as $\delta(m)$. Messages A_3 and A_4 arrive before A_2 which can be reported and repaired. If address predictability was only limited to 1 message ahead, both B_2 and B_3 would have much longer latencies.
Also note that the latencies of B_2 and B_3 are helped by advance requests: the retrieve requests for B_4 and B_5 are sent upon receipt of B_1 and B_2 and arrive at their neighbourhood at the same time as the messages B_2 and B_3 arrive at theirs, respectively. If address predictability was limited to 1 message ahead, this would negatively impact the latencies of B_2 and B_3.

Post-compromise security

A key management solution called double ratchet is the de-facto industry standard used for encryption in instant messaging. It is customary to use the extended triple Diffie–Hellmann key exchange (X3DH) to establish the initial parameters for the double-ratchet key chains (see 4.4.2).

The double-ratchet approach combines a ratchet based on a continuous key-agreement protocol with a ratchet based on a key-derivation function (Perrin and Marlinspike 2016). This scheme can be generalised (Alwen et al. 2019) and understood as a combination of well-understood primitives. It has been demonstrated to provide (1) forward secrecy, (2) backward secrecy,[3] and (3) immediate decryption and message loss resilience.

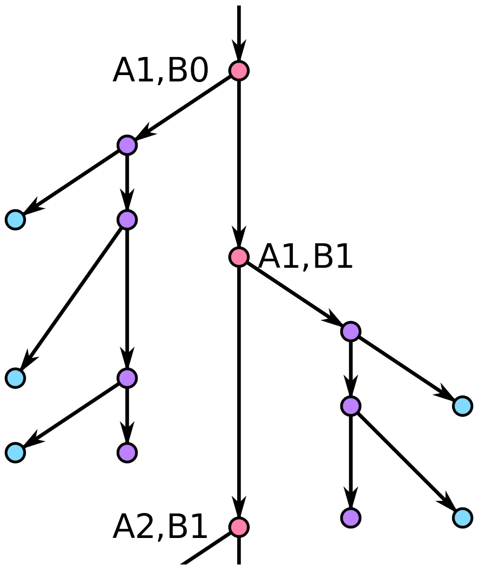


Figure 4.15: Future secrecy for update addresses

In addition to the confidentiality due end-to-end encryption, Swarm offers further resistance against attacks. Due to the forwarding Kademlia protocol, the sender can remain ambiguous and deniable. Furthermore, the normal push-sync and pull-sync traffic helps to obfuscate messages. To make it really hard for an attacker, the sequence of indexes can also provide future secrecy if we add more key chains to the double-ratchet machinery. Beside root, sending, and receiving encryption key chains, two additional keys are introduced: outgoing and incoming outbox

[3]Also known as future secrecy or post-compromise security.

index key chains, see Figure 4.15. As a result of this measure, the underlying communication channel is obfuscated, i.e. intercepting an outbox update chunk and knowing its index reveals nothing about previous or subsequent outbox update indexes. This makes subsequent messages prohibitively difficult and costly to monitor or intercept.

In 4.3.3, we used factoring in the payload hash into the indexing scheme to achieve non-mergeability of chains (unambiguous history). Inspired by this, we propose to also factor in the payload hash into the subsequent feed update index. This introduces an additional property called recover security, which, intuitively, ensures that once an adversary manages to forge a message from A to B, then no future message from A to B will be accepted by B. This is guaranteed if the authenticity of A's messages to B affects the subsequent feed index. If there is a mismatch (indicating a forged message), the messages will be looked up at the wrong address, leading to the abandonment of the communication channel and the initiation of a new one. By implementing this approach, the communication channel achieves complete confidentiality and becomes a zero-leak solution for real-time messaging.

4.4 Pss: direct push messaging with mailboxing

This section introduces *pss*, Swarm's direct node-to-node push messaging solution. Functionalities of and motivation for its existence are playfully captured by alternative resolutions of the term:

postal service on Swarm
: Delivering messages if recipient is online or depositing for download if not.

pss is bzz whispered
: Beyond the association to Chinese whispers, it surely carries the

spirit and aspiration of Ethereum Whisper.[4] Pss piggybacks on Swarm's distributed storage for chunks and hence inherits their full incentivisation for relaying and persistence. At the same time it borrows from Whisper's crypto, envelope structure and API.

pss! instruction to hush/whisper

Evokes an effort to not disclose information to third parties, which is found exactly in the tagline for pss: truly zero-leak messaging where beside anonymity and confidentiality, the very act of messaging is also undetectable.

pub/sub system

The API allows publishing and subscription to a topic.

First, in 4.4.1, we introduce Trojan Chunks, which are messages sent to storers that masquerade as chunks whose content address happens to fall in the proximity of their intended recipient. Section 4.4.2 discusses the use of pss to send contact messages to establish real-time communication channels. In 4.4.3, we explore the mining of feed identifiers to target a specific neighbourhood with the address of a single owner chunk and present the construct of an addressed envelope. Finally, building on Trojan chunks and addressed envelopes, 4.4.4 introduces update notification requests.

4.4.1 Trojan chunks

Cutting-edge systems that promise private messaging often struggle to offer truly zero-leak communication (Kwon et al. 2016). While linking the sender and recipient is cryptographically proven to be impossible, resistance to traffic analysis is harder to achieve. Maintaining sufficiently large anonymity sets requires high volumes available at all times. In the absence of mass adoption, guaranteeing high message rate in dedicated messaging networks necessitates constant fake traffic. However, with

[4]Whisper is a gossip-based dark messaging system, which is no longer developed. It never saw wide adoption due to its (obvious) lack of scalability. Whisper, alongside Swarm and the Ethereum blockchain, was the communication component of the holy trinity, the basis for Ethereum's original vision of web3.

Swarm, there is an opportunity to disguise messages as chunk traffic, effectively obfuscating the act of messaging itself.

We define a Trojan chunk as a content-addressed chunk with a fixed internal content structure (see Figure 4.17):

span

8-byte little-endian uint64 representation of the length of the message

nonce

32-byte arbitrary nonce

Trojan message

4064-byte asymmetrically encrypted message ciphertext with underlying plaintext composed of

2-byte little-endian encoding of the length of the message in bytes $0 \leq l \leq 4030$,
32 byte obfuscated topic ID
m bytes of a message
$4030 - m$ random bytes.

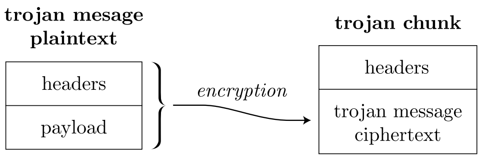


Figure 4.16: A pss message is a Trojan chunk that wraps an obfuscated topic identifier with a Trojan message, which in turn wraps the actual message payload to be interpreted by the application that handles it.

Knowing the public key of the recipient, the sender follows a specific process to send a trojan message. First, the message is wrapped in a trojan message format by prefixing it with length information and padding it to 4030 bytes. Then, the sender encrypts it using the recipient's public key to obtain the ciphertext payload of the trojan chunk by asymmetric encryption. The sender then generates a random nonce such that when it is prepended to the payload, the chunk hashes to an address that starts with a destination target prefix. The destination target is a bit sequence that represents a specific neighbourhood in the address

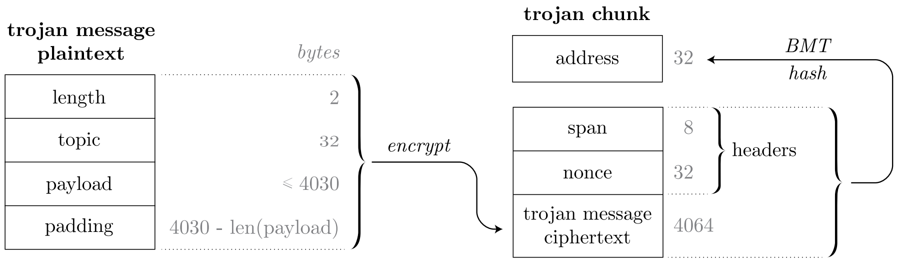


Figure 4.17: The Trojan chunk wraps an asymmetrically encrypted Trojan message.

space. If the target is a partial address derived as a prefix of the recipient's overlay address, matching the target means that the chunk falls in the neighbourhood of the recipient. If only the public key is known, it is assumed that it is the bzz account of the recipient, i.e. their overlay address can be calculated from it[5] (see 2.1.2). The sender then uploads the resulting chunk to Swarm with postage stamps of their choice which then ends up being synced to the recipient address' neighbourhood. If the recipient node is online and the bit length of the matching target is greater than the recipient's neighbourhood depth, they will receive the chunk. In practice, targets should be $n+c$ bits long, where n is the estimated average depth in Swarm and c is a small integer.

Receiving Trojan messages

The recipient only knows that a chunk is a pss message once they have successfully opened the Trojan message with the private key corresponding to the public key that they advertise as their resident key (see 4.4.2) and perform an integrity check/topic matching. Nodes that want to receive such Trojan Messages will continue attempting to decrypt all messages that they are closest to. Forwarding nodes (or anyone else apart from sender and recipient) have no way to distinguish between a random encrypted chunk and a Trojan message, which means that communication is perfectly obfuscated as generic chunk traffic.

[5]Alternative overlays can be associated with a public key, and several public keys can be listened on by a node at a particular address.

After the recipient has opened the envelope using asymmetric decryption, they proceed with a combined step of integrity check and topic matching step. Knowing the length of the payload (from the first 2 bytes of the message), the recipient takes the payload slice and calculates the Keccak256 hash of it. For each topic the client is subscribed to, the recipient then hashes the payload hash together with the topic. If the resulting segment xor-ed with the topic matches the obfuscated topic ID in the message, then the message is indeed meant as a message with the said topic and the registered handler is called with the payload as argument.

Mailboxing for asynchronous delivery

If the recipient is not online, the Trojan chunk will prevail as any other chunk would, depending on the postage stamp it has. Whenever the recipient node comes online, it pull-syncs the chunks from the closest neighbourhood, including all Trojan chunks and their own unreceived messages. In other words, through Trojan messages, pss automatically provides asynchronous *mailboxing* functionality, allowing undelivered messages to be preserved and accessible to the recipient when they come online without any additional action needed from the sender. The duration of mailboxing is controlled with postage stamps, just like the storage of chunks, in fact, it is indistinguishable from regular chunk storage.

Mining for proximity

The process of finding a hash close to the recipient address is analogous to mining blocks on the blockchain. The nonce segment in a Trojan chunk also serves exactly the same purpose as a block nonce: it provides sufficient entropy to guarantee a solution. The difficulty of mining corresponds to the length of the destination target: The minimum proximity order required to ensure that the recipient will receive the message needs to be higher than the neighbourhood depth of the recipient[6] when it comes online, so it is logarithmic in the number of nodes in the network. The expected number of nonces that need to be tried per Trojan message before an appropriate content address is found is exponential in the difficulty, and therefore equal to the number of nodes in the network. In practice, mining a Trojan chunk will never be prohibitively expensive or slow even for a single node, as the expected number of computational cycles needed to find the nonce is equal to the network size. Only a small delay in the second range may occur in a network of a billion nodes, and even that is acceptable given that Trojan messages are meant to be used only for one-off instances such as initiations of a channel. Subsequent real-time exchanges will happen using the previously described bidirectional outbox model using single owner chunks.

Anonymous mailbox

Asynchronous access to pss messages is guaranteed as long as the postage stamp has not expired. The receiver only needs to create a node with an overlay address corresponding to the destination target advertised to be the recipient's resident address. This allows for the creation of an anonymous mailbox, which can receive pss messages on behalf of a client and then publish them on a separate, private feed. The intended recipient can then read the messages whenever they come back online.

Register for aggregate indexing

As discussed in 4.3.2, aggregate indexing services help nodes in monitoring sporadic feeds. For instance, a forum indexer can aggregate the contribution feeds of registered members, enabling the efficient tracking and access to forum updates. In the case of public forums, off-chain registration is a viable option that allows users to register without di-

[6]It makes sense to use the postage batch uniformity depth (see 3.3) as a heuristic for the target proximity order when mining a Trojan chunk. This is available as a read-only call to the postage stamp smart contract.

rectly interacting with the blockchain. This can be achieved by simply sending a pss message to the aggregator.

4.4.2 Initial contact for key exchange

Encrypted communication requires a handshake protocol to establish the initial parameters that are used as inputs to a symmetric key generation scheme. One such protocol is the extended triple Diffie–Hellmann key exchange, or X3DH, is one such protocol (Marlinspike and Perrin 2016). X3DH is used to establish the initial parameters for a post-handshake communication protocol, like the *double-ratchet scheme* discussed earlier in the section on feeds (see 4.3.5).

To implement the X3DH protocol with pss in a serverless setting. Swarm utilises the same primitives as are customary in Ethereum, i.e. secp256k elliptic curve, Keccak256 hash, and a 64-byte encoding for EC public keys.

The Swarm X3DH protocol facilitates the establishment of a shared secret between two parties, which serves as the input used to determine the encryption keys used during two-way messaging after the handshake. The *initiator* is the party that initiates a two-way communication with the *responder*. The responder is supposed to advertise the information necessary to allow parties previously unknown to the responder to initiate contact. Zero-leak communication can be achieved by first performing an X3DH. This protocol is used to establish the seed keys used by the double-ratchet protocol for the encrypting data, as well as the feed indexing methodology used. This will enable the responder to retrieve the updates of the outbox feed.

X3DH uses the following keys:[7]

K_r^{ENS}
: responder long-term public identity key

[7]The protocol specifies one-time pre-keys for the responder, but these can be safely ignored since they only serve as replay protection, which is solved by other means in this implementation.

K_r^{Res}

responder resident key (aka signed pre-key)

K_i^{ID}

initiator long-term identity key

K_i^{EPH}

initiator ephemeral key for the conversation

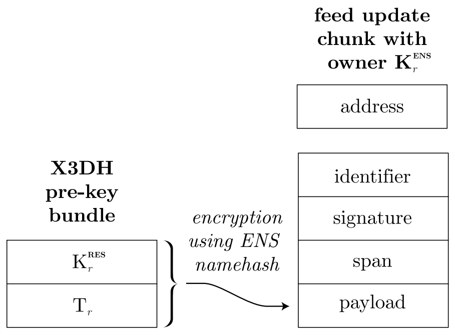


Figure 4.18: The X3DH pre-key bundle feed update contains the resident key and resident address and is optionally together encrypted with the ENS name hash to prove uniqueness and provide authentication.

A pre-key bundle consists of all information the initiator needs to know about responder. However, rather than storing this information on external servers, it is instead stored in Swarm. For human-friendly identity management, ENS can be optionally used to provide familiar username-based identities. The owner of the ENS resolver represents the authenticated long-term public identity key for the persona. By utilising the long-term identity address, an epoch-based feed with a topic ID can be created, indicating that it provides the pre-key bundle for potential correspondents. When initiating communication with a new identity, the initiator retrieves the latest update from the feed, which contains the current *resident key* (aka *signed pre-key*) and current *addresses of residence*, i.e. the (potentially multiple) overlay destination targets where the persona expects to receive pss messages. The signature within the feed update chunk signs both the resident key (cf. signed pre-key) and the destination targets. The public key that is recovered from this signature gives the long-term identity public key, see Figure 4.18.

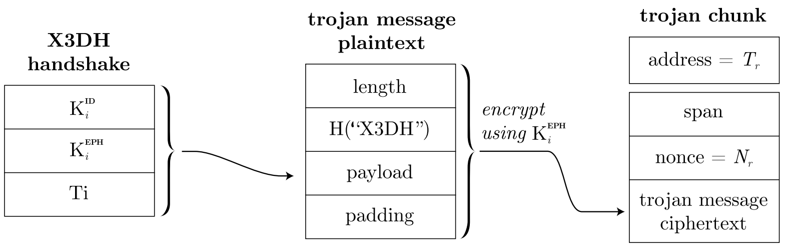


Figure 4.19: X3DH initial message. Initiator retrieves the ENS owner as well as the latest update of responder's pre-key bundle feed containing the resident key and resident address. Initiator sends their identity key and an ephemeral key to responder's resident address using the resident key for encryption.

In order to invite a responder to an outbox-feed based private communication channel, the initiator first looks up the responder's public pre-key bundle feed and sends an initial message to the responder (see Figure 4.19), indicating their intent to communicate. She then shares the parameters required to initiate the encrypted conversation, including the public key of her long-term identity and the public key of the ephemeral key-pair generated specifically for that conversation. These details are delivered to the potential responder by sending a Trojan pss message addressed to the responder's current address of residence, which is also advertised in their pre-key bundle feed.

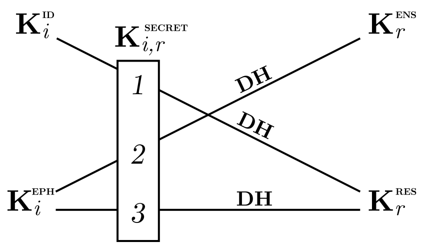


Figure 4.20: X3DH secret key. Both parties can calculate the triple Diffie-Hellmann keys and xor them to get the X3DH shared secret key used as the seed for the post-handshake protocol.

After the responder receives this information, both parties have all the ingredients needed to generate the triple Diffie-Hellmann shared secret (see Figure 4.20).[8] This shared secret constitutes the seed key for the double-ratchet continuous key agreement protocol as used in the signal protocol. The double-ratchet scheme ensures forward secrecy and post-compromise security to the end-to-end encryption. By applying separate key-chains for the outbox feed's indexing scheme, additional recover security, i.e. resilience to message insertion attack, can be achieved. Most importantly, however, adding forward and backward secrecy to outbox addresses, obfuscates the communication channel, which renders sequential message interception contingent on the same security assumptions as encryption. This eliminates the only known attack surface for double-ratchet encryption. The obfuscation and deniability of the channel based on outbox feeds, together with the initial X3DH message being disguised, indistinguishable from a regular chunk, warrants classifying this communication approach as zero-leak communication.

4.4.3 Addressed envelopes

Mining single owner chunk addresses

The question immediately arises whether it is feasible to mine single owner chunks. Since the address in this case is the hash of a 32-byte identifier and a 20-byte account address, the ID provides sufficient entropy to mine addresses even if the owner account is fixed. So for a particular account, if we discover an ID such that the resulting single owner chunk address is close to a target overlay address, the chunk can be used as a message, similar to Trojan chunks. Importantly, however,

[8] If the X3DH does not use one-time pre-keys, the initial message can in theory be re-sent by a third party and lead the responder to assume genuine repeated requests. Protocol replay attacks like this are eliminated if the post-handshake protocol adds random key material coming from the responder. But the initial Trojan message can also be required to contain a unique identifier, e.g. the nonce used for mining the chunk. Reusing the ID is not possible since it leads to the same chunk.

since the address can be mined before the chunk content is associated with it, this construct can serve as an addressed envelope.

Let us make explicit the roles relevant to this construct:

issuer (I)
: creates the envelope by mining an address.

poster (P)
: puts the content into the envelope and posts it as a valid single owner chunk to Swarm.

owner (O)
: possesses the private key to the account part of the address and can thus sign off on the association of the payload to the identifier. This effectively decides on the contents of the envelope.

target (T)
: the constraint for mining: a bit sequence that must form the prefix of the mined address. It represents a neighbourhood in the overlay address space where the envelope will be sent. The length of the target sequence corresponds to the difficulty for mining. The longer this target is, the smaller the neighbourhood that the envelope will be able to reach.

recipient (R)
: the party whose overlay address has the target sequence as its prefix and therefore the destination of the message.

The envelope can be perceived as open: since the poster is also the owner of the response single owner chunk, they are able to control what content is placed into the chunk. By constructing such an envelope, the issuer effectively allows the poster to send an arbitrary message to the target without the need for computational resources to mine the chunk. See Figure 4.21.

When the poster wants to send a message to the recipient, they simply need to create a Trojan message and sign it against the identifier using the private key of the same account that the issuer used during the address mining process. By doing so, the resulting chunk will be valid. See Figure 4.22.

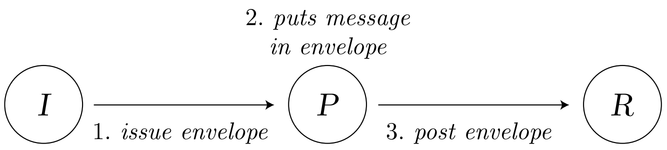


Figure 4.21: Stamped addressed envelopes timeline of events. Issuer *I* creates the envelope encrypted for *P* with an identifier such that *P* as the single owner of the chunk, produces an address that falls in the recipient *R*'s neighbourhood. As a result, (only) *P* can fill the envelope with arbitrary content and then use simple push-syncing to post it to *R*.

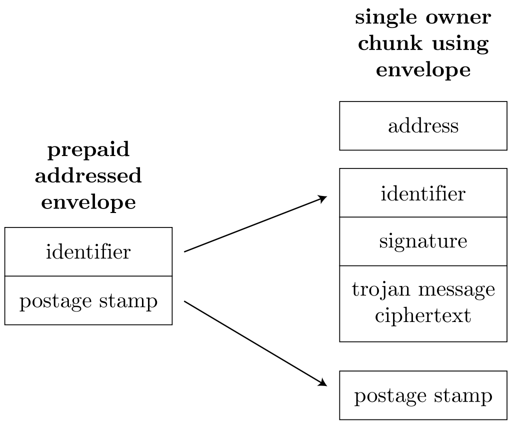

single owner chunk using envelope
address
identifier
signature
trojan message ciphertext
postage stamp
prepaid addressed envelope
identifier
postage stamp

Figure 4.22: A stamped addressed envelope issued for *P* and addressed to *R* consists of an identifier which is mined so that when used to create a single owner chunk owned by *P*, it produces an address which falls within *R*'s neighbourhood. This allows *P* to construct a message, sign it against the identifier and using the postage stamp, post it using the network's normal push-syncing to *R* for free.

Pre-paid postage

These chunks exhibit the same behaviour as normal Trojan messages, maintaining their privacy properties, and in some cases, even improving them. The issuer/recipient can associate a random public key for encrypting the message or use symmetric encryption. If a postage stamp is pre-paid for an address and given to someone to post later, they can use push-sync to send the chunk to the target without the poster incurring any additional cost, as the postage has already been covered by the stamped addressed envelope. This construct effectively implements *addressed envelopes with pre-paid postage* and serves as a base layer solution for various high-level communication needs, such as (1) push notifications to subscribers without any computational or financial postage burden on the sender, (2) free contact vouchers, and (3) zero-delay direct message response.

Issuing a stamped addressed envelope

Issuing a stamped addressed envelope involves the following process:

assume
: issuer I, prospective poster P, and prospective recipient R with public keys K_I, K_P, K_R and overlay addresses A_I, A_P, A_R.

mine
: I finds a nonce N_R such that when used as an identifier to create a single owner chunk, the address of the chunk hashes to H_R, which is in the nearest neighbourhood of A_R.

pay postage
: I signs H_R to produce a witness for an appropriate postage payment to produce stamp PS_R.

encapsulate
: package N_R and PS_R, which represent the pre-paid envelope pre-addressed to recipient address, and encrypt it with K_P then wrap it as a Trojan chunk.

mine
: find a nonce N_P such that the Trojan chunk hashes to H_P, which is in the nearest neighbourhood of A_P.

Receiving a stamped addressed envelope

A prospective poster P is assumed to receive a Trojan message that consists of pre-paid envelope E. In order to open it, she carries out the following steps:

decrypt
: decrypt message with the private key belonging to K_P

deserialise
: unpack and identify PS_R and N_R, extract H_R from PS_R

verify
: postage stamp PS_R and check if N_R hashed with the account for K_P results in H_R to ensure the associated address is in fact owned by P.

store
: store N_R and PS_R

Posting a stamped addressed envelope

When the poster wants to use the envelope to send an arbitrary message M to R (with recipient R potentially unknown to the sender), they must follow the following steps:

encrypt
: encrypt the message content M with K_R to create a payload and wrap it in Trojan message T

hash
: hash the encrypted Trojan message resulting in H_T

sign
: sign H_T against the identifier N_R using the private key that belongs to K_P, producing signature W

encapsulate
: include nonce N_R as ID, the signature W and the Trojan message T as the payload of a valid single owner chunk with address H_R

post
: post the chunk with the valid stamp PS_R

Receiving a posted addressed envelope

When R receives chunk with address H_R

verify
: verify postage stamp PS_R and validate the chunk as a single owner chunk with payload T.

decrypt
: decrypt T with the private key belonging to K_R.

deserialise
: deserialise the plaintext as a Trojan message, identify the message payload M and check its integrity.

consume
: consume M.

4.4.4 Notification requests

This section elaborates on the concept of addressed envelopes and presents three flavours, each implementing different types of notifications.

Direct notification from publisher

If an issuer wants to notify a recipient of the next activity on a feed, she needs to construct a stamped addressed envelope embedded in a regular Trojan message and send it to the publisher, as depicted in Figure 4.23. If the issuer is also the recipient, the same account can be used in both the request and the response envelope.

When the owner of a feed publishes an update, they include a reference to the update chunk in the envelope and send it to the recipient. More formally, the publisher creates a single owner chunk using the identifier of the pre-addressed envelope and signs off on the identifier associated with the feed update content as the payload of the single owner chunk. Subsequently, the publisher, now acting as the poster, push-syncs the chunk to the swarm. This process is known as direct notification from publisher.

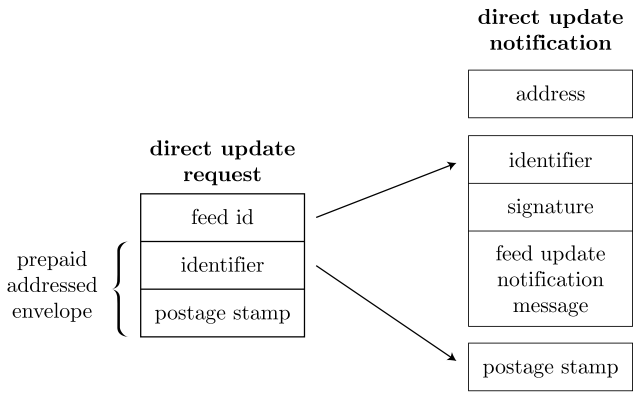


Figure 4.23: A direct notification request contains a reference to a feed and wraps a pre-paid envelope that is mined for P (the publisher or a known distributor of the feed) and addressed to recipient R. The response follows the same process as generic stamped addressed envelopes, with the only difference being that the message is expected to be the feed update or a reference to its content.

The Trojan message is encrypted using the public key and specifies in its topic that it is a notification. As the address is mined to match the recipient overlay address on a sufficiently long prefix, the message ends up push-synced to the recipient's neighbourhood. When the recipient comes online and receives the chunk, she detects that it is intended as a message. This can be done either by successfully decrypting the chunk content using the key for the address they had advertised, or by looking it up against the record of the address they saved when it was issued, in the case where the recipient has issued the pre-addressed envelope themselves. See Figure 4.24 for the timeline of events.

Notifications coming directly from publishers allow the poster to include arbitrary content within the envelope. The poster, who is also the owner of the envelope, has the authority to sign off on any content against the identifier when posting the envelope. To create the notification chunk address in advance, the issuer needs to know the account of the prospective poster. However, it is not necessary for the feed update

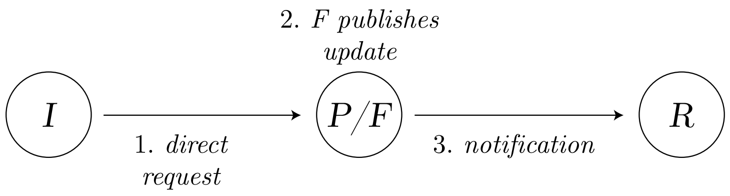


Figure 4.24: Direct notification from publisher timeline of events. Issuer I constructs a prepaid envelope for the publisher or a known distributor of the feed P/F and addresses to recipient R. Together with a feed topic I, it is sent to P/F wrapped in a pss Trojan message. P/F receives it and stores the request. When they publish the update, they wrap it in the envelope, i.e. sign the identifier received from I against the feed update notification message and post it as a chunk, which R will receive and hence, be notified of the feed update.

address to be fixed, making this scheme applicable to (sporadic) epoch-based feeds.

Notification from neighbourhood

Consider a scenario where the owner of a feed has chosen not to reveal their overlay (destination target) or has declined to implement notifications. In this case, the feed is updated sporadically using simple sequential indexing, making it impractical to rely on polling for checking the latest update. Furthermore, the consumer may also go offline at any given time. Is there a method to ensure that consumers are still notified?

We introduce another construct, a neighbourhood notification, which works without the issuer of the notification knowing the identity of prospective posters. However, it requires the content or its hash to be known in advance so that it can be signed by the issuer themselves.

To ensure that a recipient is notified of the next update, the issuer can create a neighbourhood notification request by wrapping a message in a Trojan chunk. This message contains an addressed envelope (identifier, signature, and postage stamp) that the poster can use to construct the single owner chunk that serves as the notification. Note that the notification message need not contain any new information; simply receiving it is sufficient for the recipient. The payload of the notification contains the feed update address to indicate what it is a notification of. Upon receiving the notification, the receiver can simply send a regular retrieve request to fetch the actual feed update chunk that contains (or points to) the content of the message. See Figure 4.25 for the structure of neighbourhood notifications and notification requests.

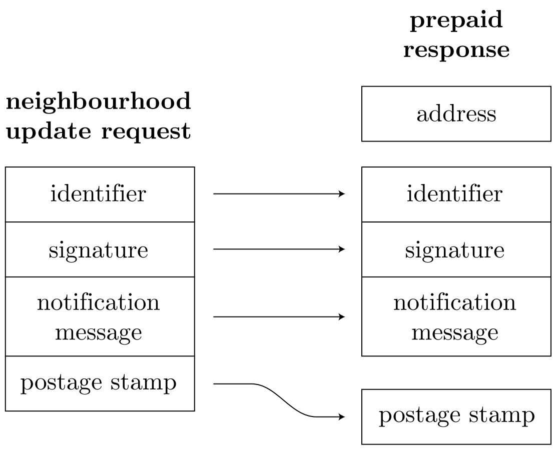


Figure 4.25: Neighbourhood notification requests include not only the identifier and postage stamp but also a notification message and its signature, attesting it against the address. Thus, P needs to construct the actual notification and when publisher F posts their update to P's neighbour, P can post the notification to recipient R.

If the notification only needs to contain the feed update address as its payload, the association with the identifier can be signed off by the issuers themselves. This signature, along with the identifier, should be considered a necessary component of the envelope and must be included in the notification request. Unlike *open* envelopes used with publishers directly, neighbourhood notifications can be viewed as *closed* envelopes, where the content is pre-approved by the issuer.

In this case, the issuer, not the poster, becomes the owner of the chunk, and the signature is already available to the poster when they create and post the notification. As a consequence, no public key or account address information is required from the poster. In fact, the identity of the poster does not need to be fixed, as any peer could qualify as a candidate poster. Issuers can send the notification request to the neighbourhood of the feed update chunk. The nearest neighbours will keep holding the request chunk as specified by the attached postage stamps until they receive the appropriate feed update chunk, which confirms the receipt of the notification. See Figure 4.26 for the timeline of events when using neighbourhood notifications.

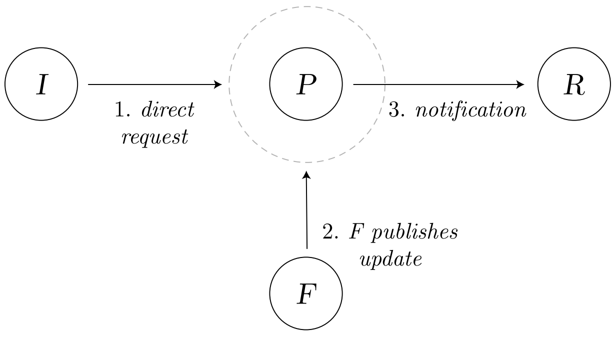


Figure 4.26: Neighbourhood notification timeline of events. Issuer *I* mines an identifier for a single owner chunk, with themselves as the owner, such that the chunk address falls within recipient *R*'s neighbourhood. The issuer, being the owner, also must sign the identifier against a prefabricated reminder and remember which node should be notified. When *P* syncs the feed update, the notification is sent to *R* through the usual push-sync mechanism.

But how can we make sure that notifications are not sent too early or too late? While the integrity of notification chunks is guaranteed by the issuer as their single owner, additional measures are required to prevent nodes that manage the notifications from sending them prematurely. It would be ideal if the notification could not be posted before the arrival of the update, otherwise false alarms could be generated by malicious nodes that service the request.

A simple measure is to symmetrically encrypt the message in the request using a key that is only revealed to the prospective poster upon receiving the feed update. For instance, the hash of the feed update identifier can serve as that key. In order to reveal that the notification request needs to be matched on arrival of the feed update, the topic must be left unencrypted, so here we do not encrypt the pss envelope asymmetrically but only the message and symmetrically.

Note that the feed update address as well as identifier can be known if the feed is public, so neighbourhood notifications are to be used with feeds whose subsequent identifiers are not publicly known.

Targeted chunk delivery

Normally, in Swarm's DISC model, chunks are obtained using retrieve requests, which are forwarded towards the designated neighbourhood designated based on the requested chunk address (see 2.3.1). The first node on the route that has the chunk will respond and deliver the chunk as a backwarded response travelling back along the same route. In certain cases, however, it may be beneficial to have a mechanism to request a chunk from a specific neighbourhood where it is known to be stored and send it to a different neighbourhood where it is known to be needed. A construct called targeted chunk delivery is meant for such a use case: the request is a Trojan pss message, while the response, the delivery, must be a single owner chunk that wraps the requested chunk. The address of this delivery chunk is mined to fall into the recipient's neighbourhood.

These 'chunk-in-a-soc' responses are structurally similar to neighbourhood notifications in that the payload's hash is already known (the content address of the chunk requested). The requestor can then sign off on its association with the identifier and include it, along with the signature, in the request message (see Figure 4.28). When a node receives such a request and has the requested chunk stored, it can construct a valid single owner chunk addressed to the recipient's neighbourhood as a response. This makes the request generic, i.e. not tied to the identity of the prospective poster, therefore it can be sent to any neighbourhood that requires the content. Even multiple requests can be sent simultaneously, as the uniqueness of the valid response ensures the integrity of chunks (see 2.2.3 and 4.3.3). Targeted delivery is used in missing chunk recovery, see 5.2.3.

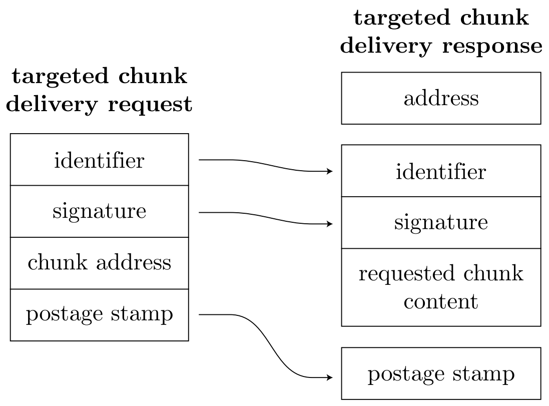


Figure 4.27: Targeted chunk deliveries are similar to neighbourhood notifications in that they are pre-addressed, pre-paid, and pre-signed. Similarly, the identifier is mined so that given issuer *I* as the owner, it produces an chunk address that falls in recipient *R*'s neighbourhood. Here, the issuer signs the identifier against the hash of a content addressed chunk that they want to see posted to *R*. If the targeted chunk delivery request lands with any node that has the requested chunk, they can use the envelope and the chunk's content to produce a valid response, which is a single owner chunk wrapping a content addressed chunk.

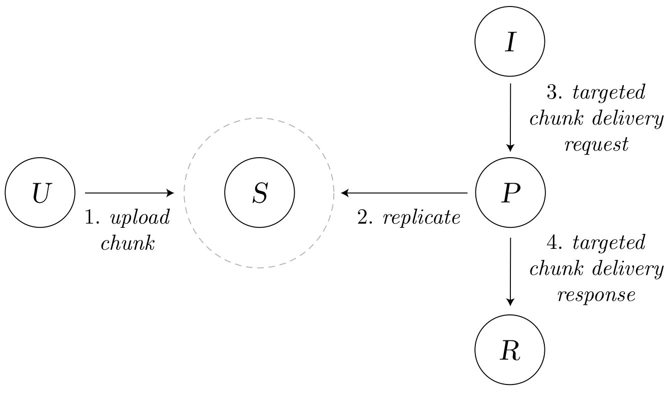

I
3. targeted chunk delivery request
U
1. upload chunk
S
2. replicate
P
4. targeted chunk delivery response
R

Figure 4.28: Targeted chunk delivery timeline of events. Uploader *U* uploads a chunk to Swarm, and it lands with a storer node *S*. Nodes within *P* replicate and pin this chunk. Now, if issuer *I* wants this chunk delivered to *R*, they take the prepaid envelope addressed to *R* and send it unencrypted to the neighbourhood of a known host. This way, anyone who has the chunk can construct the notification and send or store it for later.

The difference is that neighbourhood notifications do not provide any new information, while targeted chunk delivery supplies the chunk data. Additionally, a chunk delivery wrapped in a single owner chunk does not involve message wrapping and does not have a topic. Encryption is not used in either the request or response. A consequence of not using encryption is that if there are multiple targets, it is sufficient for the initial Trojan request to match any one of these targets.

Table 4.1 summarises various properties of the three notification-like constructs.

type	owner	poster	request encryption	notification
direct	poster	publisher	asymmetric on pss	feed update content
neighbourhood	issuer	any	symmetric on envelope	feed update arrival
targeted delivery	issuer	any	none	chunk content

Table 4.1: Requests of and responses to types of feed update notifications and targeted chunk delivery.

5. Persistence

In this chapter, we focus on data persistence, i.e. the ways of ensuring that content remains available on Swarm. We introduce error coding schemes that can provide cross-neighbourhood redundancy to secure availability against churn, albeit at the cost of increased storage overhead. In particular, erasure codes (5.1) and entanglement codes provide redundancy optimised for documents with different access patterns. Additionally, we introduce the notion of local pinning in 5.2, allowing users to mark specific content as "sticky" in their Swarm local storage. We will discuss how this local pinning can help achieve global persistence across the network through the concept of *stewardship*. We define a missing chunk notification protocol, which allows content maintainers to ensure that their published content is restored in case some chunks are garbage collected. This restoration is facilitated by proxying retrieval through selected content pinners.

In Section 5.3, we discuss how an immutable chunk store can support user-controlled deletion of content.

5.1 Cross-neighbourhood redundancy: erasure codes and dispersed replicas

First, in 5.1.1, we introduce erasure codes. We then walk through in 5.1.2 how they are applied to files in Swarm. In 5.1.3, we present a construct that enables cross-neighbourhood redundancy for singleton chunks that completes erasure coding. Finally, in 5.1.4, we explore systematic codes that facilitate various retrieval strategies of erasure-coded files, while preserving random access capabilities.

5.1.1 Error correcting codes

Error correcting codes are widely utilised in the context of data storage and transfer to ensure data integrity even in the face of a system fault. Error correction schemes define how to rearrange the original data by adding redundancy to its representation before upload or transmission (*encoding*) so that it can correct corrupted data or recover missing content upon retrieval or reception (*decoding*). The different schemes are evaluated by quantifying their strength (*tolerance*, in terms of the rate of data corruption and loss) as a function of their cost (*overhead*, in terms of storage and computation).

In the context of computer hardware architecture, synchronising arrays of disks is crucial to provide resilient storage in data centres. In *erasure coding*, in particular, the problem can be framed as follows: How does one encode the stored data into shards distributed across the disks so that the data remains fully recoverable in the face of an arbitrary probability that any one disk becomes faulty? Similarly, in the context of Swarm's distributed immutable chunk store, the problem can be reformulated as follows: How does one encode the stored data into chunks distributed across neighbourhoods in the network so that the data remains fully recoverable in the face of an arbitrary probability that any one chunk is not retrievable?[1]

Reed-Solomon coding (RS) (Bloemer et al. 1995, Plank and Xu 2006, Li and Li 2013) is the father of all error correcting codes and also the most widely used and implemented.[2] When applied to data of m fixed-size blocks (message of length m), it produces an encoding of $m + k$ *codewords* (blocks of the same size) in such a way that having any m out of

[1]It is safe to assume that the retrieval of any one chunk will fail with equal and independent probability.

[2]For a thorough comparison of an earlier generation of implementations of RS, see Plank et al. (2009).

$m + k$ blocks is enough to reconstruct the original data. Conversely, k puts an upper bound on the number of *erasures* allowed (number of blocks unavailable) for full recoverability, i.e., it expresses (the maximum) *loss tolerance*.[3] k is also the count of *parities*, quantifying the data blocks added during the encoding on top of the original volume, i.e., it expresses *storage overhead*. While RS is, therefore, optimal for storage (since loss tolerance cannot exceed the storage overhead), it has high bandwidth demands[4] for local repair processes.[5] The decoder needs to retrieve m chunks to recover a particular unavailable chunk. Hence, ideally, RS is used on files which are supposed to be downloaded in full,[6] but it is inappropriate for use cases needing only local repairs.[7]

When using RS, it is customary to use *systematic* encoding, which means that the original data forms part of the encoding, i.e., the parities are actually added to it.

5.1.2 Erasure coding in the Swarm hash tree

Swarm uses the *Swarm hash tree* to represent files. This structure is a Merkle tree (Merkle 1980), whose leaves are the consecutive segments of the input data stream. These segments are turned into chunks and are distributed among the Swarm nodes for storage. The consecutive chunk references (either in the form of an address or an address and an encryption key) are written into a chunk on a higher level. These so-

[3]Error correcting codes that has a focus on correcting data loss are referred to as *erasure codes*, a typical scheme of choice for distributed storage systems (Balaji et al. 2018).

[4]Both the encoding and the decoding of RS codes takes $O(mk)$ time (with m data chunks and k parities). However, we found computational overhead insignificant in the context of chunk retrieval happening via network transfer.

[5]Entanglement codes (Estrada-Galinanes et al. 2018, 2019) require a minimal bandwidth overhead for a local repair, but at the cost of storage overhead that is in multiples of 100%.

[6]Or in fragments large enough to include the data span over which the encoding is defined, such as videos.

[7]Use cases requiring random access to small amounts of data (e.g., path lookup) benefit from simple replication to optimise on bandwidth, which is suboptimal in terms of storage (Weatherspoon and Kubiatowicz 2002).

called *packed address chunks* (PACs) constitute the intermediate chunks of the tree. The branching factor b is chosen so that the references to its children fill up a full chunk. With a reference size of 32 or 64 (hash size 32) and a chunk size of 4096 bytes, b is 128 for unencrypted, and 64 for encrypted content (see Figure 5.1).

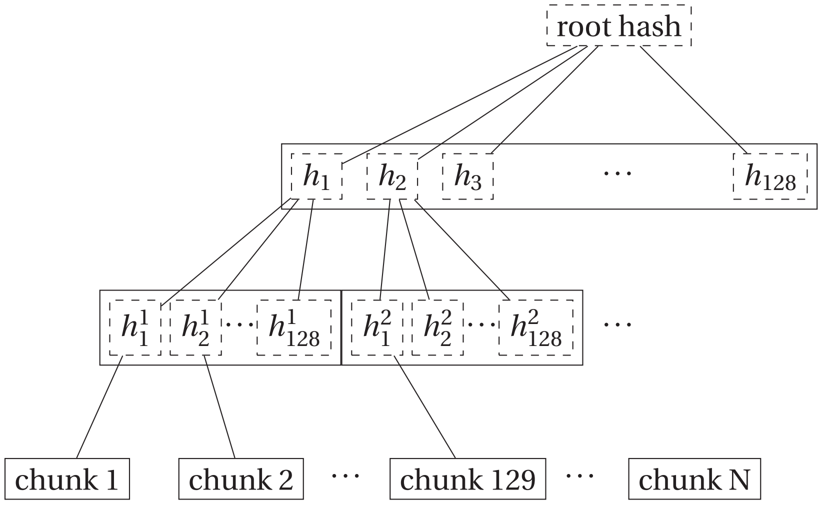


Figure 5.1: The Swarm tree is the data structure encoding how a document is split into chunks.

Note that on the right edge of the hash tree, the last chunk of each level may be shorter than 4K: in fact, unless the file is exactly $4 \cdot b^n$ kilobytes long, there is always at least one *incomplete chunk*. Importantly, it makes no sense to wrap a single chunk reference in a PAC, so it is attached to the first level where there is open chunks. Such *"dangling" chunks* will appear if and only if the file has a zero digit in its b-ary representation.

During file retrieval, a Swarm client starts from the root hash reference and retrieves the corresponding chunk. Interpreting the metadata as encoding the span of data subsumed under the chunk, it decides that the chunk is a PAC if the span exceeds the maximum chunk size. In case of standard file download, all the references packed within the PAC are followed, i.e., the referenced chunk data is retrieved.

PACs offer a natural and elegant way to achieve consistent redundancy within the swarm hash tree. The input data for an instance of erasure coding is the chunk data of the children, with the equal-sized bins corresponding to the chunk data of the consecutive references packed into it. The idea is that instead of having each of the b references packed represent children, only m would, and the rest of the $k = b - m$ would encode RS parities (see Figure 5.2).

The *chunker* algorithm that incorporates PAC-scoped RS encoding would work as follows:

1. Set the input to the actual data level and produce a sequence of chunks from the consecutive 4K segments of the data stream. Choose m and k such that $m + k = b$ is the branching factor (128 for unencrypted, and 64 for encrypted content).
2. Read the input one chunk at a time. Count the chunks by incrementing a counter i.
3. Repeat Step 2 until either $i = m$ or there's no more data left.
4. Use the RS scheme on the last $i \leq m$ chunks to produce k parity chunks resulting in a total of $n = i + k \leq b$ chunks.
5. Concatenate the references of all these chunks to result in a packed address chunk (of size $h \cdot n$ of the next level) of the level above. If this is the first chunk on that level, set the input to this level and spawn this same procedure from Step 2.
6. When the input is consumed, signal the end of input to the next level and quit the routine. If there is no next level, record the single chunks as the root chunk and use the reference to refer to the entire file.

This pattern repeats itself all the way down the tree. Thus, hashes H_{m+1} through H_{127} point to parity data for chunks pointed to by H_0 through H_m. Since parity chunks P_i do not have children, the tree structure does not have uniform depth.

5.1.3 Incomplete chunks and dispersed replicas

If the number of file chunks is not a multiple of m, it is not possible to proceed with the last batch in the same way as the others. We propose that we encode the remaining chunks with an erasure code that guaran-

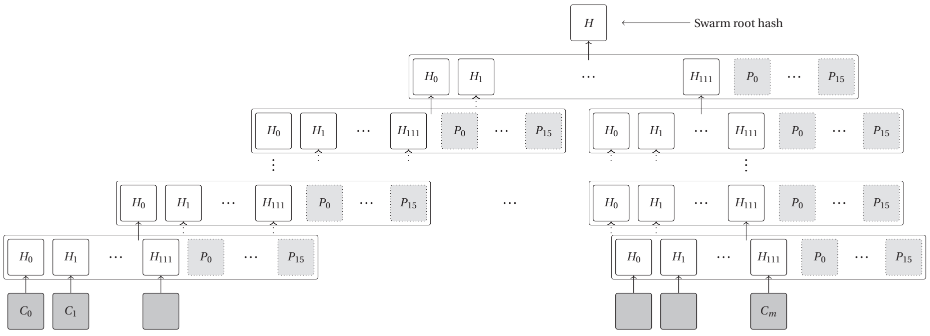


Figure 5.2: The Swarm tree with extra parity chunks using $m = 112$ out of $n = 128$ RS encoding. Chunks P_0 through P_{15} are parity data for chunks H_0 through H_{111} on every level of intermediate chunks.

tees at least the same level of security as the others.[8] Overcompensating, we still require the same number of parity chunks even when there are fewer than m data chunks.

This leaves us with only one corner case: it is not possible to use our m-out-of-n scheme on a single chunk ($m = 1$) because it would amount to $k+1$ copies of the same chunk. The problem is that copies of the same chunk all have the same hash and therefore are automatically deduplicated. Whenever a single chunk is left over ($m = 1$) (i.e., the root chunk itself), we would need to replicate the chunk in a way that (1) ideally, the replicas are dispersed in the address space in a balanced way, yet (2) their addresses can be known by retrievers who ideally only know the reference to the original chunk's address.

Our solution uses Swarm's special construct, the *single owner chunk* (SOC; see 2.2.3). Replicas of the root chunk are created by making the chunk data the payload of a number of SOCs. The addresses of these SOCs must be derivable from the original root hash following a deterministic convention shared by uploaders and downloaders.

[8]Note that this is not as simple as choosing the same redundancy. For example, a 50-out-of-100 encoding is much more secure against loss than a 1-out-of-2 encoding, even though the redundancy is 100% in both cases.

The address of a SOC is the hash of its ID and the Ethereum address of its owner. In order to create valid SOCs, uploaders need to sign the SOC with the owner's identity, therefore the owner of the SOC must be a consensual identity with their private key publicly revealed. [9]

The other component of the address, the SOC ID, must satisfy two criteria: (1) it needs to match the payload hash up to 31 bytes and (2) it must provide the entropy needed to mine the overall chunk into a sufficient number of distinct neighbourhoods. (1) is added as a validation criterion for the special case of replica SOCs, while (2) takes care that we can find replicas uniformly dispersed within the address space. This construct is called *dispersed replica*:

Let us assume c is the content-addressed chunk we need to replicate; n is the number of bits of entropy available to find the nonces that generate 2^k perfectly balanced replicas; initialise a chunk array ρ of length 2^k and start with n-bit integer $i = 0$ and replica counter $C = 0$.

1. Create the SOC ID by taking $addr(c)$ and changing the last byte (at index position 31) to i.
2. Calculate the the SOC address by concatenating ID id and owner o[10] and hash the result using the Keccak256 base hash $a_i := H(id \oplus o)$, and record $c_i = SOC(id, o, c)$.
3. Calculate the bin this hash belongs to by taking the k-bit prefix as big-endian binary number j between $0 \leq j < 2^k$.
4. If $\rho[j]$ is unassigned, then let $\rho[j] := c_i$ and increment C.
5. If $C = 2^k$, then quit.
6. Increment i by one, if $i = 2^n$, then quit.
7. Repeat from Step 1.

[9]This has the added benefit that third parties can also upload replicas of any chunk.

[10]The single-owner chunk representing the dispersed replicas must be signed by the arbitrary private key `0x010000000...0000000`. The corresponding ethereum address is `0xdc5b20847f43d67928f49cd4f85d696b5a7617b5`.

With this solution, we are able to provide an arbitrary level of redundancy for the storage of data of any length. [11]

Then, depending on the strategy, the downloader can choose which address to retrieve the chunk from. The obvious choice is the replica closest to the requesting node's overlay address.

5.1.4 Prefetching strategies for retrieval

When downloading, systematic per-level erasure codes allow for different *prefetching strategies*:

NONE = *direct with no recovery; frugal*
: No prefetching takes place, RS parity chunks are ignored if present. Retrieval involves only the original chunks, no recovery.

DATA = *prefetching data but no recovery; cheap*
: Prefetching data-only chunks, RS parity chunks are ignored if present, no recovery.

PROX = *distance-based selection; cheap*
: For all intermediate chunks, first retrieve m chunks that are expected to be the fastest to download (e.g., the m closest to the node).

RACE = *latency optimised; expensive*
: Initiate requests for all chunks within the scope (max $m+k$) and will need to wait only for the first m chunks to be delivered in order to proceed. This is equivalent to saying that the k slowest chunk retrievals can be ignored, therefore this strategy is optimal for latency at the expense of cost.

All in all, strategies using recovery can effectively overcome the occasional unavailability of chunks, be it due to faults such as network contention, connectivity gaps in the Kademlia table, node churn, overpriced

[11] Note that if n is small, then generating all 2^k balanced replicas may not be achievable, and if $n < k$, this is certainly not possible. In general, given n, k at least m miss has a probability of $(1 - m/2^k)^{2^n}$.

neighbourhoods, or even malicious attacks targeting a specific neighbourhood.

Similarly, given a typical model of network latencies for chunk retrieval, erasure codes in RACE mode can guarantee an upper limit on retrieval latencies.[12]

5.2 Data stewardship: pinning, reupload and recovery

This section introduces the notion of pinning, i.e. a method to protect locally sticky content from being removed through the garbage collection routines of its storage nodes (5.2.1). In 5.2.2, we discuss how content pinners can play together to pin content for the entire network globally. Section 5.1 defines a recovery protocol that downloaders can use to notify storers of missing chunks belonging to content they are responsible for pinning globally. With such on-demand repair and the uninterrupted download experience it enables, recovery implements a poor man's persistence measure that can ensure the network-wide availability of specific chunks without requiring the financial outlay of insurance.

5.2.1 Local pinning

Local pinning is the mechanism that makes content sticky and prevents it from being garbage collected. It anchors the content only in the node's local storage to enable local persistence of data and speedy retrieval. The pinning process operates at the level of individual chunks within the client's local database and exposes an API for users to pin and unpin files and collections in their local node (see 6.1.4).

[12]For instance, in the temporally sensitive case of real-time video streaming, for any quality setting (bitrate and FPS), buffering times can be guaranteed if the batch of chunks representing a time unit of media is encoded using its own scope(s) of erasure coding.

In order to pin all the chunks comprising files, clients need to maintain a reference count for each chunk. This count is incremented when a chunk is pinned and decremented when the chunk is unpinned. As long as the reference count remains non-zero, the chunk is considered to be part of at least one pinned document and is therefore immune to garbage collection. Only when the reference count returns to zero—meaning the chunk has been unpinned for every time it was previously pinned—does it become eligible for garbage collection again.

Local pinning can be thought of as a feature that allows Swarm users to mark specific files and collections as important, and therefore not removable. Pinning a file in local storage will also make it perpetually accessible for the local node, even without an internet connection. As a result, using pinned content for the storage of local application data enables an offline-first application paradigm, with Swarm seamlessly managing network activity upon re-connection. However, if a chunk is not within the node's area of responsibility, local pinning alone is not enough to ensure the chunk's availability to other nodes, in a general sense. This limitation arises due to the pinner not being in the Kademlia neighbourhood where the chunk is meant to be stored and subsequently searched for when requested using the pull-sync protocol. In order to provide this functionality, we must implement a second half of the pinning protocol.

5.2.2 Global pinning

If a chunk is removed due to garbage collection by storers in its designated neighbourhood, local pinning in nodes elsewhere in the network cannot independently retrieve it. In order for pinning to aid global network persistence, two challenges must be addressed:

- global pinners need to be notified when a chunk belonging to the content they have pinned is missing, so they can re-upload it,
- chunks that are garbage collected but globally pinned must remain retrievable, ensuring uninterrupted downloads for users.

One naive way to achieve this is to periodically check for pinned chunks in the network and re-upload the contents if they are not found. However, this method involves a lot of superfluous retrieval attempts, has immense bandwidth overhead, and ultimately provides no reduction in latency.

An alternative, reactive way is to organise notifications to the pinner which are somehow triggered when a user attempts to access the pinned content but encounters an unavailable chunk. Ideally, the downloader would send a message to the pinner that triggers two actions: (1) the re-upload of the missing chunk, and (2) the delivery of the chunk in response to the downloader's request.

Fallback to a gateway

Let us assume that a set of pinner nodes have locally pinned the content and our task is to allow fallback to these nodes. In the simplest scenario, we can set up the node as a gateway (potentially load-balancing to a set of multiple pinner nodes): Users learn of this gateway if it is included in the manifest entry for the file or collection. If the user is unable to download the file or collection from the Swarm due to a missing chunk, they can simply resort to the gateway and find all chunks locally. This solution benefits from simplicity and therefore is likely to be the first milestone towards achieving global persistence.

Mining chunks to pinners' neighbourhoods

A more sophisticated solution, albeit with more complexity, involves the publisher organising the chunks of a file in a way that they all fall within the neighbourhood of the pinner (or of any pinner node in the set). In order to do this, the publisher needs to find an encryption key for each chunk of the file so that the encrypted chunk's address matches one of the pinners on at least their first d bits, where d is chosen to be comfortably larger than that pinner's likely neighbourhood depth.[13]

These solutions can achieve persistence, but they also reintroduce a degree of centralisation and place the burden of maintaining and controlling server infrastructure on publishers. Additionally, they suffer from the usual drawbacks of server-client architecture, namely decreased fault-tolerance and the likelihood of compromised performance due to more concentrated requests. These solutions also fail to address the question of content distribution to pinner nodes and neglect privacy considerations. For these reasons, although the low-level pinning API is provided for Swarm users, it is a less desirable alternative to the incentivised file insurance system, which is seen as the gold standard. As such, use cases should be carefully evaluated to ensure that they would not benefit from the enhanced privacy and resilience provided by the incentivised system.

5.2.3 Recovery

In the following section, we outline a simple protocol for notifying pinners about the loss of a chunk. Pinners can then react by (1) re-uploading the lost chunk to the network and at the same time (2) responding to the notifier by delivering to them the missing chunk.

When replicas of a chunk are distributed among willing hosts (pinners), downloaders who cannot locate a particular chunk can fall back to a recovery process by requesting it from one of these hosts using the missing chunk notification protocol called prod. As usual, the resolutions of this acronym capture the properties of the protocol:

protocol for recovery on deletion

A protocol between requestor and pinners to orchestrate chunk

[13]It is important to note that if the pinner nodes do not share infrastructure and the mined chunks need to be sent to pinners with the push-sync protocol, then each postage batch used will be used a maximum of n times. Although this non-uniformity implies a higher unit price, if pinners choose to pin content out of altruism (i.e. not for compensation), only a minimum postage price needs to be paid.

recovery after garbage collection. The process is triggered by downloaders when they fail to retrieve a chunk.

process request of downloader
Recovery hosts continuously listen for potential recovery requests from downloaders.

provide repair of DISC
Prod provides a service to repair the Swarm DISC in the event of data loss.

pin and re-upload of data
Hosts pin the data and re-upload it to its designated area upon receiving a recovery request.

prompt response on demand
If the requestor demands a prompt direct response, the host will post the missing chunk using a recovery response envelope along with the required postage stamp.

Recovery hosts

Recovery hosts are pinners who voluntarily provide pinned chunks for the purpose of recovery. These pinners have explicitly indicated their willingness to take on this task to the publisher and to have downloaded all the relevant chunks and have pinned them in their local instance.

To advertise their publication as globally pinned or repairable, publishers gather the overlay addresses of these volunteering recovery hosts. In fact, it is sufficient to collect just the prefixes of the overlay with a length greater than Swarm's depth. These partial addresses are referred to as recovery targets.

Publishers will advertise the recovery targets for their content to data consumers via a feed called a recovery feed. Consumers can track this feed following a convention that constructs the topic using a simple sequential indexing scheme.

Recovery request

Once the recovery host's overlay targets are revealed to the downloader node, the downloader should "prod" one of the recovery hosts by send-

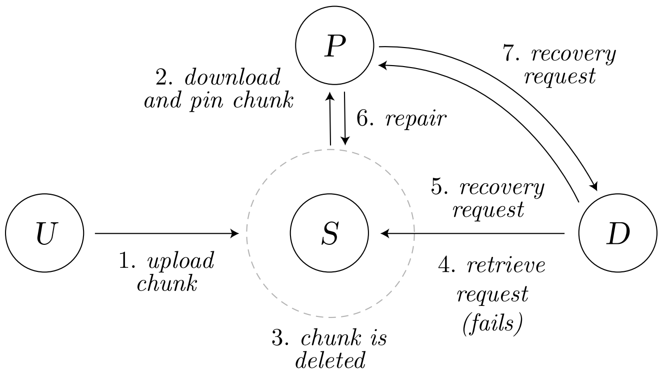


Figure 5.3: The process of notifying about a missing chunk is similar to that of targeted chunk delivery. Here, a downloader mines the identifier to match their own address, i.e. a self-notification. If downloader *D* encounters a missing chunk (a request times out), they send a recovery request to one of several neighbourhoods where there is a possibility of finding the missing chunk. If the recovery request is successful, *D* receives a response in the form of a single owner chunk that wraps the missing chunk. The chunk is also re-uploaded to the appropriate location within the network.

ing them a recovery request whenever a missing chunk is encountered. This instance of targeted chunk delivery (see 4.4.4) is a public unencrypted Trojan message that contains at least the address of the missing chunk (see Figure 5.4).

In order to create a recovery request, a downloader needs to (1) create the payload of the message (2) find a nonce that, when prepended to the payload, produces a content address that matches one of the recovery targets indicated by the publisher. The matching target indicates that push-syncing the chunk will send it to the recovery host's neighbourhood associated with that target prefix.

If the targeted recovery host is online, they will receive the recovery request, extract the address of the missing chunk, retrieve the corresponding chunk from their locally pinned storage, and re-upload it to the network with a new postage stamp.

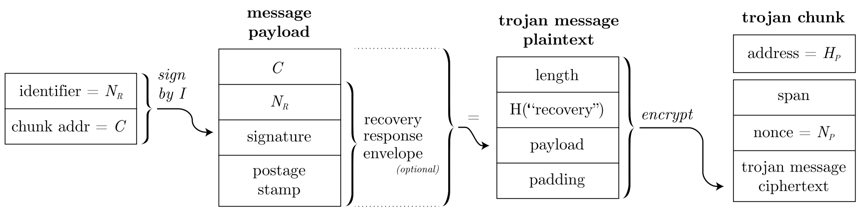


Figure 5.4: A recovery request is a Trojan chunk used for missing chunk notification. It is unencrypted and its payload is structured as a pss message containing the address of the chunk that needs to be recovered. Optionally, the recovery request also includes a special recovery response envelope, which is an identifier with a signature verifying the association between the identifier and the missing chunk hash.

Recovery response envelope

A recovery response envelope is used to enable recovery hosts to promptly and directly respond to the originator of the recovery request, without incurring additional costs or computational burdens. It is a form of targeted chunk delivery response (see 4.4.4), which is an addressed envelope construct that remains neutral to the poster but fixed for the content. The request message includes the necessary components for prospective posters to create the valid targeted chunk delivery response: an identifier with a signature that verifies the association between the identifier and the missing chunk hash. The identifier is chosen so that the address of the single owner chunk (the hash of the ID with the owner account) falls into the requestor's neighbourhood and is automatically delivered by the network's push-sync protocol implementation.

If the targeted recovery host is online, they receive the recovery request and extract the missing chunk address, identifier, and signature from the recovery response. After retrieving the corresponding chunk pinned in their local storage, they can proceed to create the recovery response. To create the recovery response, the recovery host combines the hash of the identifier and the payload hash to form the plain text of the signature. The signature received in the recovery request allows her to recover the public key of the requestor. Using this public key, they are able to calculate the requestor's address and finally, by hashing the re-

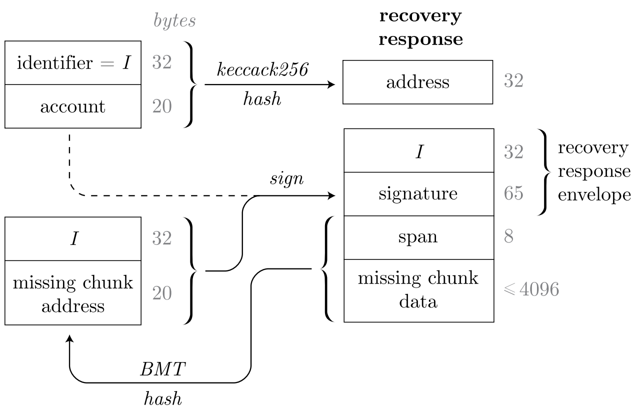


Figure 5.5: Recovery response is a single owner chunk that wraps the missing chunk. Anyone in possession of the headers and the chunk data is able to construct a valid single owner chunk and send it to the downloader for free.

questor's address with the identifier, obtain the address of the single owner chunk. It is beneficial to attach a postage stamp to the request, which can be sent along with the recovery response. Requestors have the ability to cover the Swap costs associated with returning the chunk, compensating the global pinner. This scheme enables downloaders to intelligently cover the operating costs of nodes through micro-payments, thus ensuring the availability of data throughout the network.

5.3 Dream: deletion and immutable content

The increasing digitisation of data and the widespread use of cloud services have amplified concerns surrounding the privacy and control of personal information like never before. In response, regulators often impose requirements on removability without recognising that it is virtually impossible to make material once seen become unseen. However, the reality is that entities operating infrastructure that underpins digital publishing have control over the technology that serves the content and can implement "removal" by denying access. This centralised gatekeeping approach may seem appealing from a regulatory standpoint, as it can be thought of as an instrument of law enforcement. Although such interventions rarely address the breach of unrealistic privacy rights, the gate-keeper still provides a well-defined responsible party with the effective course of action: not serving censored content. While this gives the unwary a phony sense of security, it only exemplifies the larger issue of censorship: publishing platforms possess the technological means to filter content, and centralised control makes it more affordable to exert influence over the content. What starts out as sensible measures of content curation gradually transforms into extant censorship. This is all the more problematic with social platforms that have gained quasi-monopolistic status as a result of network effects. Due to the high costs associated with switching platforms, innocent content creators increasingly find themselves ’deplatformed’. Similarly, the ability to identify hosts and deny access to content through legal means gives powers to be the means to infringe on freedom of speech.

In the decentralised paradigm of web 3, there is no longer a single operating entity controlling the publishing platform or the hosting infrastructure. This renders the cost of censorship infeasible. And yet, the potential permanent exposure of personal data remains a significant concern for most individuals. Therefore, there is a need for novel solutions that can restore the sense of security that centralised gate-keepers purportedly represent.

5.3.1 Deletion and revoking access

First, notice that any reference to removal of information in the sense of erasing it from all physical storage devices is both unenforceable and impractical. Even the most rigorous data protection audits do not require the erasure of offending data from backup tapes. In general, the tacit assumption is that information ordered to be removed should become inaccessible through *typical precedented methods of access.*

In what follows, we formulate the strongest meaningful definition of deletion applicable to decentralised storage systems and offer a construction that implements it. Importantly, this approach is purely technical, focusing on the capabilities and costs of primary actors, rather than relying on procedural measures that impose obligations on intermediaries to respect the rights of primary actors.

The primary actors in this context are the *uploaders* who wish to share content by granting read access to a number of parties, called *downloaders*. Granting access is defined as providing a canonical *reference* to the content, allowing the system to eventually retrieve the complete information that is intended to be disclosed. Any party that is privileged to access this information is able to store, re-code, and potentially disseminate it. This provides a myriad of ways to make the content accessible at any later point in time, bypassing any process that would qualify as deletion or removal of access. There is, by definition, no protection possible against such adversity. As a consequence, any legally sound notion of deletion (retrospective revocation of access) is meant to be interpreted in a narrower sense: *the viability to replay the same access method* at a lower cost than the *full cost* of storing the content.[14]

Let us now define deletion as a scheme for uploading content with access revocation, meeting the following requirements:

Specialisation
: The uploader is able to choose at the time of publishing a specialised construct[15] allowing retrospective revocation of access.

Sovereignty
: The uploader is the sovereign owner of the data and is in sole possession of the means to revoke access from any party that was previously granted access.[16]

Security
: After the revocation of access, a grantee is unable to access the

[14]That is, the total storage cost paid for the full size of the content starting from the time access was revoked until the attempted breach.

[15]From a user's perspective, content that is meant to be reliably deleted should be uploaded as such. The costs of uploading such content is allowed to be a (small integer) multiple of the cost of regular, censorship-resistant but non-deletable uploads.

[16]The uploader's credentials are necessary to delete their own deletable content. Deletables must also allow access control, i.e., they are only available to a specific set of recipients.

content using the same reference or any other cue shorter than the deleted content.[17]

Note that regularly uploaded content may be *forgotten*: if nobody pays for storing it and the content is not accessed frequently, the chunks constituting it will be garbage collected. However, chunks with expired postage stamps cannot be regarded as reliably deleted in order to satisfy the requirements of sovereignty and security.

5.3.2 Construction

The goal of this section is to arrive at a formal construction of a DISC-based revocable access model. We will restrict our scheme to *chunks*, the fundamental fixed-sized storage units of Swarm's DISC model. The proposed *dream* construct implements a deletable content storage and access model that fulfills the requirements of specialisation, sovereignty, and security. The use of the word 'dream' alludes to the somewhat unexpected finding that such a construct is even possible in the immutable DISC model. On top of this, as customary in Swarm, it serves as a mnemonic acronym, resolving to the 5 *dream attributes* expressing requirements of access control.

D – *deniable*
: The dream key serves as a one-time pad for decryption. Since multiple content chunks (in fact any arbitrary content) can use the same dream pad, the key's association to any content is plausibly deniable.

R – *revocable*
: Access granted through dream keys is revocable. Revoking access from all parties, including oneself, is considered as deletion.

E – *expirable*
: The scheme allows for one-time use, i.e., the key can only be retrieved once.

[17] In other words, if the downloader has *not* stored at least as much information as the deleted information itself, they will have no way of retrieving it.

A – *addressable*
: Access can be granted to a neighbourhood, where only clients operating a node within a particular an overlay address range are able to access the content.

M – *malleable*
: The construct is resilient to churn and dynamic changes in network size; it is reusable across independent grantees and upgradeable.

The scheme is built on top of DISC's APIs and can be implemented entirely as a second-layer solution. Despite its rich feature set, the scheme does not use complex cryptography, but instead leverages the interplay of various component subsystems.

Assume we have a pseudo-random deterministic function that generates a longer (e.g., chunk-sized = 4K) sequence c from a key-sized (32 byte) generator g.[18]

The central construct called a *dream* is a chunk-sized one time pad which acts as a decryption key for the deletable content. The dream chunk is collectively created by a set of nodes following a network protocol. Each node in the sequence of participating peers receives a piece of data and combines it as input with data from their reserve to produce an output, which is then sent to the neighbourhood of the next node in the chain. As long as each node in the chain performs the same calculation and forwards the same result, the same one-time pad can be generated, enabling the retrieval and reading of the deletable content.

The insight here is that retrieving a deletable chunk's references involves calculations using a set of immutable chunks controlled by the uploader. The uploader's ability to change this underlying set holds the key to providing the necessary mutability required by any notion of deletion.

Let b be the batch ID (a 32-byte hash) of a postage batch owned by U, and let $Chunks(\gamma, b, p)$ stand for all chunks stamped by b at block γ in

[18]For example, the Keccak sponge function used throughout Ethereum for hashing does have this capability. Alternatively, the blockcipher encryption using initial nonce g could be applied to a fixed constant chunk such as all zeros.

the bucket designated by the pivot p. Define $\overline{\chi}(\gamma, b, p)$ as the chunk stamped by batch b in the bucket designated by p older than γ whose address is closest (has minimal XOR distance) to pivot p.

$$\begin{aligned}
\overline{\chi} &: \Gamma \times \mathit{Batches} \times \mathit{Segment} \mapsto \mathit{Chunks} && (5.1)\\
\overline{\chi}(\gamma, b, p) &\stackrel{\text{def}}{=} \operatorname*{arg\,min}_{c \in \mathit{Chunks}(\gamma, b, p)} \chi(p, \textsc{Address}(c)) && (5.2)
\end{aligned}$$

If batch b is underutilised, a bucket designated by p may not contain any chunks belonging to the batch bucket. As a result, there will not be a chunk closest to p, rendering the $\overline{\chi}$ function undefined in such cases.

Let us now define the OTP update function $\Delta(\gamma, b)$ for batch ID and input address p as follows:

$$\begin{aligned}
\Delta &: \Gamma \times \mathit{Batches} \mapsto \mathit{Chunks} \mapsto \mathit{Chunks} && (5.3)\\
\Delta(\gamma, b) &: \mathit{Chunks} \mapsto \mathit{Chunks} && (5.4)\\
\Delta(\gamma, b)(c) &\stackrel{\text{def}}{=} \mathscr{G}\,[4K]\,(\textsc{Address}(\overline{\chi}(\gamma, b, c))) && (5.5)
\end{aligned}$$

Since uniformity depth of batches is intended to be greater than the nodes' storage depth, it is expected that all chunks in a batch bucket designated with p are present in the reserve of every node within the neighbourhood designated by p.

However, if Swarm grows and there are nodes whose storage depth is higher than the uniformity depth of the batch, then the neighbourhood designated by p may not contain all the chunks in the bucket, thus compromising the computability of the OTP update function.

Nevertheless, if two conditions are met, namely: 1) the bucket of batch b designated by p is not empty and 2) the neighbourhoods include one or more buckets, then the update function is computable by any storer node within the neighbourhood designated by p.

Since the update function can be applied to its own output, we can define the *dream path* as follows:

$$\Pi(b,g) \overset{\text{def}}{=} c_0,\ldots,c_n \in \mathit{Chunks}\{n\} \tag{5.6}$$

$$c_i \overset{\text{def}}{=} \begin{cases} \mathcal{G}\,[4K]\,(g) & \text{if } i = 0 \\ \Delta(b, c_{i-1}) & \text{otherwise} \end{cases} \tag{5.7}$$

The dream path function is a pseudo-random generator that is defined by finite recursion. A *dream* is a particular pairing of a generator and a one time-pad, which serve as the input and output of a dream path. Given a dream path of length n and grantee overlay address a, along with a batch b with a uniformity depth of d, the uploader needs to find the generator g such that the n-th chunk of the dream path falls within a's neighbourhood (i.e., $PO(a, \text{ADDRESS}(c_{n-1})) \geq d$).

$$\mathit{dream}(b,n,a) \subset \mathit{Keys} \times \mathit{Chunks} \tag{5.8}$$

$$\langle g,k\rangle \in \mathit{dream}(b,n,a) \tag{5.9}$$

$$\Longleftrightarrow \tag{5.10}$$

$$k = \Pi(b,g)\,[n] \wedge \tag{5.11}$$

$$PO(a, H_{bmt}(k)) \geq d \tag{5.12}$$

The uploader is able to construct the dream pad, which also allows them to calculate k given g. Since $H(k)$ is uniform, the chance of $PO(a, H(k)) \geq d$ is 1 in 2^d.

Now we can turn to the definition of a dream, which is a network protocol based access method that is deniable, revocable, expirable, addressable, and malleable. In order for downloaders to calculate the dream pad, they must rely on the network, where each recursive step is calculated by a node in the neighbourhood designated by the respective input chunk's address.

In order to guarantee the correct termination, the following criteria must be fulfilled:

— all buckets of batch b designated by $p_0,\ldots,p_{n-1}$ must be non-empty

— the uniformity depth of the batch must remain higher than the storage depth of nodes in the neighbourhoods designated by $p_0, \ldots, p_{n-1}$.

— the output of each step, produced by a node in the neighbourhood designated by p_i, must be sent to the neighbourhood designated by p_{i+1}.

— nodes in the neighbourhoods along each hop of the dream path (designated by $p_0, \ldots, p_{n-1}$) must be incentivised to compute the OTP update and forward the resulting output chunk to the next neighbourhood.

Let us define a network protocol called *dream*. Participants in the protocol listen to single owner chunks that wrap the input. We assume that they extract the batch identifier b, and the payload CAC c as parameters to the OTP update function. They calculate the output pad, wrap it as a dream chunk, and send it to the network towards the address of the output chunk. This allows the destination neighbourhood to calculate the next step. If the protocol is followed up to n steps, then the target node receives $k = c(n)$ at address a.

We now turn to the construction of dream chunks. Uploader U wishes to grant downloader D (at overlay address a) revocable access to content chunk C. U chooses a postage batch b it owns, ensuring that it is not completely filled. Additionally, U chooses a step-count n and a depth d. U creates a dream generator $\langle g, k \rangle \in \mathit{dream}(b, d, n, a)$, then calculates the "ciphertext" $C' = C \veebar k$ and uploads it to Swarm, obtaining $r = H(C')$ as parity reference. Now U creates the *dream reference* as $\mathit{ref}(C) = \langle r, b, g \rangle$ which can be given to the downloader grantee D.[19]

[19]So far, references to swarm content included an address (*Swarm hash* for unencrypted content) or an address with a decryption key (for encrypted content). The dream reference now defines a third type of reference, serialised in four segments comprising the parity address, the batch ID, the initial generator, and a decryption key.

5.3.3 Correctness, security and privacy

Retrieval

D, in possession of a dream chunk reference as $\langle r, b, g\rangle$ calculated by U as $\mathit{ref}(C)$, constructs $p = \mathcal{G}[4K](g)$, wraps it as a dream chunk, and sends it to Swarm. When D it receives the dream chunk for b, it extracts payload k.

D retrieves the parity chunk C' using reference r and then decodes $C = C' \veebar k$. The retrieval process is trivially correct as long as:

1. The parity chunk C' is retrievable via normal retrieval methods.
2. The dream protocol is followed by cooperating nodes.
3. The batch bucket bottom remains unchanged for the neighbourhoods along the dream path.

Deletion

We are now turning to access revocation, which is equivalent to deleting content by revoking all access.

Uploader U had granted D (at address a) access to C through the dream reference $\langle r, b, g\rangle$. U revokes D's access by uploading extra chunks to batch b such that $\overline{\chi}$ changes.

As long as there is at least one honest neighbourhood walked by the protocol, such that the nearest chunk to pivot p from batch b changes, downloader D will no longer be able to retrieve content C.

To prove this, first let us assume that there is a bucket designated by some p_i on the dream path such that the $\overline{\chi}$ for the bucket has changed since the uploader constructed the dream. When the participating node in the neighbourhood designated by p_i calculates the OTP update function, the result will be completely different and the dream chain will not terminate.

Privacy

The reference does not leak any information about the step-count or the neighbourhoods involved. Neither are the participants in the protocol aware of their position in the chain or any details about the other neighbourhoods, except for the immediate next one to which they are push-syncing their chunk.

The construction of the dream reference is deniable. Beside our sensitive content C, let us consider A, any uncontroversial content chunk. When producing C', the owner also produces $A' = A \veebar k$ and uploads it. When asked about k, producing A makes the denial of other content, including C, more plausible.

Resolution of attacks

A powerful adversary could potentially infiltrate every neighborhood of Swarm and archive all information that has ever been uploaded (even without being able to decipher it). They could also keep logs of what has been uploaded in what order, which would allow it to serve up deleted content on demand. But there is a huge price on such indiscriminate archiving of all Swarm's content, and that is the only way to reliably defeat the dream construction.

We now turn to the discussion how to calibrate the step-count in relation to the security model. Let us assume a network-wide neighbourhood infiltration rate of $\frac{1}{2}$, meaning that half of the neighbourhoods in the network is assumed to be malicious and colluding.

When access is revoked, the owner uploads new chunks in each neighbourhood along the dream path. Given a particular dream chain, however, if even a single neighbourhood on the dream path is honest, they will respect the newly arrived chunks and divert the dream path, preventing it from terminating with the grantee.

Thus, for a breach of access to happen, all neighbourhoods must be malicious. In our security model, a neighbourhood is malicious with uniform and independent probability. For an overall infiltration rate of

1 out of k, the chance of all neighbourhoods on a given random dream path being malicious is k^{-n}. For a security requirement of success rate of σ "nines", where the error rate is less than $10^{-\sigma}$, we can formulate the requirement as

$$\frac{1}{k^n} < \frac{1}{10^{-\sigma}} \tag{5.13}$$

Now, expressing k as 10^{κ}, taking the logarithm of both sides and multiplying by -1, we get

$$n > \frac{\sigma}{\kappa} \tag{5.14}$$

With one in every 10 neighbourhoods being malicious, the dream path must have as many hops as the number of nines expressing the success rate.[20]

[20] I.e., with malicious node probability 0.1, a 6-hop-long path will effectively revoke access with certainty of 99.9999%.

—— 6. Developer interface ——

This chapter approaches the Swarm features introduced in the previous chapters from the user's perspective. In 6.1, we discuss the developer interface for configuring uploads including aspects of postage, pinning, erasure coding, as well as tracking the progress of chunk propagation into the network using upload tags. Then we turn to the storage API, specifically uploading collections, in 6.2. Finally, we provide an overview of the communication options available in 6.3.

6.1 Configuring and tracking uploads

The upload interface is the cornerstone of Swarm's functionality, allowing users to easily transfer their data into the network. Section 6.1.1 presents the request headers (or alternatively, query parameters) used for configuring the upload APIs. In 6.1.2, we introduce upload tags that allow tracking the upload process through progress bars together with an estimate of how long it will take for the process to complete. Additionally, tags also record partial root hashes, enabling the resumption of interrupted uploads. In 6.1.3, we sketch the scenarios relating to payment for upload and dispersal into the network, including how users can purchase and attach stamps to chunks. Finally, 6.1.4 runs through optional parameters such as encryption, pinning, and erasure codes.

6.1.1 Upload options

The local HTTP proxy offers the `bzz` URL scheme as a storage API. Requests can specify Swarm-specific options such as:

`tag`
: use this upload tag] generated and returned in response header if not specified.

`stamp`
: upload using this postage subscription] if not given, the one used most recently is used.

`encryption`
: encrypt content if set] if set to a 64-byte hex value encoding a 256-bit integer, then that is used instead of a randomly generated key.

`pin`
: pin chunks] pin all chunks of the upload if set.

`parities`
: apply RS erasure coding] use this number of parities per child batch for all intermediate chunks

These options can be used as URL query parameters or specified as headers. The name of the header is obtained prefixing the parameter name with `SWARM-`, written in uppercase, e.g., `SWARM-PARITIES`.

6.1.2 Upload tags and progress bar

When uploading a file or collection, it is useful for the user to know when the upload is complete, meaning that all newly created chunks are synced to the network and have arrived at the neighbourhood where they can be retrieved. At this point, the uploader can "disappear", i.e. they can quit their client. A publisher can disseminate the root hash and be assured that the file or collection is retrievable from every node on Swarm.

To track the progress of an upload, we utilise the push-sync protocol's statements of custody receipts for individual chunks. By collecting and counting these receipts, we can track the ratio of sent chunks and returned receipts, which provides the data to a *progress bar*. An upload tag is an object that represents an upload and tracks its progress by counting how many chunks have reached a particular state. The states are:

split
: Number of chunks split; count chunk instances.

stored
: Number of chunks stored locally; count chunk instances.

seen
: Count of chunks previously stored (duplicates).

sent
: Number of distinct chunks sent with push-sync.

synced
: Number of distinct chunks for which the statement of custody arrived.

With the help of these counts, it is possible to monitor the progress of 1) chunking 2) storing 3) push-syncing, and 4) receipts. If the upload tag is not specified in the header, a random tag will be generated and returned as a response header once the file is fully chunked. In order to monitor the progress of chunking and storing during the upload, the tag needs to be created beforehand and supplied in the request header. Thus, the tag can be queried concurrently while the uploaded content is being processed.

Known vs. unknown file sizes

If the file size is known, it is possible to calculate the total number of chunks that will be generated. This allows for meaningful progress tracking of both chunking and storage from the beginning, in proportion to the total number of chunks.

However, if the size and total number of chunks split are not known prior to the upload, the progress of chunk splitting is undefined. After the chunker has finished splitting the file, the total count can be set to the split count. From that point on, a percentage progress and estimated time of arrival (ETA) are available for the rest of the counts.

Note that if the upload also includes a manifest, the total count will only serve as an estimation until it is set to the split count. This estimation converges to the correct value as the size of the file increases during the upload process.

Duplicate chunks

Duplicate chunks refer to chunks that occur multiple times within an upload or across different uploads. In order to have a locally verifiable definition, we define a chunk as a duplicate (or seen) if and only if it already exists in the local store. Since chunks enter the local store via upload and are push-synced, there is no need for seen chunks to be push-synced again.

In other words, only newly stored chunks need to be counted when assessing the estimated time of syncing an upload. If we want to track progress based on sent and synced counts, they must reflect the completeness of stored distinct chunks in proportion to the overall progress.

Tags API

The HTTP server's `bzz` URL scheme provides the `tags` endpoint for the tags API. This endpoint supports the creation, listing, and viewing of individual tags. Most importantly, it offers an option to track the changes of a tag in real time using HTTP streams.

6.1.3 Postage

To impose a cost on uploads and efficiently allocate storage resources in the network, all uploads must be paid for. This concept may be unfamiliar in the context of the web, so a novel user experience needs to be developed. The closest and most relatable metaphor is that of a subscription.

Postage subscriptions

The user can create a subscription for a specific duration and storage capacity (e.g. 1 month for 100 megabytes) and make the corresponding payment based on the price provided by the client software (similar to how transaction fees are determined for the blockchain). Price estimates can be obtained from the postage lottery contract. Subscriptions are named, but these names are only meaningful locally. The API will offer a few default options for the chosen storage period, on a logarithmic scale, e.g.:

minimal (a few hours)
: Useful for immediate delivery of pss messages or single owner chunks that are part of ephemeral chat or other temporary files.

temporary (week)
: Files or mailboxed messages that are not meant to be stored for long, but rather picked up by third parties asynchronously.

long term (year)
: The default option for long-term storage.

forever (10 years)
: Important content that should not be lost/forgotten; intended to survive the network's growth and subsequent increase of batch depth even if the uploader remains completely offline.

When uploading files, the user can indicate which subscription they would like to use by specifying the value of the `stamp` upload parameter. If no subscription is specified, the most recent one is used as the default. If the size of the upload is known, the user can receive a warning if it exceeds the available postage capacity.

Postage reuse strategies

As mentioned in 3.3, encryption can be used to mine chunks to make sure they align with the collision slots of postage batches. This strategy of mining chunks into batches makes sense for users who only want to upload a particular file/collection for a particular period or want to keep the option open to change the storage period for the file/collection independently of other uploads.

The alternative is to prepay a large set of postage batches and maintain a fixed number of them open for every period. This ensures that there is always an available collision slot in one of the batches for any chunk. The postage batches are ordered based on the time of purchase, and when attaching a stamp to a chunk, the first batch with a free slot for the chunk address is utilised. This profitable strategy is used most effectively by power users including insurers who can afford to tie up liquidity for longer time periods. The choice of the preferred strategy must be specified when creating a subscription.

The postage subscription API

In order to manage subscriptions, the `bzz` URL-scheme provides the `stamp` endpoint for the postage API. This API allows users to perform various actions such as creating postage subscriptions, listing them, viewing details, topping them up, or draining and expiring them.

When checking their subscription(s), the user is informed how much data has already been uploaded to that subscription and how long it can be stored given the current price (e.g. 88/100 megabytes for 23 days). If the estimated storage period is low, indicating the risk of the files using the subscription being garbage collected, users are encouraged to top up their subscription to ensure the content remains protected.

6.1.4 Additional upload features

Additional features such as swap costs, encryption, pinning, and erasure coding can be specified during upload by using relevant request headers.

Swap costs

Uploading content incurs swap costs, which are associated with the push-sync protocol and reflected in the SWAP accounting system (3.2.1). When the balance tilts beyond the effective payment threshold on a peer connection, a cheque is issued and sent to the peer. If, however, the checkbook contract does not exist or lacks sufficient funds to cover the outstanding debt, the peer connection is blocked. This may lead to unsaturated Kademlia and during that time, the node is considered a light node. While the download process can still continue with potentially fewer peers, the average cost of retrieving a chunk may be higher since some chunks may need to be sent to peers that are not closer to the request address than the node itself.

To provide transparency to the user, information such as the average number of peers, average swap balance, and the number of unavailable peer connections due to insufficient funds can be accessed through the SWAP API.

Encryption

Encrypted upload can be enabled by setting the option `encryption` to a non-zero value. If the value provided is a hexadecimal representation of a 32-byte seed, that seed is used for encryption. Since encryption and decryption are handled by Swarm itself, it must only be used in situations where the transport between the HTTP client and Swarm's proxy server can be guaranteed to be private. As such, it should not be used on public gateways, but rather through local Swarm nodes or private environments with well-configured TLS and self-signed certificates to ensure the necessary privacy and security.

Pinning

When uploading content, users have the option to specify if they want the content to be pinned locally by setting the `pin` upload option to a non-zero value. Beyond this, the local HTTP server's `bzz` URL scheme provides the `pin` endpoint for the pinning API, which allows users to manage pinned content. By making a `GET` request on the pinning endpoint, users can retrieve a list of pinned files or connections. The API also accepts `PUT` and `DELETE` requests on a hash (or domain name that resolves to a hash) to pin and unpin content, respectively.

When a file or collection is pinned, it is supposed to be retrieved and stored. Pinning triggers the traversal of the hash tree and increments the reference count on each chunk. If a chunk is found to be missing locally, it will be retrieved. After pinning, the root hash is saved locally for future access. Unpinning triggers the traversal of the hash and decrements the reference count of each chunk. If a chunk is missing locally, it is ignored and a warning is included in the response. After unpinning, the hash is removed from the list of pinned hashes.

Erasure coding

Erasure coding (see 5.1) can be enabled during an upload by setting the `parities` upload option to specify the number of parity chunks among the children of each intermediate chunk. It is worth noting that erasure coded files cannot be retrieved using the default Swarm downloader. Therefore, when using erasure coding, it is important to indicate the erasure coding settings in the encapsulating manifest entry by setting the `rs` attribute to the number of parity chunks.

6.2 Storage

In this section, we will introduce the storage API provided through the `bzz` family of URL schemes by Swarm's local HTTP proxy.

6.2.1 Uploading files

The `bzz` scheme allows for uploading files directly through the `file` API. The file is expected to be encoded in the request body or in a multipart form. All the query paramaters (or corresponding headers) introduced in 6.1.1 can be used with this scheme. The `POST` request will chunk and upload the file. A manifest entry is created, which includes the reference to the uploaded content and reflects the configuration of the upload, e.g. the number of parities per batch for erasure codes specified by the `rs` attribute. The manifest entry is provided as a response. The upload tag. which allows us to monitor the status of the upload, will contain the reference to the uploaded file as well as the manifest entry.

Appending to existing files

The `PUT` request is used to append data to pre-existing data in the swarm and requires the URL to point to the specific file. If the file is directly referenced, the settings, such as the number of parities for erasure coding, are taken from the upload headers. Otherwise, if the file is not directly referenced, the settings obtained from the enclosing manifest entry will be used. The response follows the same format as in the case of a `POST` request.

Resuming incomplete uploads

As a special case, append is used when resuming uploads after a crash or user-initiated abort. In order to facilitate this, it is necessary to track partial uploads by periodically recording root hashes on the upload tag. When the specified upload tag in the header is not complete, it is assumed that the request is intended to resume the same upload. The last recorded root hash in the tag is used as an append target: the right edge of the existing file is retrieved to initialise the state of the chunker. The file sent with the request is read from where the partial upload ended, with the offset set to the span of the root chunk recorded on the tag.

6.2.2 Collections and manifests

As described in Section 4.1.2, a manifest can represent a generic index that maps string paths to entries. This means that a manifest can serve as the routing table for a virtual website, the directory tree of a file collection, or even as a key–value store.

Manifest entries vs.singleton manifests

Manifest entries are essential not only for collections, but also for single files as they contain key information about the file, including content type and erasure coding details necessary for correct retrieval. A manifest with a single entry for a file located on the empty path is called a singleton manifest. In this case, the manifest contains no additional information beyond the entry itself.

To facilitate the storage of collections, the HTTP server provides the `bzz` URL scheme, which implements the collection storage API. When a single file is uploaded via a `POST` request using the `bzz` scheme, a manifest entry is created and stored, and the response contains the reference to the created entry.

Uploading and updating collections

The `bzz` URL scheme provides an API that supports uploading and updating collections. When utilising the `POST` and `PUT` requests with a multipart payload containing a tar stream, the directory tree structure encoded within the tar stream is translated into a manifest. Simultaneously, the files within the collection are chunked and uploaded, with their respective Swarm references included in the corresponding manifest entries. The `POST` request is used to upload the resulting manifest, and the response includes the Swarm reference associated with it. The `PUT` request requires the request URL to reference an existing manifest that will be updated with the contents of the tar stream. The update process involves merging the new paths with the paths of the existing manifest. If there are identical paths, the entry coming from the upload will replace the corresponding entry in the existing manifest.

The API enables inserting a path into a manifest, updating a path in a manifest (`PUT`), and deleting (`DELETE`) a path from a manifest. In case of a `PUT` request, a file is expected in the request body, which is uploaded and its manifest entry is inserted at the path present in the URL. If the path already exists in the manifest, the existing entry is replaced with the entry generated with the upload, effectively performing an update. If the path is new, the upload inserts a new entry into the manifest.

The collection API supports the same headers as the file upload endpoint, including those that configure postage subscription, tags, encryption, erasure coding, and pinning.

Updating manifests directly

Manipulating manifests is also supported directly: the `bzz` URL scheme `manifest` endpoint supports the `PUT` and the `DELETE` methods and behaves similarly to the collection endpoint. However, unlike the collection endpoint, the manifest endpoint does not handle the files referenced in the manifest entries. When using a manifest endpoint, the URL path is expected to reference a manifest with a path p. For `PUT`, the request body should contain a manifest entry which will be placed at path p. The chunks needed for the new manifest are created and stored, and the root hash of the new manifest is returned in the response. The `DELETE` method expects empty request body and removes the entry on the path from the manifest: i.e., it creates a new manifest where the referenced path in the URL is no longer present.

The `POST` request made directly on the manifest API endpoint installs a manifest entry. Practically, calling a manifest `POST` on the output of a file `POST` is equivalent to making a `POST` request on the generic storage endpoint.

Given manifest references a and b, sending a `POST` request on `manifest/merge/<a>/<b>` merges b onto a (merge with giving preference to b in case of conflicts), creates and stores all the chunks constituting the merged manifest, and the root reference of the merged manifest is returned as a response.

In case the URL path references a manifest, another manifest can be included in the request body, which is then merged into the referenced manifest. In case of conflicts, the one that is uploaded wins.

6.2.3 Access control

Access control, as described in 4.2, is facilitated through the `bzz` URL scheme, which provides the `access` API endpoint. This API offers a convenient way for users to apply access control to files, collections, or sites, as well as manage grantees.

If the URL path references a collection manifest, then a `POST` request with access control (AC) settings sent as a JSON-encoded request body will encrypt the manifest reference and wrap it with the submitted AC settings in a so-called root access manifest. This manifest is then uploaded, and the unencrypted reference to it is returned as the response body.

If the URL path references a root access manifest and the access control settings specify an ACT, then the ACT can be created or updated using `POST`, `PUT`, and `DELETE` requests. All requests expect a JSON array of grantee public keys or URLs in the request body. If a grantee is referenced by a URL, the resolver is used to extract the owner's public key through ENS.

The `POST` request will create the ACT with the list of grantees. `PUT` will update an existing ACT by merging the grantees specified in the request body. `DELETE` removes all the grantees listed in the request body. The new ACT root hash is then updated in the root access manifest, which is uploaded, and its Swarm address is returned in the response.

6.2.4 Download

Downloading is supported by the `bzz` URL scheme. This URL scheme assumes that the domain part of the URL is referencing a manifest as the entry point.

It is worth noting that the processes involved in downloading are the same, even if a file is only partially retrieved. As shown in 4.1.1, random access to a file at an arbitrary offset is supported at the lowest level. Therefore, `GET` requests on a URL pointing to a file can include range queries in the header. These range queries will trigger the retrieval of only the necessary chunks of the file that cover the desired range.

Retrieval costs

Downloading files in Swarm incurs costs in terms of SWAP accounting (as described in Section 3.2.1). These costs are associated with retrieving chunks from the network. When a node's balance tilts beyond the effective payment threshold on a peer connection, a cheque is issued and sent to that peer. If, however, the checkbook contract does not exist or lacks sufficient funds to cover the outstanding debt, the peer connection is blocked. This may lead to non-saturated Kademlia and during that time, the node will count as a light node. The download can continue potentially using a smaller number of peers, however, since some chunks will need to be sent to peers that are not closer to the request address than the node itself, the average cost of retrieving a chunk will be higher.

To provide transparency to the user, it is valuable to display the average number of retrieve requests, the average swap balance, and the number of peer connections not unavailable due to insufficient funds. This information can be accessed through the SWAP API, which is available on the `swap` endpoint of the `bzz` URL scheme.

Domain Name Resolution

The domain part of the URL can be a human-readable domain or sub-domain with a top level domain (TLD) extension. Depending on the TLD, various name resolvers can be invoked. The TLD `eth` is linked to the Ethereum Name Service contract on the Ethereum main chain. If you register a Swarm hash to an ENS domain, Swarm is able to resolve that by calling the ENS contract as a nameserver would.

Authentication for access control

If the resolved domain references a root access manifest, the retrieved URL is subject to access control (see 4.2). Depending on the credentials used, the user may be prompted for a password or a pair of keys (key 1 for lookup and key 2 for decrypting the access key). The Diffie–Hellmann shared secret is hashed with $0x00$ to derive *the lookup key* and with $0x01$ to derive the *access key decryption key*. The Swarm address of the ACT manifest root chunk is obtained from the root access manifest. The lookup key is then appended to the ACT address, resulting in a URL used to retrieve the manifest entry. The reference within this entry is then decrypted using the access key decryption key, and the resulting access key is used to decrypt the original encrypted reference stored in the root access manifest.

Next the manifest entry corresponding to the path of the URL is retrieved. The retrieval process considers the following attributes:

`rs`
: structure with attributes needed to use RS erasure coding for retrieval, e.g. the number of parity chunks required.

`sw3`
: structure with attributes needed for litigation, which includes challenging insurer regarding a missing chunk.

If the `rs` attribute is provided, the user can set the prefetching strategy for redundancy decoding (see 5.1.4).

The default strategy choice is `race`, if the user wants to prioritise saving on downloads, then the fallback strategy can be enforced by setting the header `SWARM-RS-STRATEGY=fallback`. Alternatively, the RS strategy can be completely disabled by setting `SWARM-RS-STRATEGY=disabled`. The number of parities for an erasure coded batch is taken from the `rs` attribute in the enclosing manifest. However, this can be overridden with the header `SWARM-RS-PARITIES`.

Missing chunks

If a requested chunk is found to be missing, we can fall back on the missing chunk notification protocol (see 5.2). The reference to the root of the data structure representing the set of recovery targets can be found at the latest update of the recovery feed.

When a chunk request times out, the client can initiate the creation of a recovery message using the set of pinner hosts. Once the recovery message is created, it is sent to the host. If this request also times out, the next recovery chunk is tried using a different pinner host node. This process is repeated until the recovery chunk is successfully retrieved or all the pinners and insurers have been exhausted.

6.3 Communication

Somewhat surprisingly, Swarm's network layer can serve as a highly efficient communication platform with robust privacy features. This section aims to showcase how a small set of primitives can be utilised as the fundamental building blocks for a comprehensive communication infrastructure. The capabilities cover the full range of communication modalities including real-time anonymous chat, sending and receiving messages from previously unconnected and potentially anonymous senders, mailboxing for asynchronous delivery, long-term notifications, and publish/subscribe interfaces.

Swarm core offers the lowest-level entry-points for communication-related functionality:

- The pss module provides an API for sending and receiving Trojan chunks
- The bzz module offers a way to upload single owner chunks. The retrieval of single owner chunks only requires the functionality provided by the storage APIs, without any additional requirements

Since Trojan message handling has distinct characteristics from storage operations, Swarm introduces its own URL-scheme called `pss`. The pss scheme provides an API specifically for sending messages. When sending a `POST` request, the URL is interpreted as referencing the X3DH pre-key bundle feed update chunk. This chunk contains the necessary public key for encryption as well as the destination targets. One of the destination targets should match the address for the Trojan message (see 4.4.1).

Destination targets are represented as the buzz serialisation of the target prefixes as a file. The URL path points to this file or is a top-level domain. The topic is specified as a query parameter and the message as the request body.

Receiving messages is supported only by registering topic handlers internally. In the context of the API, this typically involves push notifications via web-sockets.

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Part III

Indexes

GLOSSARY

access control

The selective restriction of access to read a document or collection in Swarm.

access control trie

A tree-like data structure containing access keys and other access information.

access key

A symmetric key used for encryption of reference to encrypted data.

access key decryption key

The key granted by the publisher to a party in a multi-party selective access scenario, used to decrypt the global access key.

accessible chunk

A chunk that is accessible by routing a message between the requester and the node closest to the chunk.

addressed envelope

A construct where the address of the single owner chunk is created before the chunk content is associated with it.

anonymous retrieval

The act of retrieving a chunk without disclosing the identity of the requestor node.

anonymous uploads

Uploading data while keeping the uploader's identity hidden, leveraging the forwarding Kademlia routing.

area of responsibility
: The area of the overlay address space in the node's neighbourhood. A storer node is responsible for chunks belonging to this area.

authoritative version history
: A secure audit trail of the revisions of a mutable resource.

backwarding
: A method of delivering a response to a forwarded request, where the response simply follows the request route back to the originator.

balanced binary tree
: A binary tree in which subtrees of every node differ in height by at most 1.

batch
: A group of chunks referenced under an intermediate node.

batch bins
: Equivalence classes of chunks from the point of view of batch expiry, with the same proximity order and same batch.

batch depth
: The postage batch size specified as a power of 2.

batch size
: The amount of chunks that can be stamped with a postage batch. See also issuance volume.

bin ID
: A sequential counter per PO bin acting as an index of locally stored chunks on a node.

binary Merkle tree
: A binary tree in which each leaf node is labelled with the cryptographic hash of a data block, and each non-leaf node is labelled with a hash of the labels of its child nodes.

binary Merkle tree chunk
: The canonical content addressed chunk in Swarm.

binary Merkle tree hash
: The method used for calculating the address of binary Merkle tree chunks.

BitTorrent
: A communication protocol for peer-to-peer file sharing used to distribute data and electronic files over the Internet.

blockchain
: An immutable list of blocks, where each subsequent block contains a cryptographic hash of the preceding block.

bzz network ID
: The unique identifier assigned to the Swarm network.

challenge
: User can submit a challenge when they attempt to retrieve insured content and fail to find a chunk.

cheque
: An off-chain payment method where the issuer signs a cheque specifying a beneficiary, a date, and an amount, which is given to the recipient as a token of promise to pay at a later date.

chequebook contract
: Smart contract that allows the beneficiary to choose when payments are to be processed.

chunk
: A fixed-sized data blob, the basic unit of storage in Swarm's DISC keyed by its address. Chunks can either be content addressed or single owner.

chunk span
: The length of data subsumed under an intermediate chunk.

chunk synchronisation
: The process in which a peer locally stores chunks received from an upstream peer.

chunk value
: The value assigned to a chunk based on the price of the postage batch it is stamped with. It determines the order of chunks when a node prioritises for garbage collection.

claim phase
: A phase in each round of the redistribution game when the winner submits a claim.

collect-and-run attack
: Situation where a party would collect the funds for some promised work, but not actually do the work.

collective information
: Data generated through collective effort, such as public forum discussions, reviews, votes, polls, and wikis.

collision slot
: The collection of maximum length prefixes that any two chunks stamped with a postage batch are allowed to share. Each stamped chunk occupies a collision slot.

commit phase
: A phase in the redistribution round of the Schelling game.

committed stake
: The amount of stake the stakers commit to in the staking contract.

content addressed chunk
: A chunk is content addressed when its address is determined by the chunk content itself. The address usually represents a fingerprint or digest of the data using some hash function. In Swarm, the default content addressed chunk uses the Binary Merkle Tree hash algorithm with Keccak256 base hash to determine its address.

data silo
: An isolated collection of information within an organisation that is not accessible by other parts of the organisation. In more general terms, it refers to the large datasets that organisations often keep exclusively for their own use.

data slavery
: Refers to a situation where individuals lack control over their personal data and do not receive sufficient remuneration for its commercial use by companies.

decentralised network
: A network architecture designed without any central nodes that other nodes would need to depend on.

deep bin
: A bin that is relatively close to a particular node and hence contains a smaller part of the address space.

denial of service (DoS)

Denying of access to services by flooding those services with illegitimate requests.

destination target

A bit sequence that represents a neighbourhood in the address space. In the context of chunk mining, it refers to the prefix that the mined address should match.

devp2p

A set of network protocols forming the Ethereum peer-to-peer network. Implemented as a set of programming libraries with the same name.

direct delivery

Chunk delivery occurring in a single step via a lower-level network protocol.

direct notification from publisher

The process where a recipient is directly notified of a feed update by the publisher or other parties known to have it.

disconnect threshold

The debt threshold between peers that determines when a peer in debt will be disconnected.

distributed hash table

A distributed system that provides an efficient lookup service, enabling any participating node to retrieve the value associated with a given key.

distributed immutable store for chunks

Swarm's version of a distributed hash table for storing files. Swarm does not maintain a list of file locations, instead it actually stores pieces of the file directly on the node.

distributed storage

A network of storage where information is stored on multiple nodes, possibly in replicated fashion.

distributed web application

A client side web application that leverages Web 3.0 technologies (e.g. Ethereum network) and does not rely on any central server.

double ratchet
: An industry-standard key management solution providing forward secrecy, backward secrecy, immediate decryption, and resilience to message loss.

duplicate chunk
: We define a chunk as a duplicate (or seen) if and only if it is already found in the local store.

effective demand
: The total number of chunks that have been successfully uploaded.

elliptic curve Diffie-Hellman
: A key agreement protocol that allows two parties, each possessing an elliptic-curve public–private key pair, to establish a shared secret over an insecure channel.

encrypted reference
: Symmetric encryption of a Swarm reference to access controlled content.

enode URL scheme
: A URL scheme used to describe an Ethereum node.

entanglement code
: An error correction code optimized for bandwidth of repair.

epoch
: A specific time period with a defined length, starting from a particular point in time.

epoch base time
: The specific point in time when an epoch starts.

epoch grid
: The arrangement of epochs where rows (referred to as levels) represent alternative partitioning of time into various disjoint epochs of the same length.

epoch reference
: A combination of an epoch base time and level used to identify a specific epoch.

epoch-based feeds
: Special feeds that allow feeds with sporadic updates to be searchable.

epoch-based indexing
: Indexing based on the epoch in which an action took place.

erasure code
: An error correction coding scheme which optimally inflates data of n chunks with k parities to allow any n out of the $n+k$ chunks to recover the original data.

Ethereum Name Service
: A system analogous to the DNS of the old web, translating human-readable names into system-specific identifiers, i.e. references in the case of Swarm.

Ethereum Virtual Machine (EVM)
: A Turing-complete byte code interpreter responsible for calculating state changes by executing the instructions of smart contracts.

eventual consistency
: The guarantee that all chunks are redundantly retrievable once the neighbourhood peers have synchronised their content.

extended triple Diffie–Hellmann key exchange
: The standard method used to establish the initial parameters of a double ratchet key-chain.

FAANG
: Facebook, Apple, Amazon, Netflix, and Google.

fair data economy
: An economy of processing data characterised by fair compensation of all parties involved in its creation or enrichment.

feed aggregation
: The process of combining multiple sporadic feeds into a single periodic one.

feed index
: A component of the identifier for the feed chunk, used for identification and retrieval purposes.

feed topic
: A component of the identifier for the feed chunk, representing the topic or subject of the feed.

feeds
: Data structures based on single owner chunks, suitable for representing a variety of sequential data, such as versioning updates of a mutable resource or indexing messages for real-time data exchange. Feeds offer a persisted pull messaging system.
: Special kind of feeds, updates of which are meant to be accumulated or added to earlier ones, e.g. parts of a video stream.
: Feeds that publish updates at regularly recurring intervals.
: Feeds where the update frequencies may vary within the temporal range of real-time human interaction.
: Special kind of feeds representing a series of content connected by a common thread, theme, or author, such as social media status updates, a person's blog posts, or blocks of a blockchain.
: Feeds with irregular asynchronicities, i.e. updates can occur with unpredictable gaps.

forwarding Kademlia
: A recursive flavour of Kademlia routing that involves message relay.

forwarding lag
: The time it takes for healthy nodes to forward messages.

freeriding
: The practice of benefiting from or taking advantage of shared or limited resources without providing appropriate compensation or contributing to their upkeep or sustainability.

future secrecy
: A feature of specific key agreement protocols that gives assurances that all other session keys will not be compromised, even if one or more session keys are obtained by an attacker.

garbage collection
: The selective purging process of removing unnecessary chunks from a node's local storage.

garbage collection strategy
: The process that determines which chunks are selected for removal during garbage collection.

global balance
: The amount of funds deposited in the chequebook to serve as collateral for the cheques.

granted access
: A type of selective access to encrypted content that requires root access as well as access credentials comprising either an authorized private key or passphrase.

guaranteed delivery
: Guaranteed in the sense that delivery failures due to network problems will result in direct error responses.

hive protocol
: The protocol used by nodes joining the network to discover their peers.

honest peers
: The set of applicants who agree with the selected truth in the round of the Schelling game.

immutable chunk store
: A storage system where no replace or update operation is available on chunks.

incentive strategy
: A strategy that utilises rewards and penalties to encourage desired behaviour.

inclusion proofs
: A proof that a string is a substring of another string, for instance verifying that a string is included in a chunk.

indexing scheme
: Defines the way the addresses of subsequent updates of a feed are calculated. The choice of indexing scheme depends on the type and usage characteristics (update frequency) of the feed.

insider
: A peer inside the Swarm network that already has some funds.

InterPlanetary File System
: A protocol and peer-to-peer network for storing and sharing data in a distributed file system.

issuance volume

The amount of chunks that can be stamped with a postage batch. See also batch size.

Kademlia

A network connectivity or routing scheme based on bit prefix length used in distributed hash tables.

Kademlia connectivity

Connectivity pattern of a node x in forwarding Kademlia where (1) there is at least one peer in each PO bin $0 <\leq i < d$, and (2) no peer y in the network such that $PO(x, y) \geq d$ and y is not connected to x.

Kademlia table

Indexing of peers based on the proximity order of their addresses relative to the local overlay address.

A Kademlia table in which a single peer is present for each bin (up to a certain bin).

Kademlia topology

A scale-free network topology that guarantees a path between any two nodes in $O(log(n))$ hops.

key derivation function

A function that deterministically produces keys from an initial seed. It is often used concurrently by parties separately to generate secure messaging key schemes.

liars

The set of applicants who disagree with the selected truth in the round of the Schelling game.

libp2p

A framework and suite of protocols for building peer-to-peer network applications.

light node

The concept of light node refers to a special mode of operation necessitated by poor bandwidth environments, e.g., mobile devices on low throughput networks or devices allowing only transient or low-volume storage. Light nodes do not accept incoming connections.

litigation

An on-chain process where nodes violating the rules of Swarm stand to lose their deposit.

load balancing

The process of distributing a set of tasks over a set of nodes to make the process more efficient.

lookup key

One of the keys involved in the process of allowing selective access to content for multiple parties.

lookup strategy

A strategy used for following updates to feeds.

manifest entry

Contains a reference to the Swarm root chunk of the representation of a file and also specifies the media mime type of the file.

maximum syncing latency

The agreed maximum duration of latency for live syncing after a peer connection starts.

mining chunks

An example of chunk mining is generating an encrypted variant of chunk content so that the resulting chunk address satisfies certain constraints, e.g. being closer to or farther away from a particular address.

missing chunk notification protocol

A protocol used when a downloader cannot find a chunk, allowing it to initiate a recovery process and request the missing chunk from a pinner of that chunk.

mutable resource updates

Feeds that represent revisions of the same semantic entity.

nearest neighbours

Generally, peers that are closest to the node. In particular, it refers to peers residing within the neighbourhood depth of each other.

neighbourhood

An area of a certain distance around an address.

The distance from the node within which its peers are considered nearest neighbours. Also the highest PO d such that the address range designated by the d-bit-long prefix of the node's overlay contains at least 3 other peers.

neighbourhood notification
: Notification of a feed update which works without the issuer of the notification needing to know the identity of prospective posters.

neighbourhood selection anchor
: A randomly selected value that determines which neighbourhood can participate in the redistribution round.

neighbourhood size
: The number of nearest neighbours of a node.

net provider
: A node that contributes more resources to the Swarm network than it consumes.

net user
: A node that consumes more resources of the Swarm network than it contributes.

network churn
: The cycle of accumulation and attrition of nodes by a network.

newcomer
: A party entering the Swarm system with zero liquid funds.

node
: Nodes that engage in forwarding messages.
: A node that is stably online.
: A node that stores the requested chunk.

on-chain payment
: A payment made through a blockchain network.

opportunistic caching
: When a forwarding node receives a chunk, then the chunk is saved in case it may be requested again.

outbox feed
: A feed representing the outgoing messages of a persona.

outbox index key chains
: Additional key chains added to the double-ratchet key management (beside the ones for encryption) that make the feed update locations resilient to compromise.

overlay address

The address used to identify each node running in the Swarm network. It is the basis for communication in the sense that it remains stable across sessions even if the underlay address changes.

overlay address space

The address space of the overlay Swarm network consisting of 256-bit integers.

overlay network

The connectivity pattern of the secondary conceptual network in Swarm, a second network scheme overlayed over the base underlay network.

overlay topology

The connectivity graph realising a particular topology over the underlay network.

payment threshold

The value of debt at which a cheque is issued.

peer

Nodes that are in relation to a particular node x are called peers of x.

A peer that succeeds some other peer in the chain of forwarding.

peer-to-peer

A network architecture where tasks or workloads are partitioned between equally privileged participants known as peers.

pinner

A node keeping a persistent copy of a chunk.

pinning

The mechanism that makes content sticky and prevents it from being removed by garbage collection.

plausible deniability

The ability to deny knowledge of any damnable actions committed by others.

postage batch

An ID associated with a verifiable payment on the chain which can be attached to one or more chunks as a postage stamp.

pre-key bundle
: Contains all the necessary information that an initiator needs to know about the responder to initiate a cryptographic handshake.

prompt recovery of data
: The protocol used for missing chunk notification and recovery.

proof of density
: A construct that allows the winners of the Schelling game round to demonstrate that the chunks within their storage depth fill their reserve.

proof of entitlement
: Evidence provided by storer nodes in a neighbourhood to the blockchain, demonstrating that they have the required reserve.

proximity order
: A measure of relatedness of two addresses on a discrete scale.

proximity order bin
: An equivalence class of peers in regard to their proximity order.

pub/sub systems
: A publish/subscribe system is a form of asynchronous communication where any message published is immediately received by subscribers.

pull syncing
: A network protocol responsible for eventual consistency and maximum resource utilisation by pulling chunks by a certain node.

push syncing
: A network protocol responsible for delivering a chunk to its proper storer after it has been uploaded to an arbitrary node.

radius of responsibility
: The proximity order designating the area of responsibility.

range queries
: Range queries will trigger the retrieval of all but only those chunks of the file that cover the desired range.

real-time integrity check
: For any deterministically indexed feed. Integrity translates to a non-forking or unique chain commitment.

recover security

A property that ensures that once an adversary manages to forge a message from A to B, no future message from A to B will be accepted by B.

recovery

A process of requesting a missing chunk from specific recovery hosts.

recovery feed

A publisher's feed advertising recovery targets to its consumers.

recovery host

Pinning nodes that are willing to provide their pinned chunks in the context of recovery.

recovery request

A request made to a recovery host to initiate the reupload of a missing chunk known to be pinned in its local store.

recovery response envelope

An addressed envelope which provides a way for recovery hosts to directly and efficiently respond to the originator of the recovery request without incurring additional costs or computational burden.

recovery targets

Volunteering nodes that are advertised by the publisher as keeping pinned its publication globally pinned.

redundancy

In the context of the distributed chunk store, redundancy is achieved through surplus replicas or so-called parities that contribute to the resilience of chunk storage in the face of churn and garbage collection.

redundant Kademlia connectivity

A Kademlia connectivity that remains intact even if some peers churn.

redundant retrievability

A chunk is said to be redundantly retrievable with degree r if it is retrievable and would remain so even after any r nodes responsible for it leave the network.

Reed-Solomon coding
: A systemic erasure code that generates k extra 'parity' chunks when applied to data consisting of n chunks. These chunks allow for the reconstruction of the original blob as long as any n out of the total $n+k$ chunks are available.

reference count
: A property of a chunk used to prevent it from being garbage collected. It is increased when the chunk is pinned and decreased when it is unpinned.

relaying node
: A node relaying messages in the context of forwarding Kademlia.

requestor node
: A node that requests information from the network.

reserve
: A fixed size of storage space on a node dedicated to storing chunks from its area of responsibility.

reserve commitment
: The data provided by a node in the round of the Schelling game containing information about the reserve it is holding.

reserve depth
: The base 2 logarithm of the DISC reserve size, rounded up to the nearest integer.

reserve sample
: A part of the reserve used to test the consensus regarding the reserve content of a neighbourhood.

retrieve request
: A peer-to-peer protocol message that asks for the delivery of a chunk based on its address.

reveal phase
: The phase in the redistribution round of the Schelling game in which the participants who committed reveal their reserve commitment hash.

reward pot
: The total accumulated storage rent from all postage batches for a specific period.

root access
: Non-privileged access to encrypted content based on meta-information encoded in the root manifest entry for a document.

root access manifest
: A special unencrypted manifest used as an entry point for access control.

routability
: The ability for a chunk to be routed to a destination.

routed delivery
: A hypothetical method of implementing chunk delivery using Kademlia routing independently of the initial request.

routing
: The process of relaying messages via a chain of peers ever closer to the destination.

rules of the reserve
: Rules that define the content of the reserve on a node.

saboteurs
: The set of committers who either did not reveal data or revealed invalid data in the round of the Schelling game.

saturated Kademlia table
: Nodes with a saturated Kademlia table realise Kademlia connectivity.

saturation depth
: The neighbourhood depth in the context of saturation (minimum cardinality) constraints on proximity bins outside the nearest neighbourhood.

Schelling game
: A mechanism that facilitates peer cooperation in redundantly storing data for the network's benefit, structured as a sequence of redistribution rounds.

second-layer payment
: Payments processed by an additional system superimposed on a blockchain network.

security deposit
: The stake a node must put up when registering to be able to sell promissory storage receipts.

seeder
: A user who hosts the content in the BitTorrent peer-to-peer file exchange protocol.

sender anonymity
: As requests are relayed from peer-to-peer, those further down on the request cascade can never know who the originator of the request is.

session key
: One of the keys involved in the process of allowing selective access to content to multiple parties.

shallow bin
: A bin that is relatively far away from a particular node and hence contains a larger part of the address space.

single owner chunk
: A special type of chunk in Swarm whose integrity is ensured by the association of its payload to an identifier attested by the signature of its owner. The identifier and the owner's account determine the chunk address.

A 32-byte key used in single owner chunks: the payload is signed against it by the owner and hashed together with the owner's account results in the address.

The account of the owner of single owner chunk.

Part of a single owner chunk with size of maximum 4096 bytes of regular chunk data.

singleton manifest
: A manifest that contains a single entry to a file.

sister nodes
: The nodes in the other half of the old neighbourhood after a neighbourhood split.

span value
: An 8-byte encoding of the length of the data span subsumed under an intermediate chunk.

spurious hop
: Relaying traffic to a node without increasing proximity to the target address.

stake balance
: The amount of stake serving as collateral by the staker.

stake density
: The amount of stake per neighbourhood size.

staking
: Mechanism used to steer nodes to provide reliable service in their neighbourhoods where they stake some amount that represents their commitment.

stamped addressed envelope
: Addressed envelope with an attached stamp.

statement of custody receipt
: A receipt from the storer node to the uploader after successful push syncing of a chunk.

storage depth
: The lowest proximity order at which a compliant reserve stores all batch bins.

storage rent
: The amount paid for storage by purchasing postage batches.

storage slot
: A designated space in a postage batch where a specific chunk is assigned.

stream provider
: Provides of a stream of chunks to another node upon request.

swap
: A Swarm accounting protocol with a tit-for-tat accounting scheme, enabling scalable microtransactions. It also includes a network protocol referred to as Swap.

Swarm manifest
: A structure that defines a mapping between arbitrary paths and files to handle collections.

swear

Incentive scheme where nodes registered on the Swarm network are accountable and stand to lose their deposit if they are found to violate the rules of the Swarm in an on-chain litigation process.

swindle

Incentive scheme where nodes monitor other nodes to check if they comply with their promise by submitting challenges according to a process of litigation.

tar stream

In computing, tar is a computer software utility for combining multiple files into a single archive file, often referred to as a tarball.

targeted chunk delivery

A mechanism for requesting a chunk from an arbitrary neighbourhood where it is known to be stored and delivering it to an arbitrary neighbourhood where it is known to be needed.

time to live

The lifespan or lifetime of a request or other message in a computer or network.

tragedy of the commons

Disappearing content will have no negative consequence to any one storer node if no negative incentives are used.

Trojan chunk

A chunk containing a disguised message while appearing indistinguishable from other chunks.

trustless

A property of an economic interaction system where service provision is either realtime verifiable and/or providers are accountable, rewards and penalties are automatically enforced, and where – as a result – transaction security is no longer contingent upon reputation or trust and is therefore scalable.

underlay address

The address of a Swarm node on the underlay network, which might not remain stable between sessions.

underlay network
: The lowest level base network through which nodes connect using a peer-to-peer network protocol as their transport layer.

uniformity depth
: The number of storage slots or buckets within a postage batch specified in powers of 2.

upload and disappear
: A method of deploying interactive dynamic content to be stored in the cloud so it may be retrieved even if the uploader goes offline.

upload tag
: An object that represents an upload and tracks the progress by counting the number of chunks that have reached a specific state.

uploader
: An entity uploading content to the Swarm network.

upstream peer
: The peer that precedes some other peer in the chain of forwarding.

world computer
: Global infrastructure that supports data storage, transfer, and processing.

World Wide Web
: A part of the Internet where documents and other web resources are identified by Uniform Resource Locators and interlinked by hypertext.
: Websites where people were limited to viewing content in a passive manner.
: Describes websites that emphasise user-generated content, ease of use, participatory culture, and complex user interfaces for end users.
: A decentralised, censorship-resistant way of sharing and even collaboratively creating interactive content, while retaining full control over it.

ZeroNet
: A decentralised web platform using Bitcoin cryptography and the BitTorrent network.

INDEX

Acronyms and abbreviations —

AC	access control.
ACT	access control trie.
API	application programming interface.
BMT chunk	binary Merkle tree chunk.
BMT hash	binary Merkle tree hash.
BMT	binary Merkle tree.
dapp	distributed web application.
DHT	distributed hash table.
DISC	distributed immutable store for chunks.
ECDH	elliptic curve Diffie-Hellman.
ENS	Ethereum Name Service.
EVM	Ethereum Virtual Machine (EVM).
HTTP	Hypertext Transfer Protocol.
IPFS	InterPlanetary File System.
ISP	internet service provider.
MAC	message authentication code.
P2P	peer-to-peer.
PO	proximity order.
prod	prompt recovery of data.

RS	Reed-Solomon coding.
SWAP	Swarm Accounting Protocol, see swap.
SWEAR	Secure Ways of Ensuring ARchival or Swarm Enforcement And Registration, see swear.
SWINDLE	Secured With INsurance Deposit Litigation and Escrow, see swindle.
TLD	top level domain.
TTL	time to live.
WWW	World Wide Web.
X3DH	extended triple Diffie–Hellmann key exchange.