University of Bath

Membrane - Distributed File Backup

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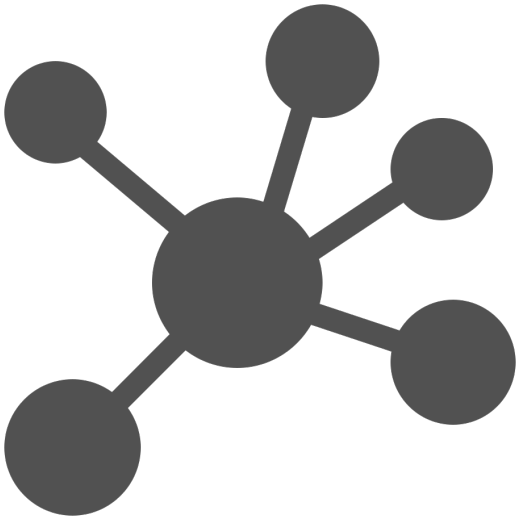

Membrane - Distributed File Backup

Submitted by *Dominic Hauton*

DECLARATION

This dissertation is submitted to the University of Bath in accordance with the requirements of the degree of Bachelor of Science in the Department of Computer Science. No portion of the work in this dissertation has been submitted in support of an application for any other degree or qualification of this or any other university or institution of learning. Except where specifically acknowledged, it is the work of the author.

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Abstract

Membrane is an amalgamation of distributed storage and backup software, designed to operate on a very large scale: terabytes of data backed up across thousands of users across the world. A Membrane user is able to trade storage space with peers across the network, allowing them to securely store their backups world wide providing the user with data resilience with high availability at no monetary cost to the peer.

The applications vary from users who require a secure backup tool with file versioning for their important documents, to corporations that need to provide data resilience to their employees without investing in infrastructure, instead making use of redundant storage space on employee terminals. Membrane seeks to offer an alternative to existing paid cloud services, guaranteeing data privacy through encryption and offering a comparable feature set by harnessing the storage potential of it's users.

In this report we explore the current distributed storage landscape and follow the design and construction of Membrane, drawing on knowledge from distributed storage software, intelligent agent technology and existing backup tools, finishing by providing a sound analysis of the completed solution, delving into the advantages and compromises of using Membrane.

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With thanks to my supervisor, Dr. Russell Bradford

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Chapter 1

Introduction

Distributed storage is a well studied and explored domain with clear advantages over storage on a single machine. In order to implement a peer-to-peer distributed agent based storage system we must first decompose the problem into several parts and explore the advances made in those fields as well as looking at advantages of existing technologies.

1.1 Project Goals

The goal of Membrane is to allow users to easily backup and recover the contents of folders on their computer without needing to pay for a subscription-based service. Looking at breadth of products available it quickly becomes evident that there is a huge desire for external backup, and many people now take popular cloud storage services such as Dropbox and Google Drive for granted. [Lynley, 2015]

To make Membrane competitive with existing solutions we must aim for two important features, ease of use and the ability to access your files from any system provided you can log into your account. On a centralised backup system this a trivial task, however, with a distributed system the concept of creating an account, logging in, finding peers and discovering which users hold your files is a much greater challenge.

In this project we are working towards a proof of concept of the idea of distributed backup, creating the fundamentals of the Membrane, focusing on the key aspects of distributed storage, but we will leave certain convenience features out for later development if the project proves successful. This is consistent with the Minimum Feature Set methodology described by Blank [2010], a practise which is now used heavily amongst technology startups. The technique aims to reduce engineering hours and get the hands in the product of early visionary users early to encourage feedback.

The first step of the project will involve looking at existing products, seeing what design lessons from them we can apply to Membrane. We will then approach potential users and inquire what features they think are important in a system such as Membrane. A technology survey will be performed to assess what technologies we can use to ease with development, the solution will be built, and tested by users, whose feedback we will incorporate in the final prototype.

1.2 Need for Membrane

With the advent of cheap high-speed internet users are now able to use monolithic cloud services to backup data. These tend to be expensive for anything but small amounts of storage and many people have expressed security concerns over holding their data in a data centre owned by another company. [Batters, 2016] Especially if their data leaves the users country where data protection laws may be different.

Over time personal storage capacities for users have also increased. It is now common for computers to come with large amounts of hard drive space which is often not filled to capacity. The project proposed promises

to swap this free hard drive space to back up other users' data in exchange for their surplus space to backup your data.

To simplify the process, the system will be able to negotiate contracts of varying complexity for space allocation on another machine, in exchange for space on itself. Unlike most distributed databases and cloud storage solutions frequent down-time will be expected across devices and contracts will have to account for this.

There is an open gap in the market for a distributed storage solution which focuses entirely on backup and trading data, rather than charging a fee for storing data. The users of Membrane would be able to benefit from the advantages of commercial services, without any of the previous highlighted downsides.

1.3 Challenges

There are multiple challenges associated with creating both decentralised systems and backup solutions.

While doing this it is important to keep resource usage down as Membrane is a background process and should not be notice by the user. To achieve this we need to explore methods of reducing bandwidth, memory and processor usage.

As part of this we need to find a way to copy the minimum amount of data required during backups, an effective way of managing where file chunks are stored, a way to encrypt the files on the remote host and a way to periodically authenticate that the host still holds the file.

Part of the required research also includes exploring the more recent technology of intelligent agents, in which we are most interested in trust metrics. Intelligent agents will allow the software to make storage decisions based on the trust and reputation of other nodes in the network that it has interacted with in the past.

1.4 Modules

Membrane will be built up of several predetermined modules performing distinct roles. This have been broadly identified at this stage as a guide for our literature review and for technology decisions.

The core of any backup system is the file system watcher that determines whether a file has been modified, added or removed. This must be able to cheaply assess if a file or folder has changed and determine whether the altered file needs to to be refreshed in the storage system.

Once a modified file has been detected that change needs to be catalogued and the bits required to restore the file must be stored locally for further processing. This causes temporary duplication, however this must be performed so modification to the real files can continue while a peer willing to store the file is located. This system must also be able to recreate the file from the bits stored.

Next a system needs to be put in place to package bits from various files into a block of data that a peer can store. This system needs to be able to determine which peer certain bits should be stored with and how many peers the file should be stored with, based on trust, availability and other useful metrics that will be explored.

Finally a module responsible for networking and authentication must be created. This must be able to authenticate the user, find peers, establish connections to new peers and deal with the challenges to creating a secure communication link to the peers.

1.5 Conclusion

We have established the need for Membrane and briefly covered the advantages compared to existing solutions. We have also discussed the basic structure of Membrane and what challenges we expect to face during development. We will explore these further in our literature review.

Chapter 2

Literature Review

The literature review aims to preempt challenges by finding solutions to similar problems in literature and existing pieces of software.

We will first explore the history of file backup, proceeding into the challenge of locating, trusting, connecting and communicating with peers. Finally we will look at authentication issues as well as exploring how a peer can prove they own a file, without re-sending the entire file back to us.

2.1 History of Problem

A simple file backup can be imagined as simply copying a file to another location. In order to keep the duplicated file in sync they must be compared. The program diff solves this through finding the longest common sub-sequence of bytes between files. In order to improve performance hashing, presorting into equivalence classes, merging by binary search, and dynamic storage allocation are used. [Hunt and MacIlroy, 1976]. This allows the user to view changes and copy the file over again if required.

2.1.1 Rsync

In a networked scenario, bandwidth from source to destination is at a premium. Rsync, introduced in 1996 presents a much better solution through copying changed file chunks (deltas). [Tridgell et al., 1996]. Rsync splits the file into shards and calculates a weak rolling checksum and strong MD4 checksum for each block that allows quick comparisons of shards along the file. When a discrepancy is found, we assume an extra byte or bytes have been added to the file. The weak checksum can be efficiency recalculated for the next offset and once there is a match, it is confirmed with the strong checksum. The new added chunk can now be transmitted. This results in a lot less data being copied than there would be with a diff file. [Tridgell et al., 1996] This combination of weak and strong checksums has been used across multiple distributed systems including low-bandwidth file systems [Muthitacharoen et al., 2001] and high performance transactional object stores. [Stephen et al., 2000].

Multiround Rsync improves on the rsync algorithm by allowing for more communication to lower bandwidth. Blocks of smaller and smaller sized are used to find holes in the old file in each round and the file until the minimum block size is reached and a copy occurs. [Langford, 2001] This works better than standard rsync in situations where the source file has been changed in many places distributed around the file.

Rsync requires both old and new copies of a file to exist on the host system during an update. This issue has been addressed by creating an in-place rsync (ip-rsync) that uses techniques used in delta compression and Lempel-Ziv compression to move the areas of the file around. In ip-rsync file sender sends add and move commands to the destination in an order that guarantees no files will be overwritten. [Rasch and Burns, 2003]

2.1.2 Git

Git is an improvement on Rsync as it provides both version history and minimises data transfer. To keep storage simple, a copy of the whole file is stored and a reference is put into the version history. By storing old files locally operations are fast. This is also an important distinction from other version control systems and one of the reasons why Git was chosen as an example versioning system compared to other versioning systems like SVN. The systems can continue to operate without a centralised server. To reduce file duplication all files are referenced using their SHA-1 hash. This means you can be sure the contents of the file hasn't changed since you last read it. [Torvalds and Hamano, 2010]

Git also uses a 3 stage workflow. A working directory, where the current files are stored, a staging area and a .git directory. The staging area prepares your next commit and then it is finally committed. When the staging is complete the change is irreversibly stored. This is a good approach that will be adopted in the final software solution. It will allow incrementally finding changed files, and assessing the need for a new version number to be saved.

2.1.3 Bittorrent

The BitTorrent protocol is a mechanism for sharing files between swarms of hosts. As BitTorrent splits files into parts, users start sharing data even before they have received the full file. Each file has a SHA-1 identifier, similar to Git. [Qiu and Srikant, 2004]

If a user wishes to download a file from the swarm, the user downloads a metadata file from the web and locates users sharing the data using a Tracker Server, Distributed Hash Table (DHT) or Peer Exchange (PEX). [Cohen, 2008]

A Tracker server is a centralised store of all current connected users along with how much of the file they hold. This approach is vulnerable to exploitation by authorities as all of the data about a swarm is stored on a single server and as a result cannot be used for the proposed system.

A DHT contacts other known users for information instead of a centralised server. The Mainline DHT as outlined in BEP No.5 is based on the Kademlia protocol that allows for decentralised peer discovery for a particular piece of content.

PEX is a method for two clients to share a subset of their peer lists. Coupled with DHT, PEX removes a vulnerability from the Bittorrent network by allowing fully distributed bootstrapping, tracking and peer discovery.

A DHT with a form of PEX a tried and tested way of successfully mapping and finding files on a network and will be used within the proposed project.

2.1.4 Resilio

Resilio Sync is an example of a distributed file storage system that utilises the BitTorrent protocol to automatically synchronise folders between a user's systems. It is not a cloud backup solution and not intended as a form of off-site storage. There is no distributed file system and as a result, no redundant data block algorithm adding complexity. [Farina et al., 2014]

As Resilio Sync uses DHT to transfer data, there is no central authority to manage authentication or log data access attempts. This makes it difficult to determine whether a file has been accessed by another user. [Farina et al., 2014] As a result in the project the assumption will be made that everyone in the network has access to all encrypted file chunks. To access and reassemble a file, a user will be required to request all of the file chunks individually and then locally reassemble them.

2.1.5 Storj

Storj is a peer-to-peer cloud storage network which aims to allow users to store

files on a decentralised platform. The platform takes special care to provide protection against Sybil attacks and other forms of fraud. [Wilkinson et al., 2014]. To store files it stores encrypted hashed shards on the network. In order to provide proof of storage it uses Merkle Audits and pregenerated audits with hash-challenges to determine whether the client still holds the required data. By adding a seed to the hash-calculation the client can enforce the workers are still in possession of the data. It prevents the client cheating a farmer through using blockchain proof-of-existence to keep both parties honest.

The most efficient form for proof of storage is through using a deterministic heartbeat. Using Feistel permutations data can be verified with $n+2\sqrt{n}$ challenges. Erasure encoding is added to shards to detect any minor changes to the data. This is less I/O intensive than a full heartbeat, but still allows an attacker to complete heartbeats with only a data integrity of 1/n, where n is the number of nodes holding the data.

In order to add extra protection to files, we can use erasure encoding to allow file recovery if one of our shard types is lost. This can be investigated in our software, however, as the shards are expected to change on a regular basis because of versioning, this may not be possible.

To prevent Sybil based attacks, Storj encrypts each shard segment with a different salt. This stops workers completing proof of storage on behalf of another node.

2.2 Peer Admission

The first step in designing the distributed file system is locating other peers within the swarm. This is accomplished through Peer Admission. Once the first peer is found data within the swarm can be located using a DHT which guarantees content can always be found.

2.2.1 Bootstrapping

There are two types of PTP networks which must be examined:

- *Asynchronous*
- *Synchronous*

Within Synchronous networks the number of nodes on the network is constant and all of the nodes are aware of each others existence. This does not allow storage networks to scale but it does allow data to be kept private. [Saxena et al., 2003] This is the simplest and first approach that will be taken in locating nodes within Membrane.

In most current P2P systems such as Gnutella [Klingberg and Manfredi, 2002], Chord and Tapestry as well cryptocurrencies such as in Bitcoin and Litecoin a bootstrapping node is contacted, which provides information about what clients are currently online. Once a bootstrapping node allows the client to find the edge of the swarm, more information can be found using peer exchange.

Within a local network we can also use Universal Plug and Play to find other nodes within the local network. This prevents an external call to a bootstrapping node and as a result is less prone to attack.

Through looking at availability metrics within Bittorrent systems Neglia et al. [2007] determined that both trackers and DHT should be used in creating a highly available distributed storage system such as BitTorrent. DHT tends to be slower at finding new data, however it is much more reliable.

Within Membrane, I plan to use a combination of Asynchronous and Synchronous techniques. Users will try to bootstrap from their last known neighbour nodes on the network, this takes advantage of the static nature of the backup data. Only if this fails, and with the user's permission will they contact a centralised bootstrapping node. This should only happen during a first install and if the user has no referrals. Throughout the lifetime of the application the cen-

tralised bootstrapping node would ideally be replaced with a referral system.

A further extension of this, would be to allow hosts to provide a DNS name along with their IP. Users that have setup Dynamic DNS (DDNS) [Bound and Rekhter, 1997] would be able to locate each other without the help of a bootstrapping server.

2.2.2 Peer Exchange

When bootstrapping is complete new Peers can increase their knowledge of the network through Peer Exchange. This is used by Bittorrent to help share swarm information with other nodes. As soon as a client connects to the swarm, peer information is collected using DHT or PEX.

There are two common extension protocols called AZMP and LTEP, which send at most one message a minute when a client leaves or exits the swarm. To reduce congestion at most 50 peers can be added or removed in one PEX message. [Vuze, 2010]

2.2.3 Shard Discovery

Bittorrent also uses the Mainline DHT to find other hosts in the network. This is a Kademlia DHT which now according to Jones [2015], now supports 25M users. It works through assigning each node and file a 160-bit string as an ID. We can work out which node is meant to store a file metadata and crawl in the direction of the node using a hill climb algorithm. Once the metadata is stored on the host, if a host host wants to download a file, it can take the metadata on the known host to find the IP of hosts with the file.

Hosts in Membrane will store a metadata file with all of the information required for the specific account to run, including friends, encryption keys as well as local mappings for which host owns which shard and which IP belongs to each host. As a result a DHT will only be required if this initial metadata is lost and needs to be recovered. The proposed version of Membrane will make use of this metadata, but recovery can be added in further iterations of the project.

2.2.4 Dynamic IP Address

Dynamic IP addresses have proven to be problematic in distributed computing, as ISP typically charge more for users to have a static, unchanging IP. Bittorrent tackles this issue through using a DHT to dynamically find the IP address of the user that owns a file. This approach is robust, however, it is a complex solution to IP address resolution.

Another widely used approach is using Dynamic DNS (DynDNS) as described by Bound and Rekhter [1997] in RFC 2136. This allows a client to automatically update a nameserver with a new IP or other information, this allows clients to have a persistent addressing method for devices that change their location. This approach requires initial configuration by the user, however, it provides a reliable way to connect with a user when their IP is lost. There are several tools such as MintDNS, cURL and Iandyn that could be used to ease the development of a built in DynDNS. When setting up a relationship with another host, both an A/AAAA Address and CNAME could be provided, where the CNAME is a backup if the A/AAAA address does not work.

To resolve IP Address resolution within Membrane, I would like to take advantage of small-world networks. [Porter, 2012], in which the mean shortest-path between two nodes increases slowly compared to the number of notes in a network. Within a group of users in Membrane hosts are likely to share multiple first, second and third degree connections. By storing a list of IP addresses from all of the hosts. It is highly unlikely that all connections within three hops will have changed IP address. We take inspiration from ARP [Plummer, 1982], and send broadcasts with a limited hop count in the network to see if anyone is aware of the current address of a host. The downside of this approach is that it relies on a node within your social network to be on-

line. Measures will need to be put in place to reduce broadcast spam.

A broadcast storms runaway broadcast events, common in networks that used broadcasting for communication, particularly when areas of the network overlap. [Tseng et al., 2002] These can be mitigated by reducing broadcast traffic, however, Membrane will rely on broadcasts to find hosts. The first step to limiting these broadcasts, is implementing a hop count on broadcasts. This is commonly seen in routing protocols such as IPv6 [Deering, 1998]. The Spanning Tree Protocol (STP) as seen in IEEE 802.1d [Group et al., n.d.; Sharma, Gopalan, Nanda and Chiueh, 2004] provides loop-free routing in LANs by pruning redundant links. Topology changes are dealt with by rebuilding the tree.

Within Membrane rebuilding a Spanning Tree would be an expensive operation. If broadcasts become a problem a 'block request' system can be used, similar to that of ICMP redirects. [Postel et al., 1981] If a node receives a duplicate broadcast message it sends a request back one hop to not send broadcasts from that source toward it for some time. The time limit would allow allow for corrections if the network topology changes. This preventative approach and could be improved by using the full Spanning Tree implementation. As a further step it could be improved by using a DHT 'closest jump' approach if required.

2.3 Data Allocation on External Nodes

In order to store data on another node Membrane must first have permission to store files on another node. In order to make a choice we must be able to look at trust information about other nodes on the network, and negotiate and trade space once a suitable candidate has been found. These two areas have been explored in the context of Multiagent Systems (MAS) in the past. [Wooldridge, 2009]

2.3.1 Negotiation

Negotiation aims to reach a level of resource allocation that is acceptable for all involved parties. [Rahwan, 2005] It allows two or more parties that value each others service, to participate in a mutually beneficial exchange of services, however, as there are multiple beneficial outcomes it can be defined as "distributed search through a potential space of agreements" [Jennings et al., 2001] Within Membrane, this service is storage space, that is physically separated from the current user. We now take a look at negotiation and how we can build a negotiation framework that our agents can use to exchange storage.

There are three main areas that are important for negotiation. Negotiation protocols, negotiation objects and the node's reasoning models. [Beer et al., 1999] The sophistication of the negotiation is determined by each of these and can take different forms such as auctions, argumentation and protocols in the style of a contract net. The simplest negotiation uses fixed size items, which Membrane shall be initially using for this reason. More complex negotiation allows for counter offers and stronger guarantees.

A simple negotiation protocol issues a call for proposals to a number of nodes and waits for their bids. To formalise this a Agent Communication Language (ACL) such as KQML (Knowledge Query and Manipulation Language) [Finin et al., 1992] or the more modern FIPA (Foundation for Intelligent Physical Agents) [Fipa, 2002]. [Rahwan, 2005] Beer et al. [1999] tells us that within KQML the agent sending the query is expected to decide how the receiver will handle it, which places limits on negotiation. On the other hand, FIPA is newer and as a result can be more error prone.

2.3.2 Negotiation Logic

The form of negotiation within Membrane also needs to be decided. We must first decide on a reasoning mechanism to use within the agent. The distinction between

monotonic and non-monotonic logic is important in the study of AI and multiagent systems. In non-monotonic logic new axioms (or knowledge) can invalidate old theorems. [McDermott and Doyle, 1980; Antonelli, 2008] This is important in the real world as we need to be able to make assumptions on facts and retain flexibility in our understanding of the world. Within a MAS a non-monotonic logic can be more difficult to implement as theorems need to be constantly asserted, and as a result they often result to first-order (or monotonic) logic. Within Membrane we need to implement a monotonic logic to assert trust in our contracts and negotiations. In the context of a negotiated contract, throughout it's duration, we cannot effort to re-evaluate our trust of the agent.

2.3.3 Negotiation Tactics

In order to exchange storage space we must find the most suitable node in the network. There are multiple negotiation tactics between agents for collaboration and coming to an agreement. [Beer et al., 1999] We shall explore the advantages and disadvantages of game-theoretic approaches [Rosenschein and Zlotkin, 1994; Kraus, 2001; Sandholm, 2002], heuristic-based approaches [Faratin, 2000; Fatima, Wooldridge and Jennings, 2002] and argumentation-based approaches [Kraus, Sycara and Evenchik, 1998; Jennings, Parsons, Noriega and Sierra, 1998] as well as exploring practical implementations negotiation. Ideally a negotiation mechanism is computationally cheap, produces good outcomes, distributed, fair to all participants, compatible with fixed strategies and is able to function without complete information. [Rahwan, 2005]

Using a *game theory* approach we assume all agents are self-interested and allows agents to analyse optimal behaviour. [Osborne and Rubinstein, 1994] We can apply this in agent reasoning by giving each combination of collaborations a utility. Doing this an optimal set of interactions can be calculated. This can even be used to help agents interact in a certain way. [Varian, 1995]. The main downsides include the assumption of unbounded computational resources, complete knowledge of the outcome space. [Rahwan, 2005] This makes a game theory approach unusable in Membrane as the network is not fully understood by each agent.

A *heuristic* approach produces 'good enough' negotiations. Instead of exploring the full extent of possibilities they focus on the subset most likely to lead to positive interactions. In the context of Membrane, this may be hosts that you have had successful interactions with before. The downsides of this approach is that it becomes difficult to predict the negotiation actions of other agents and as the full search space is not explored the result may not be optimal. [Jennings et al., 2001]

A *argumentation* approach is beneficial when a flexible negotiation is required and the agents have limited knowledge of the world. It's commonly used in the human world by advertisers to convince humans to try products. [Slade, 2002]. Instead of simply rejecting an offer a agent can say why or offer a counter-proposal, which can result in more successful negotiations. Although this approach offers far better negotiation, it is much more complex to implement and is not required within initial implementations of Membrane.

2.3.4 Practical Negotiation

We now look at practical real-world negotiation. Real world approaches take into consideration the practical implications of reasoning systems and prove that concepts work. Within cloud computing an agent is often required to request a service. The use of these resources is based on service-level agreements (SLAs) which are designed to provide users with a service when requested. [Paletta and Herrero, 2009] One critical issue in SLAs determining the Quality of Service (QoS) constraints of the offered service.

Yan et al. [2007] explores creating a SLA negotiation system, splitting SLA negotia-

tion into three parts. Defining *Negotiation Protocol* that allows participants to send offers to each other, *Negotiation Coordination* which ensures the final result of the negotiation fulfils the QoS requirements of the agent and a *Decision Making Model* which allows the parties to decide if they are satisfied with the deal.

Within Membrane, hosts are unable to know if they will be compatible with another agent. It might be the case that they both have 50% uptime, however they are never online at the same time. As a result a system will have to be created to allow agents to find if they are compatible with each other and storage decisions will have to be based on this.

Paletta and Herrero [2009] presents an negotiation mechanism which makes use of mean algorithm and protocol, using key awareness concepts first proposed by Herrero et al. [2007]. It uses an quantitative metric in the range [0, 1] to decide how much the agent should be collaborating with another agent. The agents can then communicate using the messages:

1. REQUEST - Can you perform A?
2. CONFIRM - Yes I will do A.
3. DISCONFIRM - No I will not do A.

Collaboration decisions decided using an Artificial Neural Network (ANN). Three metrics are used, physical resource availability, if the node is available for collaboration and the number of previous collaborations of the same type. The ANN used was a Multi-Layer Perceptrons (MLPs) using one hidden layer and two units.

When evaluated the mechanism was able to deal with 93% of situations and negotiation with the first node was successful 68% of times. [Herrero et al., 2007]

Within Membrane we will aim to produce a new negotiation mechanism, built into the contract system. This should be achieved using a feedback loop, where good behaviour results in upgraded contracts, that in turn result in increased good behaviour. This is discussed further in section 4.4.2. This is a fair and cheap method of matching peers as required by Rahwan [2005].

2.3.5 Service Level Agreements

In order to create a negotiation system we need to explore what makes up an successful software SLA. Keller and Ludwig [2002] defines the WSLA framework which sets out to create a SLA based negotiation frame work. They describes 3 key areas that must be present in an SLA.

1. Parties Involved
2. Service Description
3. Obligation

Within Membrane the parties involved will always be the two nodes exchanging information. The service description will be a promise to store a block of data on another host. The obligation will include various parts such as proof of storage and the ability to update and retrieve the data a set number of times. These will be explored when the SLAs for membrane is designed.

Another key area Keller and Ludwig [2002] discusses is the 5 stages of an SLA life-cycle.

1. SLA Negotiation and Establishment
2. SLA Deployment
3. Measurement and Reporting
4. Corrective Management Actions (in case of violation)
5. SLA Termination (in case of violation)

These are the backbone of every real SLA and will be explored in more detail while designing the negotiation system for Membrane.

2.4 Trust and Reputation

Agents in a distributed system need to be able to protect themselves from 'bad' agents. Pinyol and Sabater-Mir [2013] describes three main approaches to control

the acts of agents. The *Security Approach* which guarantees the authenticity and integrity of interactions. The *Institutional approach* which relies on a central authority to enforce good behaviour and finally the *Social approach* which allows agents themselves to punish other agent for 'bad' behaviour. This final approach is where trust and reputation is used.

Trust can be used to predict the behaviour of an agent. [Wooldridge, 2009] A classification presented by Balke and Eymann [2009] defines 5 stages that exist in reputation and trust models. Co-operative behaviour is first stored and then rated using a utility function. Within Membrane it is easy to see the utility being rated as shared transaction time. This cooperative behaviour is then stored in an image of the other agent at a predetermined level of detail. This image can now be recalled to infer trust. Finally the agent can use this trust to learn and adapt it's strategy.

The ReGreT model [Sabater and Sierra, 2001] is "one of the most complete reputation and trust models" [Pinyol and Sabater-Mir, 2013] so we shall use it to see what a good trust system includes. It uses direct experience, third party information and social structures to calculate trust, reputation and credibility of another agent. An important note for this model is that trust is contextual. Agent a will trust b while certain conditions are met. In the context of Membrane, perhaps another agent will refuse to return our data, if we cannot prove that we still have their data, which would mean that they would be useless if the client experienced completed data loss. We must therefore consider simulating a situation in which complete data loss was experienced.

2.4.1 Trust and Reputation Attacks

Attempts to misrepresent reliability and manipulate reputation are common in traditional communities and have been exploited by con artists for centuries. In a distributed system agents must be able to protect themselves against common trust attacks. Jøsang and Golbeck [2009] describes 9 potential attacks on reputation systems.

- Playbooks - Gain high reputation and burn it quickly with low quality actions
- Unfair ratings - Give incorrect reputation or image
- Discrimination - Give high quality service to one set of users and low quality to another set
- Collusion - A coordinated reputation attack.
- Proliferation - Offer a service through multiple channels
- Reputation Lag Exploitation - Provide a large number of low-quality services quickly
- Reentry - Change identity to recover reputation
- Value Imbalance Exploitation - Gain reputation with easy actions
- Sybil Attack - Inflate reputation with fake accounts.

When implementing a trust system in Membrane these attacks should be considered and special attention should be paid to prevent a new user being exploited for their storage space when joining the swarm.

2.5 Communication

As Membrane is a distributed system communication is key for nodes on the network to interact. It is traditional to form a protocol that agents can use to share information with each other. These protocols are often very rigid and do not allow for expansion. Formalising communication using ACLs is a more flexible approach that aims to let agent share a common understanding of the domain, and allows hosts to reason about communication themselves. Instead of using a strict protocol we shall instead take an agent-based approach to communication using ACLs.

2.5.1 Agent Communication Language

On balance, we shall be using FIPA for communication. This is an ACL based on Speech Act Theory [Labrou et al., 1999]. It splits communication into a communicative act (CA), an ACL message structure and a set of communication protocols such as XML or OWL (Web Ontology Language). In FIPA communication should be rational, in that when sending a message:

- The sender believes the proposition.
- The recipient does not already believe the proposition.
- The recipient will believe the proposition after the proposition.

In the case of Membrane this could be put into the context of asking another node to store data, it would only be reasonable to send another node data to be stored, if the two nodes had negotiated storage of that block between them previously.

To keep communication simple for nodes, we shall use two CAs

- REQUEST
- INFORM

where *REQUEST* expects a reply of some sort and *INFORM* does not. This will enable easier implementation and can be expanded if required.

2.5.2 Ontology

An ontology is a way of defining basic terms and relations comprising the vocabulary of a topic area. Sugumaran and Storey [2002] tells us the the three most commonly used relationships in an ontology are *is-a*, *synonym* and *related-to* (which is a generic association between entities). So why should we create an ontology for membrane? Noy et al. [2001] lists the benefits of ontology within distributed systems:

- Enable common understanding of the structure of information
- Enable reuse of domain knowledge
- Make domain assumptions explicit
- Separate domain and operational knowledge
- Analyse domain knowledge

Within Membrane we may benefit from an ontology during negotiation for storage space. Obligations could be predefined between agents and an agent could request a set of obligations, instead of explaining an obligation during negotiation. This allows agents to be more concise and expressive.

2.6 Peer-to-Peer Connection

Network Address Translation (NAT), defined in RFC 2663 by Srisuresh and Holdrege [1999] is used extensively to solve the IP exhaustion problem, however, it also creates a lot of well documented problems for peer-to-peer communication as the IP address a hosts has set, may be a private and only useful for peers on the same network. Multiple Membrane hosts may be using the same IP address and the TCP listening port used by a node will change between connections. In order to transfer data over NAT a NAT-Traversal Technique must be employed. There are four major techniques described by Ford et al. [2005] that we shall explore.

Relaying is a method of communicating through a well known server, that has a static IP address and port. This has the advantage of being simple, however, it has the disadvantage of using the server's processing power, network bandwidth and increases latency between peers. It is a good fallback strategy but also requires both clients to initiate the connection, which makes listening for incoming connections difficult. The TURN protocol [Rosenberg et al., 2005] describes a fairly secure method for relaying.

Connection Reversal is the use of an external server to request a 'call back' to a host. The connecting host contacts an external

server with a target host and leaves it's public IP and port. The relaying host can then choose to send a request to host behind NAT and the host behind NAT can choose to forward the request. It has similar limitations to relaying, however, it is easy to imagine an implementation that uses connection reversal for bootstrapping a P2P connection.

UDP Hole Punching is a technique defined in RFC 3027 5.1 [Holdrege and Srisuresh, 2001] that allows two clients behind NAT to connect with the use of a rendezvous (RV) server. Hosts contact the RV and leave their UDP port and address. You should be weary of poor NAT implementations translating IP addresses within data when packets are coming in and out. [Ford et al., 2005] When clients are both behind the same NAT, packets between them do not need to go through NAT. If Hairpin NAT is correctly configured they will be bounced back within the internal network, however, it could result in overheads otherwise. If this problem is detected during the implementation of Membrane private IP address could also be sent to the RV server. It's important to consider that the ports behind a NAT are dynamically allocated, so connections must be authenticated between connections, to ensure the IP address and port still direct towards the same host. The initial outbound packet from a host to a the RV server is key in 'punching a hole' through the NAT. The timeout of a hole punched port can be as low as 20 seconds, so the host must maintain the hole by sending single packets to the RV on a regular basis.

TCP Hole Punching is more complex than with UDP as clients need to establish sessions across the NAT. For hole punching to work the same port needs to be used for listening and establishing a connection. This can be done using *SO_REUSEPORT* option, which allows an application to claim multiple sockets from the same endpoint. Within the application an new port needs to used for handling the connection.

There are two practical solutions that I shall explore for implementation within Membrane. TURN [Wing et al., 2010] provides a set of methods for NAT hole punching. UPnP [Boucadair et al., 2013] is a method through which a host can request a NAT gateways to open a port for the application. There have been security concerns with UPnP which has resulted in UPnP being disabled on many routers. This will need to be explored during implementation of Membrane.

2.7 Distributed File System

Membrane shards files and stores copies on multiple nodes for redundancy. This is a technique that is commonly found in distributed file systems (DFS) such as Hadoop File System (HDFS) [Shvachko et al., 2010], Google File System (GFS) [Ghemawat et al., 2003] and Parallel Virtual File System (PVFS) [Ross et al., 2000]. This section aims to explore the reasoning and decisions taken with these file systems.

HDFS has proved to be highly successful in storing large quantities of data over thousands of nodes and is used by over 100 organisations world wide. It stores file system metadata on a central dedicated server called a NameNode [Shvachko et al., 2010]. This is a similar approach to GFS [McKusick and Quinlan, 2010]. Membrane takes this approach by storing file metadata on the client. Ceph takes this approach further, storing file meta on a distributed cluster of NameNodes, using hash function to spread metadata over the name nodes. [Weil et al., 2006] This allows for larger, more distributed system, this could be used within Membrane if meta-data proves too large to store on the client.

Files and directories are represented my inodes, these record attributes such as permissions and location. Within Membrane this will need to store information such as checksums, encryption keys and SLA for each file, to allow each file to be verified on a regular basis. When writing data to the cluster the NameNode chooses the targets for shards. The client in Membrane will be able to negotiate shard targets on the network using

mechanisms described previously.

The NameNode stores the metadata as a combination of a checkpoint and journal (a write-ahead commit log). If there is a fault on the NameNode, such as a power outage, the journal can be replayed over the latest checkpoint. In HDFS a new snapshot is created during a node restart, however, in Membrane the journal is kept to be able to restore the metadata during any point in the journal. By not removing any shard that is still in the journal we are able to rollback to any previous state in ahead of the oldest checkpoint.

In HDFS, during startup a DataNode connects to a NameNode, and performs a handshake with a unique storage ID that can identify it. In addition a DataNode will also send heartbeats and reports on a regular basis. Shvachko et al. [2010] This is a great approach as it makes the DataNode responsible for notifying the NameNode that it still holds the data. Not the other way around. A similar approach will be used in Membrane, however, the NameNode will also request some proof that the DataNode still holds the file, as in Storj.

In both GFS and HDFS data is streamed directly from the client to the DataNode in 64k chunks and a checksum is sent with the original file to assert the transfer was successful. Both systems also have a default of 3 replicas per shard, which Membrane shall adopt. TCP is used for communication as it provides reliability and a session for transfers. Chunks are given a 64bit chunk handle. Membrane will use a hash to compute this identifier. This should help nodes prevent attackers predicting a chunk handle.

2.8 Authentication and Encryption

In order to maintain a relationship a host needs to be able to verify it's identity when it connects to a host a second time. When visiting a website there is often a need to map a virtual identity to a real identity of a service user [Hericourt and Le Pennec, 2001] a bank for example, this is typically done using a certificate authority. Membrane requires authentication in two situations:

- Is this the same node I was talking to before?
- Have I found the correct node when adding a friend?

Session authentication is a common occurrence while using the web and it typically happens with every HTTPS site visit. A session cookie is stored on both clients to allow for authorisation and authentication without the use of a password in further interaction. [Mayo et al., 2008]

SSL/TLS, defined in RFC 5246 [Dierks, 2008] is often used for this authentication. It uses asymmetric public-key cryptography for initial connection, which uses a separate key is used for encryption and decryption. A client generates a public SSL certificate that it sends for any users that want to communicate with it. They encrypt their communication with it, and the server can decrypt it. This is called a SSL Handshake.

1. Server sends the client it's asymmetric public keys
2. Client creates a symmetric session key and encrypts it using the public key.
3. Server decrypts the encrypted session keys
4. Client and Server can now communicate using the symmetric key.

The client can ensure it is talking to the same server by ensuring the public key is the same. RSA is the commonly used algorithm for this.

Pre-shared key encryption uses algorithms like Twofish, AES or Blowfish to create keys. These come in two flavours; stream ciphers and block ciphers. Stream ciphers encrypt binary digit by binary digit in a stream, and block ciphers encrypt a block of data at a time. We shall be using pre-shared key encryption to encrypt data blocks using a password saved on the host, that never un-

der any circumstances leaves the Membrane host.

Studies have shown that Twofish (and Blowfish which it is derived from) has the best performance and has no know security flaws. AES showed poorest performance. [Thakur and Kumar, 2011; Rizvi, Hussain and Wadhwa, 2011; Mushtaque, Dhiman, Hussain and Maheshwari, 2014] An interview with the creator of Blowfish suggested "I'm amazed it's still being used. If people ask, I recommend Twofish instead." Schneier [2007].

2.9 Compression

Several compression algorithms were considered for Membrane. There are two important considerations for the compression algorithm selected.

- Compression Speed - How fast can data be encrypted
- Compression Ratio - How much can the file size be reduced

Three algorithms were considered: gzip (DEFLATE), LZ4 and Snappy.

gzip is a popular file format that uses *DEFLATE* for compression internally. DEFLATE relies a combination of LZ77[1] and Huffman coding[2]was developed by Deutsch [1996]. It is extensively used for compression and packaging in the Linux ecosystem, accessible via the *tar* utility and also notably used in the PNG image format and for HTTP compression.

LZ4 is an evolution of DEFLATE and belongs in the LZ77 family of compression algorithms. It gives worse compression than gzip, however, benefits from faster compression and significantly faster decompression. [Legesse, 2014] As a result it has been adopted in file system such as ZFS for real time data compression. This makes LZ4 far more appropriate for Membrane than gzip, as low resource usage is a key requirement.

Snappy is a compression algorithm used by Google for data compression it was developed to improve on the speed of DEFLATE and offers excellent compression and decompression speeds. [Google, 2017*b*]

When benchmarked against LZ4, Snappy is marginally slower [Vorontsov, 2015], however, it provides a native Java implementation. We therefore give users the option between Snappy and LZ4 compression, although we default to LZ4 due to it's superior speed and compression ratio. [LZ4, 2017]

2.10 Provable Data Possession (PDP)

A Membrane client needs a method to ensure the storage host still holds the data it says it has. To prevent Sybil attacks where agents collude to store a shard between each other, a shard will be salted before encryption and transfer. This has proven effective in Storj [Wilkinson et al., 2014].

In order to determine consistency of what the storage agent has stored a mix of different hash verification is used.

- Full Heartbeat - Expensive and complete
- Cyclic Check - This checks a sections of the file in sequence, wrapping to the start when the end is reached. Cheap but could be exposed to attacks if the storage agent wants to remove part of the file over time.
- Deterministic - Audits shards in a deterministic order known only to the client. This stops the storage agent being able to predict the next shard.

To stop the client pregenerating hashes the shard or shard chunk is seeded before hashing.

filecoin.io [2014] is another cryptocurrency operated file storage network. Transactions

[1] Lossless data compression algorithm published by Ziv and Lempel [1977].

[2] An optimal prefix (string deduplication) code used for lossless data compression developed by Huffman [1952].,

are stored in a ledger to assist with trust. At any point a client can issues a challenge to the server to clients who must the calculate the corresponding proof. These challenges are then confirmed by another node on the network who takes the file and recomputes the challenge itself.

2.10.1 Keyed-Hash Message Authentication Code (HMAC)

Using HMACs is a valid way of PDP [Ateniese et al., 2011].

HMACs combine data with a key and generate a unique hash, using of a cryptographic function. [Krawczyk et al., 1997] The following formula is used for computing this:

$$\text{HMAC}(K, m) = H((L \oplus \text{o}) \parallel H((L \oplus \text{i}) \parallel m))$$

where H is the cryptographic function, K is the secret key, m is the message to be authenticated and L is a secret key padded to the correct length, o is outer padding and i is inner padding.

These are typically used to verify data integrity and authenticate messages. The strength of the cryptographic hash function depends on the underlying hash function used.

A HMAC is used to counter attacks on trivial mechanisms of combining a key with a hash function.

$$MAC(K, m) = H(K \parallel m)$$

suffers for length extension attacks where the attacker can append data to the message and calculate a new hash.

$$MAC(K, m) = H(m \parallel k)$$

allows an attacker to find a collision in the unkeyed hash function and use it in the MAC.

$$MAC(K, m) = H(K \parallel m \parallel K)$$

offers better protection but there have been several papers claiming this can been exploitable. [Bellare et al., 1996]

Within Membrane we build HMAC challenges when deploying a block to allow for proof-of-ownership

2.11 Conclusion

In this literature review we discussed the key important areas of creating a distributed storage system.

We first explored the history of the problem by looking at solutions like Git. We saw how to exchange file and swarm information in distributed systems including BitTorrent and studied file storage systems such as Resilio and Storj that achieved distributed file storage.

Then we moved onto different challenges in creating the system, namely Peer Admission, Data Allocation, Communication and the challenges of connecting to other peers. We looked at the lessons learnt from distributed files systems and the challenges of authentication and proving ownership of a file.

Drawing on techniques explored in the literature review we will proceed to design Membrane, avoiding the pitfalls discovered by predecessors.

Chapter 3

Analysis

As Membrane is primarily an application built for home users the first step of analysis is querying potential users about what features they would like to see. This is proceeded by looking at what features existing solutions provide to create a Minimum Feature Set which, with the user requests taken into consideration, we will formally describe as software requirements. From this feature set we are able to create a development plan and explore helpful technologies that we will be able to reuse during product development. Finally we describe a target architecture for Membrane.

3.1 User Survey

In order to gather relevant user opinions we first decide at who the target user for Membrane is. Although the final product is for as wide a range of users as possible, initial versions may be a bit more difficult to use, as bugs are ironed out and features are added. We focus on those early visionary users that will be able to provide constructive and informed feedback during the early life of Membrane.

To narrow the search, we will target Linux users, who will be more accustomed to manually installing software and debugging potential issues. To gather feedback we used an online survey. These are typically answered by more technical users, have a short response time and require minimal financial resource allocation [Ilieva et al., 2002]. Eight participants were selected and asked to describe five key features they would like to see in the proposed distributed backup system.

We gathered all of the requested features and placed the most popular into five categories that we will look to implement in the first version of Membrane:

- Data Security
- File Versioning
- Maintenance Free
- Fast Recovery
- Lightweight

The most important request by survey participants is *data security*. The concerns focused on how Membrane will ensure files stored on another user's computer are guaranteed to be inaccessible to the host user. Special care will need to be taken while showcasing Membrane to address this.

File versioning is seen as a key feature. Users want to be able to recover files that have been deleted or changed accidentally. This is expected many of the survey participants are accustomed to file versioning software such as Git. This poses a storage space challenge, as files that change frequently will take up valuable space.

Users also requested that after the first setup Membrane would act transparently, with *no need for re-configuration* unless a change in functionality is required. During design we will aim to provide flexible configuration options, that will be able to gracefully recover from failure.

An unexpected feature requested is *fast recovery*. Users expressed concern about the amount of time that will be required to access files stored on the swarm. This is an interesting challenge as it is difficult to guar-

antee that users storing data will be online at any given point in time.

The final key request by potential users is that Membrane should not interfere with normal computer usage by the user, particularly processor time, memory and network utilisation. The request is particularly common among gamers who do not want to experience any slow-down to their games during backup.

We will focus on these five requests in the next steps of our analysis, however, more categorised requests can be found in the appendix in listing 7.5. Given enough time we will explore more of these once the minimum viable product is created.

3.2 Common Features

Following the user survey we will look at popular features of existing solutions. In order to discover what features users are looking for we will explore features used to differentiate backup software in comparisons. The archlinux.org [2017] wiki has a comprehensive list of available backup options and uses a feature table to allow readers to quickly determine which solution is best suited to them.

We will try to explore all of these features, and incorporate feasible features into the Minimum Viable Product for Membrane.

Compressed Storage for files. The type and style of compression used. Within software this is not a difficult feature to add as there are many compression libraries. Implementing compression will reduce the amount of bandwidth Membrane uses during operation.

Storage Encryption is extremely important in Membrane as discovered during the user survey. We will need to look into potential encryption options in-depth while designing Membrane and ensure that there is no chance of a data leak.

Delta Transfer only transfers the modified part of the file if there is a change. This is important for users as it limits bandwidth and storage requirements. Within Membrane we will need to implement this as multiple copies of any stored data need to be transfered to peers.

Encrypted Transfer checks if the data is transferred over a secure connection. This is less important for Membrane as files are encrypted for storage, however, an encrypted transfer would prevent a third party being able to see the interaction between two Membrane peers.

File system meta-data can be stored with the data so it is restored along with the file. This could be implemented in Membrane, however, as this wasn't requested by users and does not help demonstrate the advantages of peer-to-peer storage it will not be added to the Minimum Viable Product.

Easy access to files is an important feature in backup systems, however, as the MVP of Membrane seeks to show peer-to-peer backup instead of a perfect backup system, we will add this feature to future work.

Resumable Backup is very important in Membrane. If a connection to a peer is lost Membrane needs to be able to resume the backup with other peers.

Another vital feature in Membrane is the ability to *handles renames*. If a file is moved or renamed, the software needs to be able to detect this to reduce data duplication.

Users searching for backup solutions were also very interested in the software's *interface*. This needs to work well and be suited to the user. Within Membrane we will be looking to implement a fully featured *command line interface* (CLI) for configuration, as well as a *graphical user interface* (GUI) for backup monitoring. This is common in most of the featured backup solutions, so to remain competitive these need to be implemented.

The comparisons also covered platforms supported by the backup solutions. An interesting observation is that although multi-platform support has clear benefits, many of the backup solutions covered only supported

one or two of the available platforms. This will be taken into consideration while creating the formal specification for Membrane.

Finally users were also interested in the *software licence*, with an emphasis on how open-source the code for the backup solution is.

We can see there is an overlap between the features requested by users during the initial survey and what users in need of a backup solutions use to determine which software is best for them.

3.3 Requirements

In the requirements we will formalise the aforementioned research into goals to be completed during development. These requirements will be able help with planning development and designing an architecture for Membrane.

We will begin with functional requirements which describe technical features within the desired system, allow us to evaluate it's behaviour and will aid in its design by ensuring key features of interest are present [Van Lamsweerde, 2009] followed by Non-Functional Requirements which help support functional requirements Chung et al. [2012].

There is some debate about the usefulness of software requirements Kneuper [1997], so the requirements below will be kept brief, however, they will be able to help guide the software development goals and produce targets for development stages.

3.3.1 Functional Requirements

Functional requirements describe components found within software and their function; inputs, the behaviour, and outputs. These requirements consist of name and number, a brief summary, and a rationale. It's important to ensure the requirements are clear to prevent misinterpretation.

1. File System Monitoring

The system must be able to be given the name of one or more folders, and monitor all the files for changes in those folders. Another module must be able to subscribe to a stream of these changes for further processing of the modified files. The system should make use of preexisting file system features for monitoring if available.

This is core to the backup system. It cannot function without this.

2. Sharding Module

The module must be able to receive the path of a file and determine whether the file has changed since the last read. If a change, addition or deletion is confirmed this update must be sent to any subscribers for further processing. Individual file chunks for the modified file (if any exist) must be sent to any subscribers to be persisted. Updates for preexisting or suppressed files must be suppressed. On launch the system must be able to receive a list of files already stored by the system for suppression.

This strategy limits resource usage and allows for deduplication of the backups, saving storage space. Sharding also allows for better packing for the distributed modules.

3. File History

Must be able to keep a log of file system modifications. It must be able to remove entries from the log to match storage requirements by analysing the storage requirements for storing the entire history and selectively removing elements of the history to meet requirements. The history must be immediately persisted, so an application crash does not affect the operation.

This needs to be done to match the request in the user survey to store file history. In addition this will allow for delta transfers as files can be compared between versions.

3. Shard Storage

Must be able to persist and fetch requested shards to a given folder. It must perform consistency checks on retrieval and support hard limits on total storage size. Finally it must be able to return a complete listing of all shards inside the storage unit.

This is a key feature of the backup system as it persists shards, which can then be assembled into files.

4. NAT Traversal

Must be able to establish a secure TCP connection when two peers are behind a NAT Gateway. The suggested mechanism is to use UPnP Port Forwarding offered and enabled on most routers. In future iterations consider using TCP Hole Punching. This must be able to temporarily forward and maintain a port on the target router. If a port is taken another open port should be used. The system must also be able to return the external IP address.

This is required to allow two users who wish to use each others external storage, who are both behind a NAT Gateway wish to connect. It is a common feature of distributed storage such as BitTorrent

5. Authentication

Must be able to generate, persist and reload a public private key pair and X509 self-signed certificate used for establishing secure SSL connections. These details must be used throughout the application lifetime and will act as a unique identifier for the user.

This is required to allow users to create accounts on the distributed network.

6. Peer Connection

Must be able to establish a secure connection to a given an IP and port. When this connection is established the user must be authenticated using their provided SSL certificate public key. This must be converted into a unique user identifier. All messages from the peer must contain this unique identifier or they should be dropped.

This module forms the core of the connectivity in Membrane allowing users to dial each other.

7. Peer Exchange (PEX)

Must be able to send and receive connection information about yourself and other peers. Peer information about yourself needs to be signed with a time stamp for future verification. Incoming verification about specific peers needs to be verified. Needs to support peer discovery, finding peers that have never been contacted before.

This is done to allow peers to find each other if they have changed external IP address or port and to allow new peer discovery.

8. Connection Management

Given a target user count, maximum connection count and whether new users should be found, should dial known contracted peers on a regular basis, request PEX information for connected peers and send up-to-date PEX information to connected peers. Should connect to trackers if peer target has not been reached in time.

This module is responsible for providing live connections to peers that can be contracted and have data blocks sent to them.

9. Shard Distributing

Given a list of local shards and file history, needs to be able to package appropriate shards into blocks and send them to peers, depending on which peer is most suitable for storing the shards. Needs to send contract updates on a regular basis and respond to and issue proof of ownership requests for blocks to and from peers. Needs to be able to remove peers that are not worthwhile.

This is a core module connecting the local backup to the network module and required for distributed backup.

9.1 Distribution Storage

Must be able to store information about generated blocks, which blocks are given to which peers and what blocks have been provided by what peer. This includes any proof-of-ownership verification information that may be required in the future, shard contents and block unique identifier. The module must be able to persist this information and load it from disk.

This is a core module required for (9.0) to verify module information and compute which shards should be given to which connected peer.

9.2 Block Encryption

Any blocks of data sent to peers must be encrypted using TwoFish encryption using the private modulo used for network SSL connection.

This is required for data security requested by potential users during the Analysis survey.

9.3 Peer Appraisal

Peer interactions must be logged at a resolution of one hour for rating peers. Given the number of expected shards, all of the shards that have been proven to be held by the peer and any lost shards this must produce a single number between 0.0 and 1.0 rating the peer to allow for comparison.

This is required for selecting which peer is most appropriate for upload.

10. Proof of Ownership

A system that can determine whether a peer is holding a block is required. The suggested method is a mixture of salted hashing and asking for the entire block to be returned.

This needs to be done to determine whether the given peer is holding a block without having to request all of the data every time.

11. Tracker

Membrane needs to be able to run in tracker mode, in which the backup backup is disabled but peer exchange is active for other hosts to share PEX information through the tracker.

This is required for new peers, or peers that have expired PEX information.

12. Command Line Interface

A fully featured CLI needs to be present. It must allow users to monitor network activity and their backups, as well as adding other folders to backup and recovering files.

This feature is required to allow users to interact with Membrane.

13. Graphical User Interface

A GUI needs to be present to give users the ability to monitor membrane activity.

This feature was common in existing solutions and is required for Membrane to be competitive.

3.3.2 Non-Functional Requirements

Non-functional requirements, also aptly named quality requirements help support the functional requirements described above. These can be grouped into two broad categories:

- Execution Qualities - Those observable at run time including security and usability.
- Evolution Qualities - Those found in the structure of the system including extensiblity, scalability, maintainability and testing.

13. Maintenance Free

The software must be able to run without external monitoring or reconfiguration. The user cannot be asked to solve any non-configuration related issues. For example, if

a peer loses all of our blocks, the software should be able to recover without any user intervention.

This was requested by users during the analysis survey.

14. Fast Recovery

The software must be able to recover files quickly after data loss.

This was requested by users during the analysis survey.

15. Resource Usage

Membrane's resource usage must be as low as possible to minimise impact on other software running on the system.

This was requested by users during the analysis survey.

16. Open Source

The implementation must be fully open source. No closed source libraries can be used during development.

This feature will help with adoption as Membrane will be marked as open source in backup utility comparison charts. This will help to gain the trust of potential users.

17. Extensiblity/Transparency

The project should be built to allow for easy contribution from other open source programmers.

This will help with community engagement in the product. More technical users will be able to add their own features, which they will be able to push back into the main code base.

18. Testability

The project should be built with extensive tests asserting the behaviour. Tests should be automated to assist with requirement 16. It will allow easy verification of the behaviour of the modification.

3.4 Use Cases

A use case defines a set of goal-oriented interactions between a user and the system. Actors are any external parties that interact with the system [Malan and Bredemeyer, 2001]. Cockburn [1997] tells us use cases can have multiple forms and purposes.

We opt to use the scenarios below to help strengthen the requirements, with the purpose of helping developers check if the software is able to perform the use cases.

As with the requirements, we keep the use-case brief, as we expect they may change during development as better approaches to problems are found.

3.4.1 Add Watch Folder

The expected behaviour of Membrane during a normal backup operation when a new folder is added. The computer owner is primary actor.

Goal

Store redundant copies of files on the system

Steps

1. User adds folder for backup with files.
2. Folder is persisted to the configuration file.
3. New files in folder are detected.
4. Files are sharded into equal chunks and sent to shard storage.
5. The change is logged and saved in the file's history.

Extensions

1. Submitted folder does not exist:
   (a) Accept entry and wait until it does.
2. Cannot persist watch folder due to IO error
   (a) Inform the user
   (b) Do not continue
3. Shard storage full:
   (a) Do not log the change in file history.
   (b) Shorten the history until soft limit is reached.
   (c) Retry submission later.
4. Cannot log change in file history:
   (a) Leave new shards.
   (b) Retry submission later.

Variations

1. Folder is file:
   (a) continue and wait until file becomes a folder
2. File present in multiple watch folders:
   (a) De-duplicate file by sharding
   (b) log changes from both folders if path different

3.4.2 Watched File Modified

The expected behaviour of Membrane when a watched file is modified. The computer users are the primary actor.

Goal

Store a copy of the modified file in shard storage

Steps

1. User modifies files in watch folder.
2. During next scan file change is observed.
3. Assert if file modification time has changed.
4. File is sharded.
5. File shards are hashed to check for similarities.
6. Assert at least one shard has changed.
7. Chunks and sent to shard storage.
8. The change is logged and saved in the file's history.

Extensions

1. Modification time has not changed:
   (a) Ignore change
2. None of the file shards have changed:
   (a) Ignore change

3. Shard storage full:
   (a) Do not log the change in file history.
   (b) Shorten the history until soft limit is reached.
   (c) Retry submission later.
4. Cannot log change in file history:
   (a) Leave new shards.
   (b) Retry submission later.
5. File cannot be read:
   (a) Retry later.

Variations

1. File renamed:
   (a) De-duplicate file by sharding
   (b) Log as different files.

3.4.3 Remove Watch Folder

The expected behaviour of Membrane during a normal backup operation when watch folder is removed. The computer owner is primary actor.

Goal

Stop watching the provided folder

Steps

1. User removes folder for backup with files.
2. Removal is persisted to the configuration file.
3. Any queued modified files are removed.
4. Stop scanning for changes in folder.

Extensions

1. Submitted folder is not watched:
   (a) Report user error to user.
2. Cannot persist watch folder due to IO error
   (a) Inform the user
   (b) Do not continue
3. Files from folder persisted
   (a) Do not remove file history.

Variations

1. Folder is file:
   (a) treat as folder

3.4.4 Recover File

The expected behaviour of Membrane when user tries to recover a file. The computer owner is primary actor.

Goal

Recover a file into a new location

Steps

1. User asks to recover a file to a given location.
2. File log checks for most recent version of file.
3. File shards read and reassembled.
4. File written to target destination.

Extensions

1. File never saved to Membrane:
   (a) Report user error to user.
2. File deletion most recently recorded in Membrane:
   (a) Report user error to user.
3. Shards cannot be retrieved or not present
   (a) Inform the user
4. Target destination already has file in it
   (a) Do not overwrite
   (b) Report error to user

Variations

1. Given file is a folder:
   (a) Report error. Only accept files.

3.4.5 Recover Old File Version

The expected behaviour of Membrane when user tries to recover a previous version of a file. The computer owner is primary actor.

Goal

Recover a previous version of a file into a new location

Steps

1. User requests for all available versions of file.
2. Show users all known
3. User asks to recover the version of the file at a specific point in time to a given location.
4. File log checks for most recent version of file.
5. File shards read and reassembled.
6. File written to target destination.

Extensions

1. File never saved to Membrane:
   (a) Inform user no versions exist.
2. File deleted in period of time user requested:
   (a) Inform the user.
3. Shards cannot be retrieved or not present
   (a) Inform the user
4. Target destination already has file in it
   (a) Do not overwrite
   (b) Report error to user

Variations

1. Given file is a folder:
   (a) Report error. Only accept files.

3.4.6 Peer Connects

The expected behaviour of Membrane when a peer connects and wants to exchange storage. The peer should be given one free block to allow them to start storing data.

Goal

Establish a new storage contract with peer if required.

Steps

1. Peer connects.
2. Peer identity is verified.
3. If contracts are required.
4. Peer certificate is persisted
5. Peer is given to the contract manager.
6. Contract Manager gives the peer one new shard of storage.
7. Contract Manager sends a Contract Update to the Peer.

Extensions

1. Peer already contracted:
   (a) Proceed whether or not contract is required.
2. Peer identity verification fails:
   (a) Drop connection.
3. No contracts required
   (a) Keep connected
   (b) Do not contract
   (c) Do not persist certificate
4. Disconnects before contract update can be sent
   (a) Keep contracted
   (b) If peer does not provide you with one contract inequality before shutdown remove them.

Variations

1. Peer is a tracker:
   (a) Do not contract them.

3.4.7 Peer Sends Contract Update

The expected behaviour of Membrane when a peer sends a contract update. The peer should be provided with proof-of-ownership instructions for any owned blocks they have not authenticated this hour.

Goal

Provide peer with proof-of-ownership instructions.

Steps

1. Verified Peer sends Contract Update

2. Remove any blocks we thought the peer had but they have lost. Note these down in the appraisal.
3. Request any unexpected blocks (We may have lost information about them on our side)
4. Request deletion of any expired blocks which we cannot assert ownership of.
5. Request salted hash for any blocks they have not confirmed yet this hour. Include salt.
6. Record that peer has been in contact this hour.
7. Send requests back to peer.

Extensions

1. Peer not contracted:
   (a) All blocks will be unexpected.
   (b) Request all of the blocks. They might have been lost during a data loss incident.
   (c) Blocks will be deleted on the next request.

3.4.8 Peer Sends Proof of Ownership

The expected behaviour of Membrane when a peer sends a proof of ownership response. Any successful responses should be noted down for the peer.

Goal

Check ownership details for the peer and record them in appraisal if successful.

Steps

1. Verified Peer sends Proof of Ownership Response
2. Process any full blocks returned, adding missing shards.
3. Check salted hash was correct.
4. Add correctly confirmed or returned blocks to peer appraisal.

Extensions

1. Peer not contracted:
   (a) Ignore any salted hashes

Variations

1. Full block returned as response:
   (a) Decrypt the block
   (b) Decompress any compress shards in the block
   (c) Place shards in local shard store
   (d) Place any file history in the block into the file history store.

3.4.9 Distribute Shard

The expected behaviour when a shard is stored in local backup. The shard should be packaged with other similar shards into a block, and sent to a peer offering storage space.

Goal

Deploy shard to peers.

Steps

1. Shard is placed into local shard storage.
2. Distributor performs periodic local shard storage scan and finds shard.
3. Connected peers are ranked from best to worst.
4. Any peers with a rating $< 1.5\sigma$ are ignored and the contracts are cancelled.
5. Shards not yet sent to each peer are collected.
6. Shards are compressed and placed into a block until the block reaches a predetermined size.
7. The history of any files associated with the shards is placed into the block.
8. The block is encrypted.
9. The block is sent to the peer.
10. The peer sends a contract update on receipt.

Extensions

1. No contracted peers connected:
   (a) Wait for new contract or contracted peer to connect.
   (b) Retry.

2. Shard is missing from local shard storage during read:
   (a) Log the error and skip the shard during this pass.
   (b) Retry.
3. No shards fit into the block:
   (a) Log the error and move onto the next peer.
   (b) Continue as normal.
4. Shard compression is unsuccessful:
   (a) Place the shard into the block with the compression flag disabled.
   (b) Continue as normal.

Variations

1. Block does not arrive at peer:
   (a) Mark loss of block on peer appraisal.
   (b) Mark incomplete hourly report on peer appraisal.
   (c) Remove block from local contract.

3.5 Architecture

Before deciding on the technology stack used in Membrane we must consider the application architecture.

Although Membrane is a peer-to-peer network application, which is distinctive from a client server application, because peers act as a *Servent*[1], we can still make use of recent developments in client server architectures, in particular the arrival of widespread adoption of Representational State Transfer (REST)ful Web services [Rodriguez, 2008], and the tooling that the popularity has generated.

3.5.1 Structure

The first major decision in the application structure is whether the GUI and CLI will be built directly into the application or if Membrane will expose an API for interaction. To prevent coupling and enable software reuse within the application [Gamma, 1995] we will use a 3.1 or the more general n-tier architecture components of the application.

There are clear advantages to both a built in user interface and the server client architecture seen in figure 3.2 which we shall explore before selecting technologies to use.

Native Interface vs. Client Interface

A native application interface is popular among server software and frequently used for desktop applications such as Microsoft Word and Microsoft PowerPoint, however, there has recently been a shift back to using a client, running back-end services in the cloud, exposing an API which can then be interacted with client side applications.

A separate client interface has multiple advantages and with modern networking speeds a user is typically unable to distinguish between running the interface on the server or a thin remote client [Schmidt et al., 1999].

The user is given the flexibility of using their preferred client to interface with the application, switching client without needing to worry about losing data, and developers are given the option to design a new interface without affecting the core application.

The user is also given the ability to interact with multiple instances of the application running remotely with no issues, which is particularly useful when running the application on a headless server.

Development of both the client and interface can also happen in parallel leading to better time to market in large development teams.

However, we must not forget the benefits of using a native application. By making the UI interface with the application over the network, a whole host of complexity and security issues arise. The development team needs to ensure that any user interacting with the API is authenticated and secure, as well as ensuring that there are no network issues between the interface and application.

The software itself also becomes more complex with a separate client as functionality needs to be built for handling network in

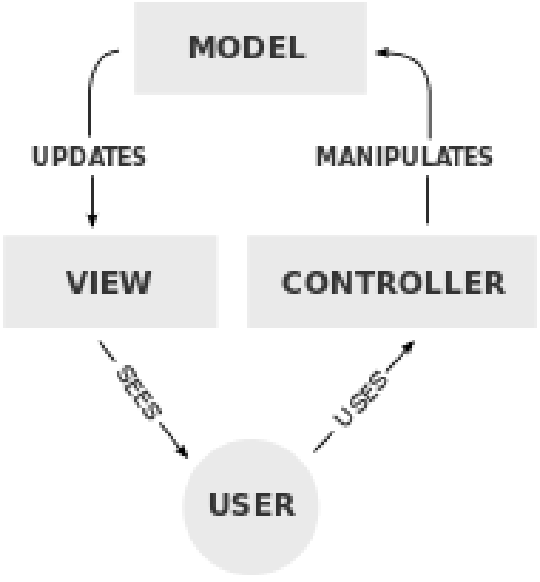

Figure 3.1: Model View Controller

[1] A term coined by Schollmeier [2001] to describe a peer acting as both a Client and Server

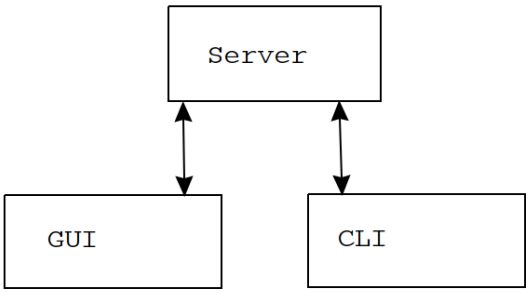

Figure 3.2: Client Server Architecture

both the UI and core application.

On balance, it makes sense for membrane to operate use a client interface. As Membrane will need to be run constantly, it needs to be able to operate as a software daemon. One of the requirements is to keep Membrane lightweight and maintenance free, running any user interface constantly would distract users.

Developers will also be able to build addition interfaces to Membrane if required, fulfilling the extensiblity requirement, and as both a GUI and CLI are required, this provides a nice way to develop both and gives users the desired flexibility between both.

Model View Controller (MVC)

The Model View Controller (MVC) pattern, first described by Krasner and Pope [1988], decouples the interface from the main logic of the program by establishing a subscribe notify protocol between them. The view must always reflect the state of the model and the model must always update the view when a change occurs.

This approach allows for code-reuse and lets the developer to create new models without rewriting the software, and provides high cohesion, meaning groups of related actions can be grouped together.

This has the disadvantage of making code harder to navigate due to added structural complexity, increasing scattering meaning multiple representations of objects need to be modified at the same time if required and increases the learning curve for developers, as they need to learn how to structure the application in a new way.

Although the MVC model provides a structurally sound way of building the application we need to generalise in into the N-Tier architecture for larger applications.

N-Tier Architecture

An N-Tier architecture is simply an extension of the MVC model, it takes the idea of layers in an application further, allowing sections of the software to be developed and tested without interfering with each other.

One of the key advantages to this approach is extra layers can be added and removed, even during run time. In Membrane we will look to take advantage of this when running in Tracker or Local Backup mode. The tracker can disable all of the local backup functionality, while the tracker only needs to run the network layer.

We can see the Membrane N-Tier architecture in fig 3.3. Only modules next to each other are able to communicate directly and modules can be disabled as required.

The local backup performs all the basic tasks of file monitoring and local shard storage. The distributor monitors the local

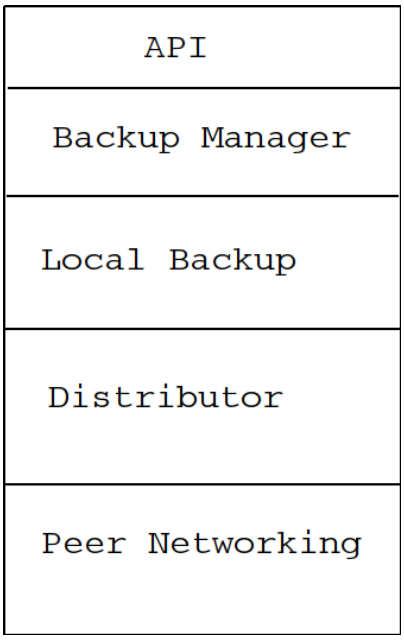

Figure 3.3: Membrane N-Tier Architecture

backup for shards to send to peers and packages them up to the Peer Networking layer for transmission. The Peer Networking layer is able to locate new peers and provides them to the Distributor if connected.

3.6 Technologies

The technologies used in a project can define the success of a software project. Incorrectly chosen tools can slow development and in some cases even cause projects to fail. While selecting technologies we will need to be weary of excitement surrounding modern technologies and look for unbiased advantages and disadvantages of each.

We will begin by selecting the language to use, followed by key libraries used within the software itself. Some of these libraries were chosen during development when the need for them arose.

3.6.1 Languages

A wide variety of languages are available for software development. We need to consider the best language for development of the Membrane Daemon, the GUI and the CLI. One of the most important features of a language is support from the developer community. An active developer community means any issues we encounter during development will most likely, already be solved by someone else.

We used the 2017 Stack Overflow Developer Survey [stackoverflow.com, 2017] to find language popularity statistics. This is an annual survey held for users of one of the most popular developer forums, covering everything from languages, to frameworks, to demographics.

Daemon

There are a few requirements when selecting a programming language for the daemon. The language must scale efficiently, restricting our choice to object-oriented languages. It must also be compiled, to reduce the chance of runtime exceptions the user would need to debug. Platform Independence is also key so Membrane can be easily ported to other platforms after the proof of concept is developed.

JavaScript

The most popular language by far is JavaScript, a high-level, dynamic, untyped language that is interpreted during runtime. [Flanagan, 2011] It is one of the three core technologies used in the world wide web, which has done a lot to push it's popularity. It has been standardised in the ECMAScript language specification, which has recently reached it's 7th edition. [Stefanov, 2010].

High-level languages uses strong abstraction to hide details of the underlying computer, such as memory management. This makes them easier to use and usually makes them much less bug prone.

Dynamic languages are a class of high level programming languages that execute behaviours usually performed at compile time in static languages during runtime. [Tratt, 2009] This typically means the language is dynamically typed (although not always). In the case of JavaScript, this is true.

An interpreted language is one for which most of the implementations execute instructions directly on the machine without compilation. The interpreter translates each statement into a sequence of subroutines that have already been compiled into machine code. In the case of JavaScript most of the runtime environments include a just-in-time (JIT) compiler, which compiles the program during runtime, allowing for dynamically recompiling frequently used code sections, optimising those sections. [Aycock, 2003]

Java

We move onto Java, the second most popular (applicable) language. This is a general-purpose language that is object-oriented, class based and concurrent, [Gosling et al.,

2014] designed to run anywhere, meaning that compiled Java code can run on all platforms that support Java without the need for recompilation. [Gosling and McGilton, 1995]

Object Orientation is a programming paradigm based on "objects" which contain data and methods that can act on that data. The class based aspect of java means that these objects are in fact instances of classes that determine their type. [Kindler and Krivy, 2011] Object are able to offer encapsulation, an desirable feature that means only objects can manipulate data inside them. This facilitates code refactoring and encourages decoupling, which makes it very desirable for large software projects.

C#

The final language we consider is C#, which is another general purpose programming language that offers strong typing, is imperative, declarative, functional and object-oriented. This makes it very similar to Java [Kreft and Langer, 2003], and in fact has been criticised as a "imitation" of Java, although this has been disputed. C# is a younger language that Java, so it was playing catch-up to Java's feature set for a long time, however, it has at this point surpassed Java.

On balance Java's popularity, larger community of users and open source nature means it is more suited to Membrane, although C# has some clear advantages, it is not as well supported on Linux, requiring Mono to be run. It is also important to take into consideration the ability of the programmers coding Membrane, who have coded predominately in Java in the past.

CLI

We also consider the language to use in the GUI and CLI. For the CLI a fast, lightweight language is required. The three languages under consideration are Python, C and Go, selected because of their popularity, and the programmers familiarity with them.

Python

Python is a general purpose, dynamic, high level programming language. It is know for it's design philosophy, which emphasises readability through forced indentation and a syntax tailored to representing algorithms in as few lines as possible. This is a strong contender for the CLI, however, the most popular implementation of Python, *CPython*, is a runtime interpreter of language making it slightly more difficult to ensure code correctness.

C

C is a general-purpose, imperative, statically-typed language developed in 1973 at Bell Labs. [Banahan et al., 1988] It has become one of the most widely used programming languages of all time, providing low-level access to the hardware, uses language constructs that map efficiently to machine instructions, and requires minimal run-time support.

One of the key disadvantages of C is that it's power makes it easy to make mistakes. This low level access is not required for the CLI of Membrane and it could potentially lead to subtle errors.

Go

The final language, Go is a complied, statically typed language with garbage collection. It is designed to be scalable, not require IDEs, support networking and concurrency, and be productive and readable. [golang.org, 2017]

This is a great compromised between the ease of programming in Python and the strictness found in C without sacrificing any of the benefits. Critics of Go say the lack of generics limit static

We also refer back to the Stack Overflow developer survey and see that Go is one of the most wanted and loved languages by developers, leading us to select Go for the CLI of the Membrane.

GUI

Finally a language for GUI development needs to be selected. This depends strongly on the choice of Electron for the GUI framework discussed in detail below. Although, as we have selected a web technology we need to use JavaScript, there are two newer languages which can transcompiles to JavaScript that enhance JavaScript's feature set. We will compare these.

CoffeeScript

CoffeeScript aims to add syntactic sugar inspired by Python, Ruby and Haskell to improve JavaScript's brevity and readability. [MacCaw, 2012] The compiled output is readable and tends to run as fast or faster as equivalent JavaScript. [coffeescript.org, 2017]

There have been concerns using CoffeeScript adds bloat to development, every change must be compiled before the effect can be seen, however, this can be solved by automating the process during development, any time a page is reloaded, the server automatically transcompiles any modified CoffeeScript files to JavaScript. [Wheeler, 2012]

Another concern is that using a transcompiled language makes debugging difficult as the debugger steps through a file you have not created, however, because the compiled output is intended to be readable, this has not caused issues for developers. [Wheeler, 2012]

TypeScript

TypeScript is a super set of JavaScript and developed and maintained by Microsoft as open source software. It is designed for development of larger applications and aims to address the challenges of dealing with JavaScript code. It supports static typing and adds features such as classes, modules and arrow function syntax, leading to better, more readable code. [typescriptlang.org, 2017]

There are two major concerns with using TypeScript. To get the most out of TypeScript, developers need to add type annotations everywhere in their code, which makes coding a bit more cumbersome in comparison to JavaScript. In addition, although TypeScript's type system is more flexible than mainstream statically typed languages, it still makes some common JavaScript software patterns difficult for developers to use. [DataArt, 2014]

This is in addition to all of the considerations of CoffeeScript. On balance, we chose to use TypeScript for the Membrane GUI. The extra type safety provided outweighs the downsides of making it slightly more tricky to write the code. In addition if any quick coding is required, it is fully compatible with JavaScript so any sections of code unsuitable for TypeScript can be written using JavaScript seamlessly.

Conclusion

We have decided on three programming languages to use to create Membrane. Java, Go and TypeScript. These are three well-supported, popular languages best suited for both the programming task required and for the developers coding the Membrane proof of concept, to produce a stable and complete product.

Other languages including Bash, HTML, CSS, Python, Markdown and Groovy will be used during development, however, these are simply a requirement of the languages, frameworks and tooling chosen.

3.6.2 Frameworks, Tools and Libraries

To aid with development multiple frameworks will be used some of these will be chosen at the start of development, whereas other will be selected during development as a need for them arises.

Java Build System

There are three major build automation systems available for Java that help with ap-

plication development, namely Ant, Maven and Gradle. These are responsible for compiling source code, running automated testing, detecting code coverage and packaging.

Apache Ant was first released in 2000 and was the first modern build tool available for Java. It is able to accept plugins and is designed to have a low learning curve, enabling anyone to use it without special preparation.

Ant uses XML based configurations, to created build scripts, which is not ideal for writing the procedural scripts required. The use of XML also makes Ant difficult to use with larger projects. The build process is the biggest advantage of Ant.

Apache Maven was released in 2004, designed to address problems developers encountered with Ant. Although it uses XML configurations like Ant, it is better designed relying on conventions and provides subroutines that can be invoked. Unfortunately the inherent downside of large build scripts remains.

One of the major advantages of Maven is the ability to download libraries and other dependencies over the network. Since this is the main purpose of Maven, custom build scripts are actually more difficult, however, these are not required by most users. [Farcic, 2014]

Gradle, developed in 2012, is the most modern build tool and attempts to combine the power of both Maven and Ant. It uses Groovy (a JVM based language) for build scripts which results in shorter and clearer build scripts and reduces the boilerplate required for creating basic configurations. [gradle.org, 2017] Gradle's flexibility is one of it's major advantages. [Casperson, 2015]

The two contenders for the build system become Gradle and Ant. Ant is preferred for developers new to build tools because of it's low learning curve, however, as the developers creating Membrane have experience using all three build system, we opt to use Gradle, because of it's clearer configurations.

Java Networking

The core feature of Membrane is it's ability to communicate with other peers. Using Java core networking libraries for this is an option, however, they provide an unnecessarily granular a control over network communications.

We look at various networking libraries in Java to see which is most appropriate for Membrane. One of the first requirements is the ability to send HTTP requests. These will be required for creating the API to interface with Membrane. Learning two networking libraries to develop Membrane would take more time with very little benefit.

The networking library of choice must also be able to establish SSL connections, which serve both the purpose of User Authentication and provide data security.

There are three major contenders Netty, Vert.x and Akka.

Netty is a low level widely used library that promises quick and easy development without maintainability or performance issues. [netty.io, 2017] It is based around the reactor pattern to handle requests concurrently, and provides a wide variety of protocols for communication. It is more difficult to debug than traditional networking libraries because of the inherent concurrency, but has a wide variety of features and options.

Vert.x is a polyglot library supporting seven languages including Java. It is built on top of Netty, focusing on a simple concurrency model, removing the complexity of debugging concurrent programs and has a simple asynchronous programming model to allow handling multiple requests at once. It aims to be a JVM alternative for Node.js, a popular JavaScript framework. [vertx.io, 2017]

Akka is a library made for concurrent and distributed JVM applications. It draws on inspiration from Erlang for it's actor-based concurrency model, focusing on immutability and allowing actor interactions across multiple hosts when required. [Gupta, 2012]

We opt to use Vert.x in Membrane, it offers all the required features for peer networking with an appropriate concurrency model and without the complexity that comes from using a low-level library.

Java Cryptography

Security was a major concern for potential Membrane users and therefore the library we use for encryption needs to be selected carefully. We again consider three libraries for this purpose. Membrane requires TwoFish encryption support and the ability to generate RSA public private key pairs and certificates, as well as signing and authenticating messages using those keys.

Apache Shiro is an open source security framework that offers authentication, authorisation, cryptography and session management, and aims to provide robust security while being easy to use. It was first released in 2010 and the latest release was 8 months prior to selection. [Shiro, 2017]

Bouncy Castle is a collection of cryptography APIs for Java and C# founded in May 2000. It is maintained by "Legion of the Bouncy Castle Inc.", a registered charity in Australia and prides itself on it's extensive test suite and standards compliance. It is by far one of the most popular cryptography libraries available. [BouncyCastle.org, 2017] The latest release was two months prior to selection.

Keyczar is a newcomer created by Google, aiming to make it easier and safer for developers to use cryptography in their applications, providing simple one line cryptography functions to developers instead of being a general-purpose cryptography library. It was first released in 2010 and the latest release was one month prior to selection. [Willden, 2017]

Shiro is a good option, however, it provides a lot of unnecessary features. It's focus is not aligned with the requirements of Membrane. Keyczar is a good library for limited use-cases, however, Bouncy Castle is best suited to Membrane. It is the oldest library by far, and it's popularity during that time makes it much less likely to have bugs.

Version Control

Version Control is an important aspect of any software project. We will be mostly focusing on the extensiblity requirement, which requests easy contribution for other open source programmers.

There are two leading platforms *Github* and *Bitbucket*. We opt to use Git for version control because of it's clear advantages, allowing for decentralised version control while working from multiple workstation, over competitors such as SVN and CVS.

Github was launched in 2008. Offers code review, issue tracking, documentation, wikis, pull requests and releases. It has 5.8M active users and 19.4M active repositories. [Github.com, 2016] offering multiple integrations for continuous integration and code quality analysis. It also offer public repository hosting for free.

Bitbucket was launched at the same time as Github in 2008 and started only hosting Mercurial projects but quickly expanded to Git as well. [bitbucket.org, 2017] It's main advantage is it's close integration with JIRA, a popular issue tracker. [Upguard, 2014]

On balance, given the popularity and available integrations, we opt to use Github for version control. We use four Github integrations in the project. *TravisCI* offers continuous integration, running testing on all targeted JVMs after every commit and notifying developers if a test fails. *VersionEye* ensures that all external dependencies used are up-to-date and have no security flaws. *CodeCov* automatically checks test coverage for every commit, warning the developer if coverage is decreasing due to the commit. Lastly *rtfd.io* provides documentation for the project, hosting the web page.

Other Libraries

We will also use *Google Guava* and *Apache Commons Collections* in Membrane, to en-

hance the standard Java libraries, offering a wider range of functions and desirable features such as immutable collections.

For marshalling data we opt to use *Jackson*, both for transmission and local storage, serialising objects to both JSON and YAML. Advanced date functionality is added using *Joda* and finally *Junit Jupiter* in conjunction with *Mockito* will be used for unit testing.

Chapter 4

System Components

The components that make up Membrane are all designed individually and connected using Java Interfaces. In this section we discuss, in detail, the goals and functionality of each explaining decisions in the final architecture of Membrane.

We begin with file ingestion and file system monitoring, following into file storage and what inspired the design of the file history storage. Continuing on through Peer Appraisal, how we determine who to give file blocks to we finish in Networking, covering the details of authentication and security.

4.1 File System Monitoring

Monitoring the file system for local changes is key to any backup system. All file changes in the watched folders need to be recorded, including deletions. First we explore methods of walking the file tree when asked to back up recursive folders. We then take two approaches to watching folders, followed by augmentations made to the chosen technique. We finish by discussing methods of deduplication for repeated files and future enhancements that could be made to the implemented monitor.

4.1.1 File Tree Walking

We allow users to select folders for backup, either explicitly, with wild-cards or recursively. When allowing users to specify folders recursively we must inspect the contents of each visited folder and record any encountered folders. This can be achieved using the Visitor pattern in Java, which defines operation for each element visited by the class. [Sugrue, 2010]

Once all of the relevant folders are found we can start watching those folders using one of the methods below. If a folder addition or deletion is observed by the watcher, this can be added or removed to the watched folder list respectively.

One of the problems with this method is when wild-card directories are added. These might not necessarily be created in watched folders so these folders must be manually scanned for on a regular basis.

When finding folders it is important to note the difference between a file or folder, hard link and soft link (also known as a symlink or symbolic link). To understand these we must first observe how files are stored in a Unix-style file system, which supports ordinary files, folders and special files.

Index Nodes (commonly refereed to as inodes) are things in the file system stored by a unique number. Directories are a way to structure and name these inodes. These contain files and each file is mapped to exactly one inode, however, each inode can have more than one file mapped to it. [Bar, 2001]

A hard link is an inode that has multiple names in the file system. A symlink is any file that contains a reference to another file or directory which will affect path name resolution. The link is an inode that exists independent of the target, and does not affect the target if deleted and continues pointing to a non-existent target when that is deleted. [Yue et al., 2011] These can be

used to link different file systems, but they change the file system from a tree into a directed graph, which greatly complicate file tree walking as files can loop and repeat.

Within Membrane we opt to ignore symlinks while walking the file tree. Users are able to specify the target of the symlink if required. To prevent backup duplication due to hard links we use a system that mirrors the inodes described, but treat them as different files for backup.

4.1.2 Polling

The first naive methods for check for folder changes simply uses polling to record the contents for folders, finding the difference between the last scan and the current scan. To check whether a file has changed the modification data provided in the file's metadata is used.

This is a simple method to implement, however it consumes a lot of memory when implemented as it needs to retain a copy of the last modification date and all of the files in the watched folders.

This method is also IO intensive. The file listing for a directory on the file system contains no file metadata, so every single inode in the folder needs to be accessed to gather it's metadata. This mostly affects potential users using storage media with poor IOPS (Input Output Operations per Second), common in older hard disk drives (HDDs). [Mansurov, 2017]

This makes polling a poor solution for Membrane, as during user surveys low resource usage was requested. Periodic spikes in IOPS could adversely impact user experience in other software.

4.1.3 Native Watching

A more advanced method of watching files is built into some file systems. This sends out File Change Notifications to subscribed services when an inode changes. There are three common scenarios when this is used. When caching a model of file systems objects, logging file system activity and gatekeeper services that ensure only permitted operations happen on the file system. [Kerrisk, 2014]

The first implementation of file change notification, *dnotify*, appeared in Linux in 2001, it suffered from a cumbersome API and most notably, it kept file descriptors open causing problems when trying to unmount the file system. [Kerrisk, 2014]

The inotify API was released in 2005 and aimed to address all of the issue lessons learned in dnotify. It consists of three dedicated system calls *inotify_init()* which maintains a list of file system objects that should be watched and a list of events generated for those objects. The commands *inotify_add_watch()* and *inotify_rm_watch()* are used to alter the list of monitored file system objects. inotify provides more information than dnotify, allows programs to deal with notifications synchronously and includes the file name modified. [Kerrisk, 2014]

Java implements the WatchService API that provides low level access to the underlying inotify API of the file system. [Oracle, 2017] We opt to use this when the API is available, but fall back to polling when inotify or similar services are unavailable.

4.1.4 Watching Enhancements

Despite the comprehensive feature set of inotify, we still require some enhancements to prevent accidental or missed file system event notifications.

In order to detect changes between Membrane runs we need to load all known and expected files into memory and scan the file system once when Membrane loads. This means resorting back to maintaining a list of all monitored files in local memory, an unfortunate but necessary step.

We now match any reported modified or deleted files against the internal state, using the modification date and hash of the file to determine if the file has been changed.

In order to lower resource usage we read any modified files in sections, never loading more than 4MBs into local memory. These chunks become shards within the backup system.

4.1.5 Deduplication

There are two viable approaches to file deduplication for Membrane. We can choose to split the file into shards and check if shard hashes match, or use a rolling checksum, similar to Rsync to find the section of the data changed, and only storing that. [Tridgell et al., 1996]

Simply splitting the file into chunks has the disadvantage of being unable to detect overlapping data, which can lead to huge duplication. When data is inserted into the middle of a file any blocks after and including the change will register as modified and need to be restored.

The approach of simply sharding the data is simple and much less prone to bugs, so we take this approach with the initial implementation of Membrane, although we will maintain support for variable size chunks for future implementations.

We need a methods of generating a unique has for file shards. Git and Subversion opt to use SHA1 [Torvalds and Hamano, 2010] to generate unique keys for files, however, we have decided to use MD5.

Both SHA1 [Wang et al., 2005] and MD5 [Stevens, 2006] are cryptographically broken, meaning that it is possible to generate a collision[1] without having to try every possible input into the hashing function. It is also possible to launch a first preimage attack on these hashes, something that would make them unusable for security as an attacker would be able to generate an input matching any given hash. As Membrane only uses this hash as an internal shard identifier, we do not have to be concerned about an external attacker.

The only situation in which this may cause issues in the future, is if the user stores two shards with the same hash accidentally, however, the chances of that are minute enough that it is not worth worrying about. This was discussed in detail by Torvalds [2006] and other git developers. An inadvertent collision was deemed so unlikely that it was reasonable to use SHA1 for Git.

MD5 only has a 128 bit output vs. the 160 bit output of SHA1, meaning collisions are slightly more likely, however we mostly concerned about hashing speed, seeing as this hash will be run very frequently on any files that have been altered, and studies have shown that MD5 is on average about 1.75 times faster than SHA1. [SAPHIR, 2007]

4.2 Local Storage System

As Membrane is a backup system, it needs to contain a log of file activity, including file meta-data and contents at that point in it's life time. In this section we first discuss the shard storage mechanism, followed by the file history persistence, and finish on the file expiry policy used in Membrane.

4.2.1 Shard Storage

When a file is backed up the file watcher shards the file into 4MB chunks and sends them directly to shard storage. The shard store manages a folder of the file system and provides functions for shard storage and retrieval.

When a shard is inserted into storage the file system first checks if the shard is already stored. If so the shard is ignored altogether and the write is avoided, saving disk IO. Otherwise the hash of the data is confirmed and the shard is written to a file on the disk.

Because of file system limitations we use a hierarchical directory structure for storing shards. A new directory is created every five characters of the shard, overcoming any restrictions on the maximum number of files per directory, of older file systems such as

[1] Two files matching a given hash

ext2 and ext3 which reportedly have performance issues with anything above 10,000 files. [Johnson, 2014]

The shard storage runs scrubbing on a regular basis, a concept taken from the ZFS file system. [Oracle, 2012] The shard store periodically checks that every shard stored is consistent with it's hash and accessible. This is a technique commonly used to prevent error before they result in failure. Although the shard store also verifies shard integrity during the read it may falsely report damaged shards as available to the user. This prevents the shard from being patched by versions stored in the peer swarm.

4.2.2 File History Storage

The file history is the central store of the backup system. It contains a log of every file addition, modification and removal providing all of the information required to retrieve it. It is important that the store is immediately persisted to the file system upon backup so nothing is lost upon unexpected shutdowns.

The naive approach to this problem uses a log to record these event, implemented in the form of a linked list, flushing entries immediately to a log file. Although this approach satisfies all of the requirements it is very expensive to search and quickly becomes very large.

Taking inspiration from distributed file systems such as HDFS [Shvachko et al., 2010] and GFS [McKusick and Quinlan, 2010] which use NameNodes to store file system modification in a checkpoint and journal. The journal is a write-ahead commit log that takes the place of the aforementioned event log. The checkpoint is a known file system state. In the event of system failure these file systems can replay the log to a checkpoint.

Within Membrane we take advantage of checkpoints to speed up search through the journal. The start and end of the journal are often queried to check current backup status, so these are given permanent checkpoints, that are always kept up to date. When the user queries for a specific point in time, the journal can be replayed from the start checkpoint to the requested time, quickly generating the required time slice.

This proved to be an effective way of storing file history, providing quick responses to the GUI, CLI and other system components, even when full of data. If this proves insufficient for future demands, indexes for specific queries can be created for quick search.

It is important to address the distinct lack of a transactional database, in a situation where the use of one seems like a natural fit. Traditional databases such as MySQL have very high memory and CPU usage [James, 2017] and although this usage can be tuned, running a full database on a users computer would go against the resource usage requirement.

4.2.3 Backup Management

One of Membrane's proposed features is flexible file history. Instead of providing a backup storage duration, backups are stored until the space allocated to Membrane is completely used.

This is a step towards the maintenance free experience requested by potential users. Many cloud solutions such as Dropbox [2017] allow users to access version history for a set amount of time, requiring extra subscriptions for additional versioning time.

In order to implement this we take the concepts used in garbage collection within programming languages and apply them to the file history. In addition to the maximum shard storage size, a target size is set. The file system monitor will add shard until the maximum limit, regardless of the requested target size.

A history compacting and garbage collection is then executed on a regular basis. This is a three step process that attempts to reach the target storage size in the least destructive way using:

1. Garbage Collection
2. Remove Unwatched Files
3. Trim Older Journal using FIFO

Garbage collection is implemented using an adapted version of Dijkstra et al. [1978]'s mark and sweep algorithm. This works in three passes.

1. Certain shards have are protected from garbage collection as they have just been added into shard storage and therefore might not have their reference inserted into the journal yet, generating set P.
2. The second pass walks the journal and removes shards mentioned in the journal creating set R
3. The final pass finds $S \setminus (P \cup R)$ where S is the set of all stored shards, and removes them.

This step is intended to remove any shards that were inserted into shard storage but never followed up with a file entry. This would be possible in the case of error during shard storage or file history storage. The code for garbage collection can be found in listing 7.1.

The next step is intended to remove any entries the user is not interested in any more. These could have been inserted after recovery from peers or may have been files that were temporarily backed up. If any files were deleted garbage collection is re-run to remove the relevant shards.

Finally the Journal is trimmed, removing any history necessary. The algorithm creates a shard count dictionary to see if removing the last file in the log will affect the storage. If it does it is removed, otherwise the algorithm moves along to the next entry. This is repeated until the target storage size is reached. The method used means no file entries are unnecessarily removed. The storage clamping procedure can be found in listing 7.2.

4.2.4 Local Backup

With both the local storage system in place and file system monitoring, we have developed a full local backup system. Files are detected by the monitor, split into shards, which are stored in shard storage, and the modification event is stored in modification history. Available files, file history and file version recovery can be requested and completed successfully.

The components described hereafter can be completely disabled for a local Membrane installation. We next describe the Application API, which allows the user to interface with the daemon.

4.3 Application API

As extensiblity is a requirement for Membrane, it is paramount that the application API is robust and assists future developers with interactions. We look at Google [2017*a*]'s and Heroku [2017]'s API design guides to form a coherent and sensible set of requests and responses for developers. The design of APIs is very important in Software Engineering and the final result can have significant impacts on usability. [Benslimane et al., 2008]

4.3.1 API Type

There are there main types of APIs considered in API design. [Boyd, 2014]

- Open - Public expose information and functionality
- Partner - Used for integration between a company and it's partners
- Private - Only used internally to facilitate communication.

The Membrane API is a Private API, only the user them self will be permitted to access the API. We opt to authenticate the user by using an source IP filter. Only interac-

tions from the loopback address[2] 127.0.0.1 will be permitted. This decision makes development easier, but it can always be expanded if the need arises.

As discussed previously, we opt to use a Representation State Transfer (REST) API. In web development, an API is typically a set of Hypertext Transfer Protocol (HTTP) request messages, with defined responses in either Extensible Markup Language (XML) or JavaScript Object Notation (JSON). We opt for JSON within Membrane because XML is more difficult to parse and JSON is shorter, quicker to read and write and can use arrays.

In the past Web APIs were typically Simple Object Access Protocol (SOAP), which focused on providing access to services. [Benslimane et al., 2008] More recently REST APIs, more focused on resource access have gained popularity. These aim for fast performance, scalability, simplicity, easy modification, communication visibility, portability and reliability. [Fielding, 2000]

There are five main guiding constraints to building a RESTful API [Fielding, 2000]:

- Client-server - By separating the user interface concerns from data storage concerns portability across platforms is improved. The components can also be allowed to evolve independently.
- Stateless - All the information required for a request is contained in one request. This reduces the need for persistence on the server side.
- Cacheable - Any intermediaries can cache a response to improve responsiveness, and responses must be marked as cacheable or not.
- Layered System - A client should be unable to tell if an intermediary is passing it's data. This improves potential scalability.
- Uniform Interface - This decouples the underlying architecture from the interface allowing both to evolve independently.

All of these properties are desirable within Membrane, for limiting resource usage and allowing future expansion. This in addition to the vast amounts of tooling, created to assist with RESTful API development, such as Postman [2017], a tool for manually making REST calls means that we opted for a RESTful API within Membrane.

4.3.2 API Design

We now need to structure the API. There are five available HTTP methods emph-POST, *GET*, *PUT*, *PATCH* and *DELETE* which can all be used to invoke actions on the server side.

We opt to split our requests into three categories '*status*', '*configure*' and '*request*' to keep the API simple, intuitive and consistent, as recommended by Google [2017*a*].

Simple status updates are available under '*/status*'. The status is split into four modules of membrane: '*network*', '*storage*', '*watcher*' and '*contract*' such that a GET request to '*localhost:13200/status/watcher*' would return JSON information regarding the file watcher. In the future we plan to further subdivide the API in case specific information is required to reduce the amount of calculations required on the server side per request.

Calls to Membrane regarding configuration are grouped under '*/configuration*'. Here the client needs to provide request information. We opt to use JSON data structures for this. Within HTTP requests data can be provided using either the URL or accompanied data. Although using URLs is useful, this may cause issues in the future when inputing folders using the same file separator as URLs and in that situation Heroku [2017] suggests requesting JSON data structures. We return HTTP status codes to indicate the result of the request, compliant

[2] An IP address that connects from the host itself. [Hinden and Deering, 2006] It is infeasible to send a request from this address unless it originates from the user.

with RFC7231 [Fielding and Reschke, 2014] as per Google [2017*a*]'s recommendation.

Last of all we require users to send requests to Membrane for file history and file recovery. Here we opt for both JSON requests and responses for the aforementioned reasons.

An important part of API design is human-readable documentation, so future developers can understand the API. [Heroku, 2017] We have created documentation for the Membrane API, made available both in listing 7.4 using the reStructuredText markup language and at `http://mbrn.rtfd.io` using version controlled documentation generation available via Github, first mentioned in section 3.6.2 when selecting Github for version control.

4.4 Shard Distribution

Membrane is a distributed backup platform. In the previous three sections we have created a functional local backup application for users wishing to backup and version file to a local storage medium, such as a removable hard drive. The following two sections focus on taking that data, securing it and passing it to peers for remote storage.

There are two important data stores that need to be distributed, the file history containing metadata required to reconstruct files and shard storage containing the data used for file reconstruction.

In this section we assume we are subscribed to a feed of peers we can send messages to. We first discuss storage blocks, the mechanism for packaging shards and metadata, followed by the contract system employed, concluding with the peer appraisal trust system applied.

4.4.1 Shard Packaging

In order to start trading data with peers a standardised container for shards needs to be created. The only limitation imposed is the size of the container. For Membrane we decide through empirical testing, a container size of 25MB is a good size. This number allows the storage of 6 full data shards, leaving 1MB for any any metadata required. It is also small enough that we can store multiple copies in-memory for data manipulation and in the write buffer while sending.

Each container hereinafter refereed to as a '*block*' requires overhead for transfer and proof-of-existence discussed in the following section (4.4.2), so it is useful to select as large a size as possible.

Compression

When crafting a block for a potential peer, shards that the peer has not yet stored are selected. Membrane then attempts to compress these shards, some shards might not be compressible (as the data has no or difficult to detect patterns) and in that case we flag the shard as uncompressed for future retrieval. We implement both Snappy and LZ4_FAST compression, as discussed in section 2.9. We include the compression algorithm in the shard data, so new and better compression algorithms can be used in the future, in line with the extensiblity requirement.

It is imperative the compression is performed before encryption as encrypted shards are made up of pseudorandom data. If the encryption algorithm follows Shannon [1945]'s laws of confusion[3] and diffusion[4].

Knapsack

To fit data in the block we are faced with the knapsack problem. This is a packing problem commonly encountered in Computer Science. [Skiena, 1999] Given a maximum container size W and a set of n items, shard sizes in our case, each with a value v_i,

[3] Each bit of the ciphertext should depend on several parts of the key

[4] If a single bit of the plaintext or ciphertext, is modified then half of the bits in the ciphertext or plaintext should change respectively

size s_i and size we must find the set

$$\max \sum_{i=1}^{n} s_i x_i$$

such that

$$\sum_{i=1}^{n} s_i x_i \leq W, x_i \in 0, 1$$

This is an NP-Hard optimisation problem, [Skiena, 1999] meaning it cannot be solved in polynomial time. In Membrane we are faced with the additional issue, that we do not know the size of all the shards without accessing the inode of the shard, an expensive operation. There are pseudo-polynomial[5] time algorithms for solving the problem, however, without all of the sizes available we cannot fully benefit from them.

We attempt to solve the solution by simply looking a subset of 100 random shards from the queue and using the dynamic programming solution with $O(nW)$ computational and space complexity. [Martello et al., 1999] We divide all weights by 128kB for this calculation to lower W to a reasonable level, a maximum of:

$$(25\text{MB}/128\text{KB}) * 100 \text{ shards} = 2000 \text{ ops}$$

This is far superior to the $n! = 100!$ naive solution. The code for this is available in listing 7.3. Although we are able to fill the block optimally, it caused starvation for blocks sized between 1MB and 4MB. Blocks of size 4MB filled the 25MB until there was 1MB left, which was filled by shards of size $\leq$ 1MB. Any shard between 1 and 4 MB was very rarely selected as blocks of size 4MB and $<$ 1MB were quickly replenished.

We therefore opt for the naive approach of filling the blocks in FIFO, skipping a shard and moving to the next one if it no longer fits, checking up to 100 shards. When tested over a standard set of sharded files taken from the document directory of three users with compression disabled, seen in table 7.6, the packing efficiency was 0.90 with a standard deviation of 0.026. The maximum inefficiency we can observe is if the block has $4MB - 1B$ remaining with only 4MB available. At that point reaching an efficiency of approximately $21/25 = 0.84$. This leaves the expected average efficiency at 0.92, is within the result. Another advantage to this naive solution is we can consider the remaining space after compression. Something that would require compression of all the blocks first in the knapsack algorithm.

In the future we may attempt to find a better solution to this problem, perhaps by favouring shards that have not been uploaded for a longer time. It is important to also remember that if all users have similar packing efficiencies, then the system remains in balance, although it would still be exploitable if another client was created with more efficient packing.

Adding metadata

Once the block is fully packed with shard data, we request the file history store for every entry involving the packed shards. This ensures, that if data is lost and the block is returned, Membrane can reconstruct files once all of the shards required have arrived.

We then insert a randomly generated salt into the block. This is small, however, because of the aforementioned law of diffusion [Shannon, 1945] this should lead to completely different encrypted data. This is done to ensure that the same block is never sent out twice, a requirement for proof of ownership in section 4.4.2.

We finally encrypt the shard using a hash of the private key used by the Membrane networking module. Twofish encryption is used, as decided in section 2.8. The block is now ready to be sent to the peer by the contract mechanism.

4.4.2 Peer Contract Manager (PCM)

In the literature review (2.3.1) we explored contract negotiation within intelligent agents. Many contract negotiation techniques studied require multiple steps to

[5] Running time is polynomial in the numeric value of the input (container size in this case)

come to an agreement. We hope to implement a new pragmatic approach to shard allocation that does not require complex negotiation. We now describe an overview of the contract mechanism, followed by an in-depth analysis of why it works.

As in Game Theory, we assume all Membrane peers are entirely self-interested. The main purpose of the peer is to distribute blocks and the only way to achieve that is by becoming attractive to other peers for block storage, which can be done by correctly storing blocks for them. This system does not depend on altruistic behaviour, instead making good behaviour the only way to benefit from the system.

New Peers

The PCM in Membrane is given a target number of peers that it should share blocks with. When a new peer is presented to the PCM when peers are required, it contracts the peer giving it an offset[6] of one. This qualifies as a Contract modification so a Contract Update (CU) is sent to the peer.

We expect a similar CU, marking the start of the contract. The mechanism can be observed in the initial part of fig 4.1.

Contracts

Contracts are Service Level Agreements (SLAs) within Membrane. Through offering an offset a peer agrees to:

- Accept and store blocks from the PCM (up to the amount the PCM is holding for it, plus the offset)
- Send CUs at least once every hour while the SLA is active.
- Complete Block Instructions issued by the PCM - Used for proof of existence and block management.

We apply four sections of Keller and Ludwig [2002]'s SLA life-cycle to these contracts, the CU allowing for three of the life-cycle stages: Establishment, Reporting and Termination. A peer is only able to provide verifiable facts in the contract update, so it is impossible for peers to be deceitful.

The offset can be modified as required throughout the SLA, with 0 terminating the SLA. Upon termination all blocks stored for the peer are removed.

Contract Update (CU)

The Contract Update consists of the following fields:

- Allowed Inequality
- List of Block you are holding for the peer.

Updates are sent whenever a peer connects, whenever a new peer block arrives and also every 15 mins. To receive a good appraisal a peer needs to send a contract update at least once every hour, so it is in the peer's interest to send contract updates, if it wishes to remain contracted.

Block Instructions

Upon receiving a contract update the PCM sends one of the following Block Instructions (BI) to the peer.

- Compute Evidence for the Block
- Remove the Block
- Send the Entire Block back

There are six possible scenarios for each block sent in the contract update.

Lost Blocks are blocks the PCM expects the peer to have that they did not report in the CU. The block is removed from the contract and the violation is marked in the peer appraisal.

Unexpected Blocks are blocks not in peer contract. These are temporarily[7] inserted into the peer contract. The entire block is requested.

[6] The number of blocks it can store more than the PCM can allocate to the peer

[7] Not influencing how much space the PCM offers the peer.

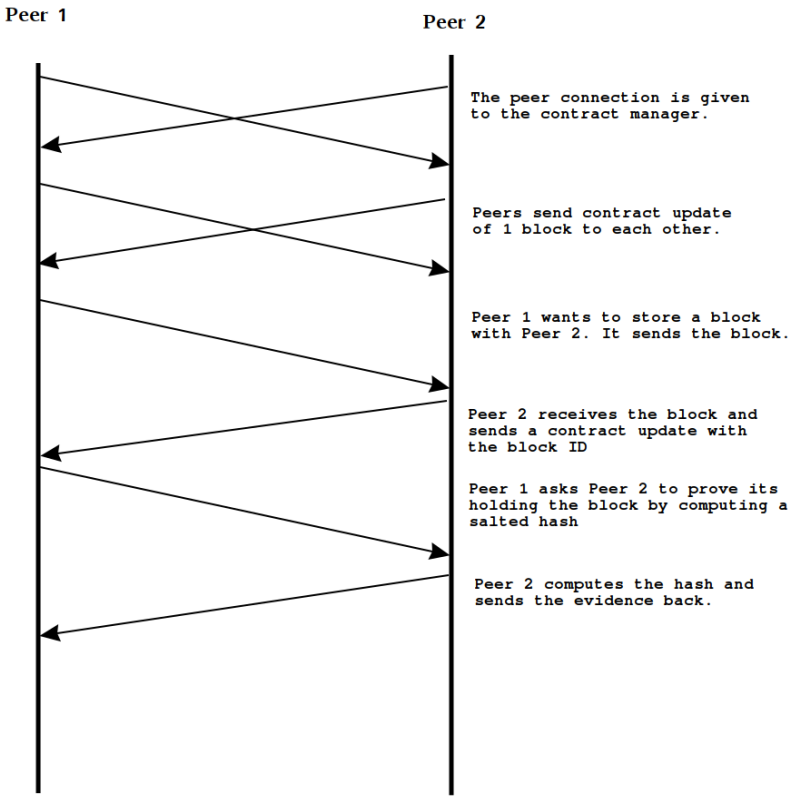

Figure 4.1: Example Peer Contract Start

If the peer is truthful, the block will be correctly decrypted and lost shards will be recovered. In the next update the block will register as expired. Otherwise this will be noted as a block the peer lost.

Required Blocks contain shards that are not present in local storage. These are requested for recovery.

Proven Blocks are blocks that have already been verified this hour and are not required, these blocks are.

Provable Blocks need to be verified for a good peer appraisal score this hour. A salt is sent to the peer to allow proof of ownership verification for the block.

Expired Blocks have no salts available for proof or contain no active shards. These are removed.

If the peer correctly responds to all of these messages it will have verified all of the blocks it claims to own, increasing it's appraisal score and making it a more likely choice for the PCM to store blocks with.

Provable Data Possession (PDP)

To allow the peer to prove the own a file the PCM calculates a set of salts and resultant HMACs for each block deployed as described in section 2.10.

We opt for the Keccak hash function, developed by Bertoni et al. [2009]. It used in SHA-3, a cryptographic standard released by NIST in 2015 [Paul, 2015]. There are no known exploits for Keccak and we use the 512-bit variant recommended by Bertoni et al. [2009] in 2013.

We take advantage of the fact that there is no known way to compute a HMAC without both the data and the key. As the PCM releases the key during the hour the peer is verifying the data, the PCM can be certain

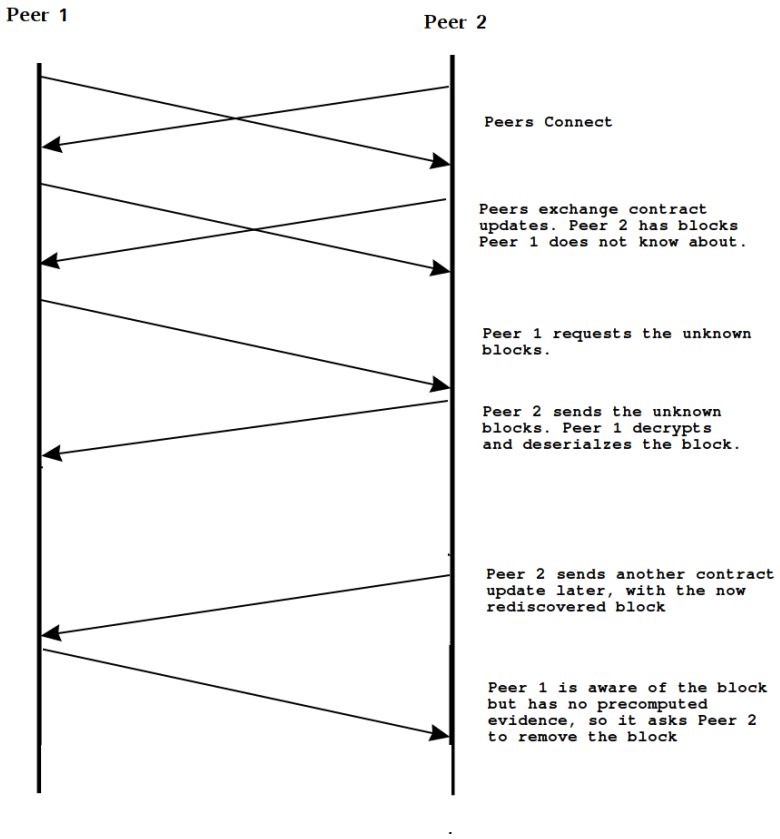

Figure 4.2: Lost Block Communication Example

the peer held the block at that point in time. [Ateniese et al., 2011]

In order to prevent all the stored blocks being loaded by the client the PCM has a 50% probability generating an empty key (except for the first and last proof), requiring no calculation by the peer. There is no way to predict this and therefore no way to abuse this feature. This is a pragmatic, very solution specific way of reducing IO required for PDP as the peer pays a huge reputation penalty for losing a block. There are more advanced methods that can be investigated [Ateniese, Burns, Curtmola, Herring, Khan, Kissner, Peterson and Song, 2011; Shacham and Waters, 2008; Bowers, Juels and Oprea, 2009], however, we opt for this solution in this proof of concept system.

Two weeks worth of HMACs are calculated, the expected lifetime of a block. After that the block is marked as expired and removed. We do not use Keccak Message Authentication Codes (KMACs), a newer more efficient keyed hash function that makes use of the sponge construction of Keccak to only hash once [**?**] as the standard is new and the cryptography library we use does not support it yet.

Contract Scaling

To accelerate block trading with favoured peers for every 10 blocks traded, the PCM increases inequality by one, allowing for more flexibility and faster growth. We choose a linear scaling system as the space made available to the peer must actual be available. Giving peers too much headroom would be detrimental.

The maximum amount of blocks transferred to each peer per upload is capped at six. This is due to a buffer limit of 256MB by the networking layer. If we assume all blocks are full and accounting for base64 encoding

used for transfers, we find that this gives space for $(256 * \frac{3}{4})/25 = 7.68$ blocks. Room is left for potential messages between clients while blocks are transferring.

The contract scaling allows adding friends in future expansions. A user can manually select a peer and increase their inequality, gifting them block space. We do not provide an interface to this in the initial implementation of Membrane.

Complete Data Loss Scenario

In the case of data loss the PCM is empty containing no contracts. Previously contracted peers locate the new PCM instance using PEX, unaware of the data loss. CUs are exchanged informing the peer that the PCM no longer holds any of their blocks, and the PCM treats all of the received blocks as lost.

If the PCM's appraisal by the peer was poor, losing all of the peers blocks may trigger contract termination, losing all of those blocks. This is offset by the fact that two other peers also hold copies of the shard. The system correctly punishes peers that constantly lose all peer blocks.

This mechanism can be seen at work in figure 4.2.

4.4.3 Peer Appraisal

Peer Appraisal is the persistent trust system that allow for peer discrimination, based around 3 core metrics: uptime, PDP checks and chance of data loss. We employ tools from intelligent agents to avoid potential attacks and design a system that uses a social approach [Pinyol and Sabater-Mir, 2013] to control the acts of agents.

We first conduct a survey to see the viability using uptime as a metric by polling users regarding their computer uptime. Within social groups uptime is correlated, as seen in fig 7.1, confirming the potential for using users to share storage for backup.

We incorporate contract updates (CU). By sending a CU a peer confirms they are online. Each peer has an array that stores a number for each hour of the week[8]. When the hour is complete we add n to completed hour of the week.

$$n = \frac{\text{PDP Checked Shards}}{\text{Expected Shards}}$$

We store a ratio of incomplete[9] and fully complete reports, heavily penalising peers for incomplete reports as this indicates deceit. In addition we store a count of blocks the peer lost, also generating a ratio of blocks lost to those that lasted their entire expected lifetime (two weeks).

We calculate peer appraisal with the following formula:

$$\text{rat} = H * R * L$$

where H is the percentage of the time the peer was online at the same time the PCM, R is the report completion ratio and L is the block loss ratio. This produces a value that indicates the probability that the user will be online and able to pass PDP checks for all held shards, with a penalty for losing blocks.

If a peer rating is $< 1.50\sigma - \mu$ away from the average we drop the peer as a contract, where σ and μ indicates the standard deviation and mean respectively.

This system was simulated in unit testing, asserting that the peer appraisal correctly punishes peers that fail to deliver PDPs, have incompatible uptime or lose blocks.

Using Jøsang and Golbeck [2009]'s nine potential attacks on reputation and trust systems described in section 2.4.1.

A lot of attacks are countered by relying solely on image, instead of both image and reputation. Peers cannot use playbook,

[8] A space of time in which we expect to see repeatable usage patterns based on the results of the survey in fig 7.1

[9] n is < 1.0

discrimination, collusion and Sybil attacks techniques.

Peers are harshly punished for low-quality actions so a playbook attack is ineffective. Trust is instantaneous so it would be difficult to exploit reputation lag.

A peer can re-enter the swarm with different credentials, but it would take a long time to regain reputation.

Lastly there are no easy actions the peer can perform that let them gain reputation.

As bad peers are shunned they will not have access to public PEX entries in high-performing peers, grouping poorly performing peer groups together, which is ideal.

4.5 Networking

The networking module is responsible for finding peers and providing a way to communicate with them. We first discuss authentication and account creation, followed by how we ensure peers can connect behind a NAT gateway, continuing to how peers communicate and how peers are able to locate each other. We end with the peer management strategy.

4.5.1 Authentication

SSL is used for communication in Membrane. As the system is decentralised we cannot rely on a certificate authority for authentication, relying on a SHA-256 hash of the RSA public key, provided with the certificate on connection. If a peer is able to establish a secure connection with the provided certificate, we are certain the peer also holds the private key. [Menezes et al., 1996] It is computationally infeasible to find the private key using only the public key, so we are guaranteed it is the same peer.

The probability that two peers will generate the same RSA key is small enough that it can be ignored. On first application launch we generate the RSA public key, public key and X509 certificate, placing it in the Membrane config folder. Future application launches search this folder and load them into the application.

It is important that users store these credentials in a safe place. We prominently display this in the usage instructions, and in the future we plan to implement a utility to encrypt transfer the authentication information to a removable storage medium.

4.5.2 Peer Connection

We can expect Membrane peers to be behind a NAT gateway, which acts as a bijective converter for ip and port combinations, grouping all internal IPs as one external IP. This poses an issue when establishing a connection with peers as NAT will typically block connections to unmapped ports. In section 2.6 we discussed four solutions, two of which we attempt. UPnP port forwarding [Boucadair et al., 2013] and TCP Hole Punching [Wing et al., 2010].

We use a UPnP communication library in Java for port forwarding. First we broadcast a UPnP request for potential gateways on the network. If a response is received we use UPnP to request a port forward for 5 minutes. If this request fails we try the next port up for a maximum of 20 attempts. In practice this has proven a large enough number to locate an available port. We then ask the gateway what the external IP is. A refresh is performed every 130 seconds to ensure the port forwarding entry never expires. A time of 5 minutes is used to ensure the port forward stops after a reasonable time.

We attempt TCP Hole Punching but find that Vert.x, the chosen network communication library does not provide a way to both listen and send messages out of the same port. If users find that UPnP is insufficient we will investigate using the underlying communication (Netty) to regain the required control.

In testing we discovered that as only one of the peers required port forwarding to generate a connection it is sufficient within the Membrane proof-of-concept.

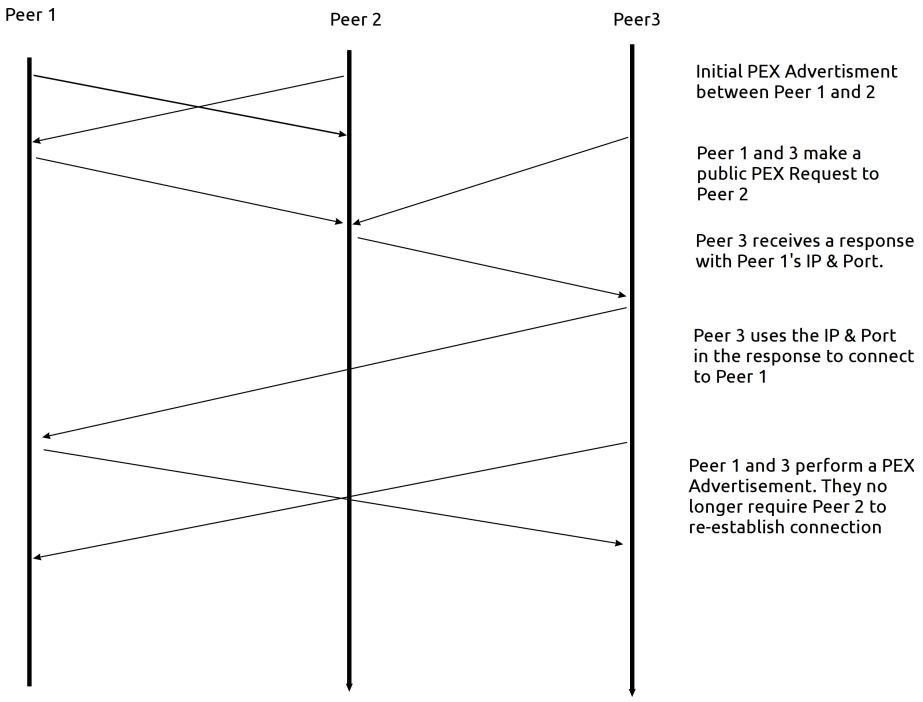

Figure 4.3: PEX New Peer Discovery Example

4.5.3 Peer Exchange (PEX)

In order to allow peers that constantly change IP address and port to find each other require a method of PEX as discussed in the literature review (2.2.2). We need to build on the PEX system using in BitTorrent in order to locate previously contracted peers in the swarm.

We introduce the concept of a PEX Advertisement, PEX Request and PEX Response. Using these three messages we allow peers to locate each other within the swarm, without exposing information about peers that do no want their information public.

PEX Advertisement

Each peer periodically sends a PEX Advertisement to all connected peers. This contains:

- IP Address
- Port
- Time Stamp
- 'Is Public?' Flag
- Signature

On receipt the peer verifies the signature and checks for other entries from the same peer within its PEX Ledger, an evicting store of Peer PEX information. If this PEX advertisement was created after the latest entry it has, the update replaces the previous entry. To ensure this system is not broken by time stamps set in the future, these are automatically dropped. By default the ledger stores 300 PEX entries in the ledger, expiring them in FIFO order if full. The Ledger is persisted to disk periodically.

If a connection to the Peer is required the PEX IP address and port can be dialled to attempt a connection.

PEX Query

In the event that connection to a peer is lost, and both peers have changed address, PEX Requests can be used to attempt to find the location of the peer. A PEX request is sent to currently connected peers, asking for the most recent PEX Advertisement in their PEX ledger for the peer. The request must contain the peer id, which as established, is a sha-256 hash of their public RSA key.

The chance of guessing the key for an existing peer is sufficiently infeasible that knowing the peer ID for the peer means the Membrane instance requesting the information has either connected to the peer before or has heard about them.

If there exists a PEX Advertisement Entry for the requested peer in the PEX Ledger of the peer sent the request, this is sent back in the PEX response as a PEX Advertisement.

As PEX Advertisements are signed using the original peers private key, we can be certain that the PEX response originated from the peer and was not forged. [Li et al., 1993] The time stamp in the advertisement prevents the peer sending old PEX Advertisement. The certificate of any contracted peer is persisted by Membrane to check for this signature. Therefore the PEX Advertisement can be reliably treated as if it came from the peer it describes.

This mechanism is demonstrated in figure 4.3. Two peers (1 and 3) attempt to relocate each other by using Peer 2.

Public PEX Entries

This mechanism is further extended to support public PEX entries. A PEX Request can also request fifty[10] public PEX entries. These are sent back without signature or peer ID information and are meant as an untrusted mechanism for attempting to establish peer connections.

These are stored in a second non-persisted temporary ledger and is a mechanism for discovering new peers. When a peer A requests peer B for public PEX entries, peer B searches all entries in their real PEX Ledger, only selecting those entries less than 15 minutes old with the 'Is Public' flag toggled.

We attempt prevent accidental DOS attacks by requiring entries spread as public must be signed at least once by a unique Peer, requiring work to be done to generate new credentials. In addition only one entry per IP can exist in the public ledger.

[10] Decided upon through observing the PEX mechanism in BitTorrent. [Vuze, 2010]

If a peer is looking for new peers to connect, it can allow peers with unknown X509 certificates to connect to it via SSL, and begin sending public PEX updates.

Tracker

A tracker is a peer found at a static IP, only running the networking module of Membrane and unable to form contracts with other peers. Is it a last resort mechanism for membrane peers if they are unable to find other contracted peers or looking for more peers to contract. The PEX mechanism functions in exactly the same way.

The domain name of all available trackers and their user IDs is stored in Membrane instances. A user may run a Membrane tracker, however, this will not be added to all Membrane instances and it will simply be useful to those users that have manually added the tracker to their Membrane instances.

Conclusion

The described system allows for peers to locate each other and discover new potential peers, fulfilling the requirements for PEX within Membrane. The ability for peer discovery demonstrated in figure 4.3 is unit tested and proven to work.

4.5.4 Communication

As established in the literature review (2.5) we design an ontology for communication in Membrane using the FIPA based agent communication language (ACL) as a container for our ontology.

Agent Communication Language

The FIPA Agent Communication Language (ACL) specification based on the Speech Act theory [Labrou et al., 1999] comprises of:

- A Communicative Act CA
- An ACL Message Structure
- An Associated Ontology

We choose to adapt the FIPA specification for use in Membrane replacing the standard performatives (CAs) with an implicit INFORM/REQUEST performative. This is a change from the performative based approach suggested in the literature review (2.5) as we decide the benefits of creating a stateless protocol with no replies[11], saving client memory and decrease in programming complexity far outweighs the benefits of the message having redundant information describing the content.

Because of the extensiblity requirement, we have designed the message API such that performatives are completely compatible with current messages, they would simply be ignored by earlier versions.

We opt to use the following fields from the FIPA ACL specification [Fipa, 2002]:

1. sender - Peer id of the sender
2. receiver - Peer id of the receiver
3. conversation-id - Unique message id for every message. This rolls around to 0 when $2^{64} - 1$ is reached.
4. in-reply-to - The message id can be included. -1 indicates an empty field
5. content - The content of the message
6. protocol - Indicates the version number of Membrane for parsing

We find this layout holds all the information required for handling messages. The 'in-reply-to' field is ONLY used for a PING-PONG message exchange, where we wait for the PONG to arrive to test connectivity.

Protocol Design

A protocol for both *Block Storage* and *Peer Exchange* messages is required. We discussed ontologies in section (2.5.2), however, on reflection the chosen contract technique does not require an ontology, as it just relies on values and doesn't rely on domain knowledge to make decisions. We therefore follow the API design guide's suggestions for formatting data to provide content for the described ACL using object oriented techniques to structure data.

There are nine messages that need to be sent:

- PING (For Debugging Only)
- PONG (For Debugging Only)
- Contract Update
- Evidence Request (Block Instruction)
- Evidence Response
- PEX Advertisement
- PEX Query
- PEX Response
- Data Block

Using the style guide suggests using base64 encoding byte arrays used for transferring blocks and salts described in RFC4648 [Josefsson, 2006]. It encodes each six bits of data as a byte, causing a $\frac{4}{3}$ expansion in data size. This allows the data to be transferred a string within the ACL specified, however, the data expansion is a huge downside.

To improve on this we can chose a more efficient encoding such as *basE91* [Henke, 2015] or transfer data without packaging it in the ACL to improve efficiency. While developing the prototype it was useful to have the data in a readable format as it was easy to debug and compare by eye, one of the main reasons it is suggested in Google [2017*a*]'s API style guide.

4.5.5 Gatekeeper

The gatekeeper is the package of the networking module responsible for dialling and receiving connections from peers. It takes the maximum number of allowed connections, and whether it should aim to connect to uncontracted peers, and ensures only desirable peers connect. We include the relevant code in listing **??**.

[11] As per the recommendation of [Google, 2017*a*]'s API guide

Chapter 5

User Interfaces

5.1 GUI

5.2 CLI

Chapter 6

Results & Evaluation

6.1 Unit Testing

6.2 Empirical Testing

6.3 Summary

Chapter 7

Conclusion

7.1 Limitations

7.1.1 Limitations of the Study

7.1.2 Limitations of the System

7.2 Further Work

7.2.1 Expansion 1

7.2.2 Expansion 2

7.2.3 Expansion 3

7.3 Summary

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Appendix

7.4 Code

Listing 7.1: Garbage Collection Implementation

```
/**
 * Removes any shards not referenced in the catalogue from the storage.
 */
long collectGarbage() {
  logger.info("Garbage collection - Start");
  Set<String> requiredShards = fileCatalogue.getReferencedShards();
  Set<String> garbageShards = shardStorage.listShardIds();
  garbageShards.removeAll(requiredShards);
  garbageShards.removeAll(tempProtectedShards);
  logger.info("Garbage collection - Found {} de-referenced shards",
      garbageShards.size());
  AtomicLong removedSize = new AtomicLong(0L);
  garbageShards.stream()
          .peek(x -> logger.info("Garbage collection - Removing shard: [{}]",
              x))
          .forEach(x -> {
            try {
              long fileSize = shardStorage.removeShard(x);
              removedSize.addAndGet(fileSize);
            } catch (ShardStorageException e) {
              // Ignore - It doesn't exist already
            }
          });
  logger.info("Garbage collection - Complete - Removed {}MB", ((float)
      removedSize.get()) / (1024 * 1024));
  return removedSize.get();
}
```

Listing 7.2: Storage Clamping Implementation

```
public synchronized long clampStorageToSize(long bytes, Set<Path>
    trackedFolders) throws StorageManagerException {
  long currentStorageSize = getStorageSize();
  long spaceToRecover = currentStorageSize - bytes;
  logger.info("Space Recovery - Reducing storage to {}MB. Current size {}MB.
      Need to remove {}MB", ((float) bytes) / (1024 * 1024), ((float)
      currentStorageSize) / (1024 * 1024), ((float) Math.max(spaceToRecover,
      0)) / (1024 * 1024));
  if (spaceToRecover > 0) {
    logger.info("Space Recovery - Collecting unnecessary shards.");
    spaceToRecover -= collectGarbage();
  }
```

```
  if (spaceToRecover > 0) {
    logger.info("Space Recovery - Finding un-tracked files.");
    Set<Path> notTrackedFiles = fileCatalogue.getCurrentFiles().stream()
            .filter(x -> !trackedFolders.contains(x.getParent()))
            .collect(Collectors.toSet());
    if (notTrackedFiles.size() > 0) {
      logger.info("Space Recovery - Removing {} un-tracked files.",
          notTrackedFiles.size());
      notTrackedFiles.forEach(x -> fileCatalogue.forgetFile(x));
      spaceToRecover -= cleanStorage(fileCatalogue.getOldestJournalEntryTime());
    } else {
      logger.info("Space Recovery - No un-tracked files found.",
          notTrackedFiles.size());
    }
  }

  if (spaceToRecover > 0) {
    logger.info("Space Recovery - Retiring older journal entries.");
    fileCatalogue.removeOldestJournalEntries((int) spaceToRecover);
    spaceToRecover -= cleanStorage(fileCatalogue.getOldestJournalEntryTime());
  }

  if (spaceToRecover > 0) {
    logger.warn("Space Recovery - Could not meet {}MB requirement. Excess is
        {}MB.", ((float) bytes) / (1024 * 1024), ((float) spaceToRecover) /
        (1024 * 1024));
  } else {
    logger.info("Space Recovery - Successful file size reduction. Reduced to
        {}MB.", ((float) (bytes + spaceToRecover)) / (1024 * 1024));
  }
  return spaceToRecover;
}
```

Listing 7.3: Knapsack Shard to Block Fitter

```
public static Set<String> calculateBestShards(String[] shardIds, int[]
    shardSizes, int blockSize) {
  boolean[][] retainShard = new boolean[shardSizes.length][blockSize + 1];
  int[][] tmpTable = new int[shardSizes.length + 1][blockSize + 1];

  for (int shardIdx = 1; shardIdx <= shardSizes.length; shardIdx++) {
    for (int size = 1; size <= blockSize; size++) {
      if (shardSizes[shardIdx-1] > size) {
        tmpTable[shardIdx][size] = tmpTable[shardIdx-1][size];
      } else {
        int keepShardSize = shardSizes[shardIdx-1] +
            tmpTable[shardIdx-1][size-shardSizes[shardIdx-1]];
        int ignoreShardSize = tmpTable[shardIdx-1][size];
        if (keepShardSize > ignoreShardSize) {
          retainShard[shardIdx-1][size] = true;
          tmpTable[shardIdx][size] = keepShardSize;
        } else {
          tmpTable[shardIdx][size] = ignoreShardSize;
        }
      }
    }
  }
```

```
  Set<String> selectedShards = new HashSet<>();
  for (int i = shardSizes.length-1; i >= 0; i--) {
    if (retainShard[i][blockSize]) {
      selectedShards.add(shardIds[i]);
      blockSize = blockSize - shardSizes[i];
    }
  }
  return selectedShards;
}
```

Listing 7.4: Peer Population Control

```
/**
 * Attempt to connect to new peers, spread PEX information and disconnect
     redundant peers.
 */
void maintainPeerPopulation() {
  logger.info("Running peer maintenance.");
  Set<String> contractedPeers = contractManager.getContractedPeers();
  Set<String> connectedPeers = connectionManager.getAllConnectedPeerIds();
  Set<String> trackerPeers = trackerManager.getTrackerIds();

  // First attempt to connect to any peers with pre-established contracts
  connectToContractedPeers(contractedPeers, connectedPeers);


  // Check if new connections are required and have space
  int knownPeerCount = getKnownPeerCount(contractedPeers, connectedPeers,
      friendPeers, trackerPeers);
  int remainingConnectionCount = remainingConnections(knownPeerCount,
      maxConnections);
  int requiredConnections = requiredPeers(knownPeerCount,
      contractManager.getContractCountTarget());

  boolean requireMoreConnections = requiredConnections > 0;
  boolean haveRemainingConnections = remainingConnectionCount > 0;

  logger.info("{} more peer connections for contracts. {} to connect to more
      peers. Should {} connect to new public peers",
      requireMoreConnections ? "Require" : "Do not require",
      haveRemainingConnections ? "Able" : "Unable",
      searchForNewPublicPeers ? "" : "not");

  Collection<Peer> connectedPeerSet = connectionManager.getAllConnectedPeers();

  if (requireMoreConnections && haveRemainingConnections) {
    PexManager.requestPexInformation(connectedPeerSet, contractedPeers,
        searchForNewPublicPeers);
    if (searchForNewPublicPeers) {
      pexManager.connectToPublicPeersInPex(connectionManager,
          requiredConnections);
    }
  }

  boolean isPexUpdatePublic = searchForNewPublicPeers &&
      requireMoreConnections;
```

```
    ExternalAddress externalAddress = portForwardingService.getExternalAddress();
    logger.debug("Sending external address {}:{}",
        externalAddress.getIpAddress(), externalAddress.getPort());
    PexManager.sendPexUpdate(externalAddress, connectedPeerSet,
        isPexUpdatePublic);

    // Disconnect from peers taking up useful connection slots

    if (remainingConnectionCount < 0) {
      logger.debug("Need to disconnect redundant peers. Too many connections.");
      disconnectRedundantPeers(-remainingConnectionCount, contractedPeers,
          connectedPeerSet);
    }

    // Connect to a tracker if struggling for peers.

    logger.info("Checking if tracker connection necessary.");
    int contractedPeerTarget = contractManager == null ? 0 :
        contractManager.getContractCountTarget();
    int connectedPeerCount = connectedPeerSet.size();
    int minutesFromStartup = Minutes.minutesBetween(startUpDateTime,
        DateTime.now()).getMinutes();
    boolean hasPexEntries = pexManager.getPexEntryCount() > 0;

    if (trackerManager.shouldConnectToTrackers(contractedPeerTarget,
        hasPexEntries, minutesFromStartup, connectedPeerCount)) {
      logger.debug("Connecting to tracker to assist locating more peers.");
      trackerManager.connectToTrackers(connectionManager, connectedPeers);
    } else {
      logger.info("Tracker connection not required.");
    }
  }
```

7.5 Documents

Listing 7.5: Membrane API Documentation

```
API
---

The Rest API is available on port ``13200`` by default.

Available Calls include:

Status
~~~~~~

- **URL** : /
- **Method** : GET
- **Response Params** : {hostname: [string], startTime: [dateTime], port:
    [number], version: [string], status: [string], tagline: [string]}
- **Response Codes** : Success (200 OK), Unauthorized (403), Internal Error (500)

Network
~~~~~~~
```

```
- **URL** : /status/network
- **Method** : GET
- **Response Params** : {enabled : [bool], connectedPeers: [number], networkUID:
    [string], maxConnectionCount: [number], peerListeningPort: [number],
    upnpAddress: [string]}
- **Response Codes** : Success (200 OK), Unauthorized (403), Internal Error (500)

Storage
~~~~~~~

- **URL** : /status/storage
- **Method** : GET
- **Response Params** : {currentFiles: [string[]], referencedFiles: [string[]],
    localShardStorageSize: [number], targetLocalShardStorageSize: [number],
    maxLocalShardStorageSize: [number], peerBlockStorageSize: [number],
    targetPeerBlockStorageSize: [number], maxPeerBlockStorageSize: [number]}
- **Response Codes** : Success (200 OK), Unauthorized (403), Internal Error (500)

Watcher
~~~~~~~

- **URL** : /status/watcher
- **Method** : GET
- **Response Params** : {trackedFolders: [string[]], trackedFiles: [string[]]}
- **Response Codes** : Success (200 OK), Unauthorized (403), Internal Error (500)

Watch Folders
~~~~~~~~~~~~~

- **URL** : /status/watch_folder
- **Method** : GET
- **Response Params** : {watchFolders: [watchFolder[]]}
- **Response Codes** : Success (200 OK), Unauthorized (403), Internal Error (500)
- **Other** : watchFolder = {directory: [string], recursive: [bool]}

Contract
~~~~~~~~

- **URL** : /status/contract
- **Method** : GET
- **Response Params** : {contractManagerActive: [boolean], contractTarget:
    [number], contractedPeers: [string[]], undeployedShards: [string[]],
    partiallyDistributedShards: [string[]], fullyDistributedShards: [string[]]}
- **Response Codes** : Success (200 OK), Unauthorized (403), Internal Error (500)

Modify Watch Folder
~~~~~~~~~~~~~~~~~~~

- **URL** : /configure/watch_folder
- **Method** : POST
- **Request Params** : {type: [string (ADD|REMOVE)], watchFolder: [watchFolder]}
- **Response Codes** : Success (200 OK), Partial Fail (304), Invalid Request
    (400), Unauthorized (403), Internal Error (500)
- **Other** : watchFolder = {directory: [string], recursive: [bool]}


Request Storage Cleanup
~~~~~~~~~~~~~~~~~~~~~~
```

```
- **URL** : /request/cleanup
- **Method** : POST
- **Response Codes** : Success (200 OK), Invalid Request (400), Unauthorized
    (403), Internal Error (500)


Reconstruct File
~~~~~~~~~~~~~~~~

- **URL** : /request/reconstruct
- **Method** : POST
- **Request Params** : {filepath: [string]}
- **Response Codes** : Success (200 OK), Partial Fail (304), Invalid Request
    (400), Unauthorized (403), Internal Error (500)


Request File History
~~~~~~~~~~~~~~~~~~~~

- **URL** : /request/history
- **Method** : POST
- **Request Params** : {filepath: [string], targetFilePath: [string],
    dateTimeMillis: [number]}
- **Response Params** : {filePath: [string], fileHistoryEntryList:
    [fileHistoryEntry[]]}
- **Response Codes** : Success (200 OK), Partial Fail (304), Invalid Request
    (400), Unauthorized (403), Internal Error (500)
- **Other** : fileHistoryEntry = {dateTime: [string], hashes: [string[]], size:
    [number], remove: [boolean]}
```

7.6 Tables

	Total File Size (MB)	Total Number of Blocks	Effective Block Size (MB)	Efficiency
User 1	4111	176	4400	0.93
User 2	8556	387	9375	0.88
User 3	758	34	850	0.89

Table 7.1: Storage Usage vs. Actual File Size

7.7 Surveys

Listing 7.6: Membrane Feature Survey

```
Question: What 5 features would you be looking for in a distributed backup
    system, that uses a network of peers to add resilience to your data?

Response 1:
- Make sure my data is safe
- Should be easy to setup and not require my attention
- Should avoid using too much of my network as I have limited data
- Should not slow down my games
- I would like a web interface like dropbox has
```

Response 2:
- I don't want to have to care about it after setup
- Should let me see old copies of my work
- People storing my data shouldn't be able to see it
- I want to be able to view the backups in a window
- I need to be able to get my files back quickly if I delete them accidentally (like a recycle bin)

Response 3:
- I don't want to have to rely on the speed of peer's connections to recover files.
- I want to be able to move my files from system to system, like onedrive does.
- Don't use data when connected to a phone hotspot from my laptop
- No-one can be able to see my files.
- A way to recover files by just plugging a USB stick in.

Response 4:
- Strong encryption - something that, to the best of the knowledge in the community, has not been ''broken'' and would take even super computers and exorbitant amount of time to brute force
- I use OneDrive to move files from my desktop to my laptop, this would need to be able to do the same.
- I don't wat to ever have to think about the backup service unless I'm recovering files. Should be completely transparent to me.
- The option to be able to use my own server for backup. I don't want to only rely on the network for backup.
- A good syncing feature like OneDrive so what is in the backup is always up to date, with at least a OneDrive level of versioning or better (deleted files are recoverable but changes are not)

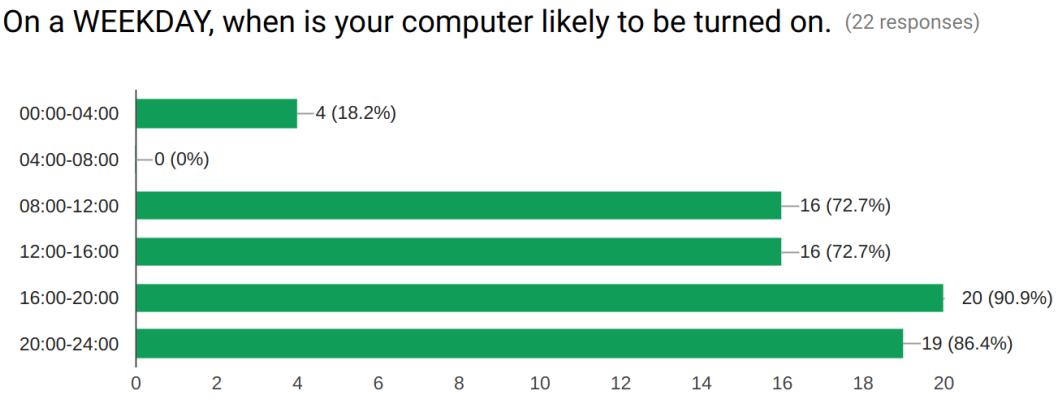
Response 5:
- The people storing my files cannot see them
- Should be able to see old documents. If I make a change to something and want to go back to the previous version I should be able to.
- I use Google Photos for image backups. A system that showed my a nice album of the images I backed up would be cool.
- Transfer Files Between System
- I want to be able to use this from a USB stick, plug it in and it immediatly starts backing up and recovering files.

Response 6:
- This needs to be able to work without my babysitting it, and cannot break!
- It needs to use an unbreakable encryption for my files. I don't want any chance of someone seeing the data they are backing up for me. I also want to be sure I'm not backing up anything illegal for anyone else!
- I need quick access to any files I backup. Otherwise this is useless.
- This can't be a drain on my laptop battery. If I noticed my fans spin up on my laptop because of backup, I would immedialy uninstall it.
- I sometimes use Google Drive to access my file from uni for example. It would be nice if I could do the same with this.

Response 7:

```
- I want to be able to just backup to my friends
- No wait for file recovery
- Should be able to see old file version, like in dropbox
- Can't slow down my computer
- I want to be able to add friends who I trust


Response 8:
- This cannot use too much of my laptop battery.
- I use dropbox for file versioning sometimes, this needs to be able to do the
    same.
- This needs to be able to run without me noticing it, just like dropbox.
- It needs to be able to show my old versions of files. I also want to be able
    to share files I've backed up from other people's computers.
- It wouldn't be a must by any stretch, but I think it would be nice to have 1
    backup tool that handles everything. As in, it does this cloud sync thing,
    but you can also plug in an external drive and it uses the same tech to
    fill it up, etc.
```



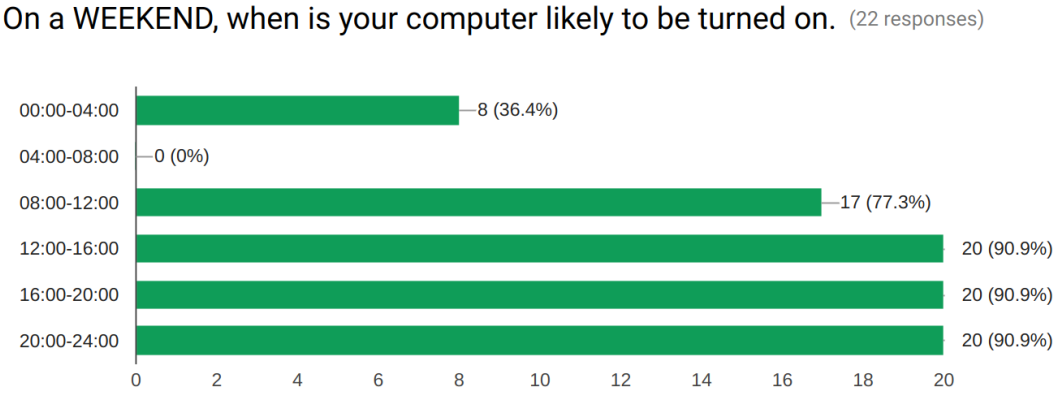


Figure 7.1: Uptime Survey