DECENTRALIZED STORAGE SYSTEM WITH VERIFICATION

(KISS)

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ABSTRACT

KISS is a decentralized storage system with verification mechanisms. The main goals of this system are to ensure durable replicated storage and to prevent or at least limit malicious peers' influence on the network while maintaining a high level of performance. In particular, attacks that aim to disrupt the integrity and storage guarantees of a decentralized storage system. The system implements a key-value storage (aka. a distributed hash table) like many others. It attempts to improve the resilience of network by introducing a verification mechanism, which are not present in other similar systems.

The nodes in the network are split into two kinds - one strictly storing files, and one for indexing and validation. Most other systems focus on the storage part and optimizing the latency as well as balanced distribution of the data. KISS aims to build on top of that and introduce verification mechanisms that aim to stop malicious peers. The storage nodes implement the Kademlia protocol and store the actual data, while the verification nodes keep track of what data should be stored and periodically verify that the data is still there. The verifier is implemented by connecting it to a ledger storage - an instance of ImmuDB, where it stores metadata about the files stored in the system and transactions. Since all requests go through the verifier nodes, they regulate what data goes into the system, what stays there, and for how long. In other words the verifier nodes are the super-users of the system that keep track of which nodes behave correctly and need to be rewarded or are malicious and need to be punished.

The current iteration of the system relies on 1 verifier node for simplicity reasons. In the future the verifier nodes will be part of a decentralized network as well, as this is a center point of failure and a bottleneck for the throughput of the system, as shown by the evaluation.

1 INTRODUCTION

Peer-to-peer (p2p) networks are distributed systems where there is no central authority. Such networks are often used for file sharing (decentralized storage). Such networks are considered resilient to attacks, because they are distributed and usually scale to numerous nodes. A lot of these networks implement a Distributed Hash Table (DHT) to store the data. There are generally two ways to implement a DHT efficiently - Chord [8], which implements a ring structure, and Kademlia [5], which implements a binary tree.

However, there are attacks that can disrupt the integrity and storage guarantees of a decentralized storage system. For example, a malicious peer can store a file and then delete it from the system, or a malicious peer can store a file and then modify it. These attacks are possible because the peers in the network are usually not controlled. There are multiple extensions to such systems to make them more secure and resilient to attacks, which we will discuss in the Related Work section.

This project proposes a system that aims to improve the resilience of a decentralized storage system by introducing a verification mechanism.

The main goals of the system are:

- Ensure durable replicated storage.
- Prevent or at least limit malicious peers' influence on the network.
- Ensure performance does not degrade by introducing the verification mechanism.
- Make all parts of the system decentralized (including the verifier in the future).
- Make the system easy to use and deploy.

As a side effect the system generates cover network traffic, which makes it harder to track the real traffic. This is not the main goal of the system, but it hides real traffic from malicious peers, or at least makes it harder to differentiate.

The system should be able to withstand attacks from malicious peers that:

- Store a file and then delete it.
- Store a file and then modify it.

- Lie about storing a file.
- Many malicious peers collude and try to disrupt the network.
- Many malicious peers join the network rapidly.
- Many malicious peers leave the network rapidly.
- Many malicious peers try to disrupt the network by flooding it with requests (DoS).

Some of these goals will be postponed for future work, since the first iteration of the system will have a centralized verifier.

2 RELATED WORK

Many decentralized storage systems have been proposed and implemented. Modern distributed storage systems achieve up to logarithmic time for insert, lookup, and delete operations. To name a few such systems - Chord [8], Pastry [6], and Kademlia [5]. The main difference between these systems is the way they organize the nodes in the network. Chord and Pastry use a ring structure, while Kademlia uses a binary tree. Kademlia is more resilient to churn and performs faster lookups, but generates more network traffic [7]. Most of these systems serve as a foundation for applications that implement some kind of decentralized storage, but we won't go into detail about them, because they are not the focus of this project.

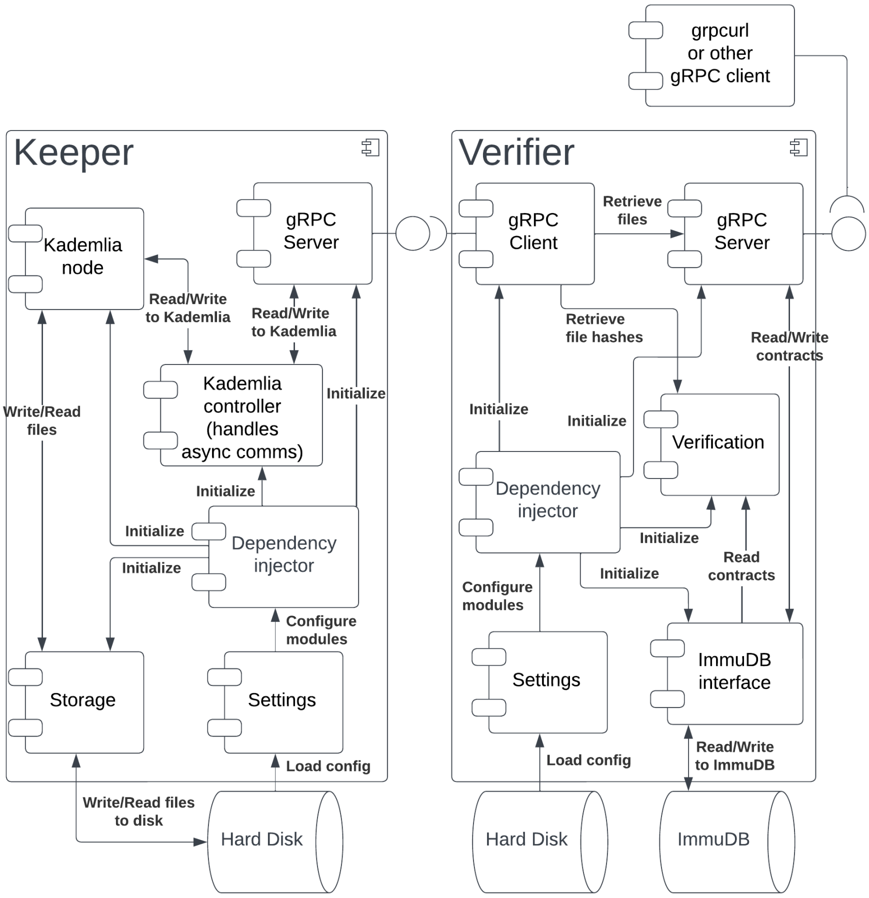
There are also multiple proposals on how to make decentralized storage systems more resilient to malicious peers. To name a few - ARA [3], Freenet , and S/Kademlia [2]. The main idea behind these proposals is to have some kind of auditing mechanism that checks if the peers are behaving correctly. ARA proposes a system where peers allocate "credits" to other peers they communicate with. If a peer A requests files from another peer B, B gains "credits", while A informs other neighboring peers that B has received "credits" from A. Peers also share information about these "credits" with other peers and use them as auditing mechanism. S/Kademlia focuses on node authentication with expensive node ID generation and verifiable messages using public and private key cryptography. S/Kademlia also routes requests through multiple different nodes at the same time in order to reduce the chance of a request falling into a malicious subnet. Freenet's approach to security is to encrypt all data and route requests through multiple nodes. It works in a way similar to Tor - nodes in the path to the target cannot tell what other nodes are in the path, except for the previous and the next node. Nodes storing the data are also obscured in the response, so the source cannot be tracked.

Tarzan focuses on anonymity of peers in the network by generating fake traffic and hiding the real traffic.

Comparison between performance between decentralized storage systems has been done before [1, 7]. The results are that Pastry is the best performer for networks with under 1000 peers, but the paper also suggests that Kademlia would probably outperform Pastry for larger networks. The results in the 2 papers differ somewhat from the results in [4], which suggests that theoretically Chord should outperform Kademlia, but the paper does not do in-depth evaluation of networks with high churn rate like [7].

3 ARCHITECTURE & IMPLEMENTATION

3.1 ARCHITECTURE



The system is split into 2 components - Keeper and Verifier. Keepers implement the Kademlia protocol and store the actual data, while Verifiers keep track of what data should be stored and periodically verify that the data is still there. In the current version there is one Verifier for simplicity reasons, but in the future the Verifiers will be part of a p2p network as well.

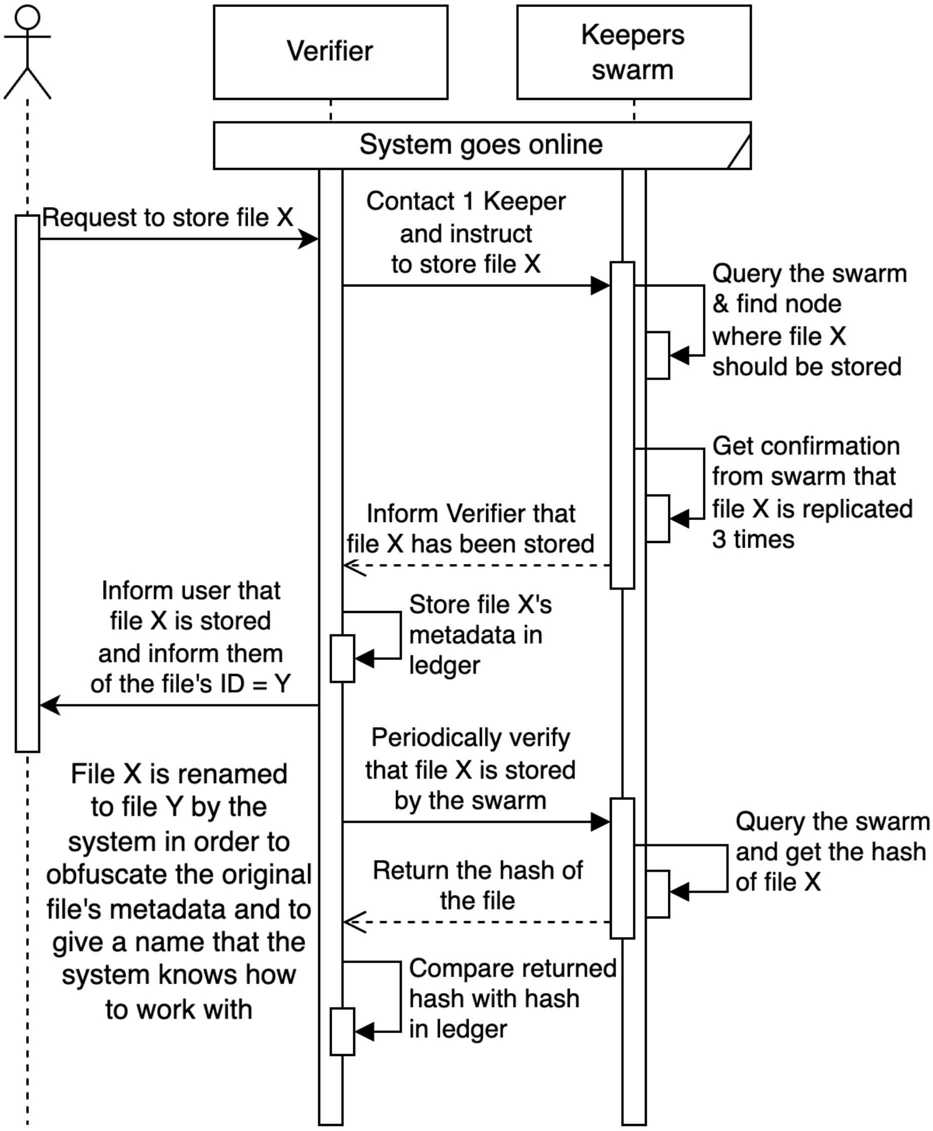
The Keepers communicate between each other using the Kademlia protocol. Kademlia is the backbone of the Keepers as it implements the peer discovery and routing. All Kademlia communication is event-based and asynchronous. In order to keep track of the Kademlia messages the Keepers use a local Hash Table.

The Verifiers communicate with the Keepers using gRPC. This protocol was chosen because it is language agnostic and fast. The Verifiers also use gRPC to communicate with the database - ImmuDB.

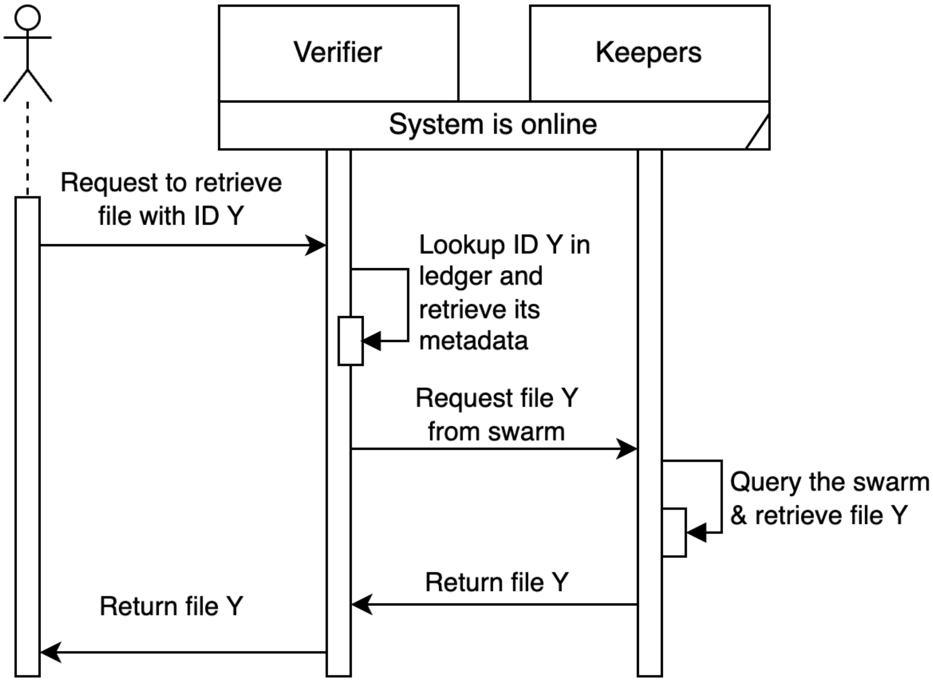
ImmuDB is an immutable database that uses Merkle trees to ensure data integrity. The Verifiers use ImmuDB to store metadata about the files stored in the system. The metadata includes the file name, and the hash of the file's content and the expiration date of the file. The expiration date is used to determine when a file should be deleted from the system. Deletion is implemented as a soft deletion - the Verifiers simply stop checking for the file's existence.

There was no library that implemented an API for ImmuDB in Rust and ImmuDB did not document how to create one, so we had to reverse engineer the python library and implement a Rust library. The Rust library is very limited as it implements only the necessary endpoints for this project. The library is fairly simple as it performs a login request, which returns a token and then every subsequent request uses this token to authenticate itself.

Below we can see a diagram of the process of saving a file in the system, followed by a diagram of the process of retrieving a file from the system.



Verifier
Keepers swarm
System goes online
Request to store file X
Contact 1 Keeper and instruct to store file X
Query the swarm & find node where file X should be stored
Get confirmation from swarm that file X is replicated 3 times
Inform Verifier that file X has been stored
Store file X's metadata in ledger
Inform user that file X is stored and inform them of the file's ID = Y
File X is renamed to file Y by the system in order to obfuscate the original file's metadata and to give a name that the system knows how to work with
Periodically verify that file X is stored by the swarm
Query the swarm and get the hash of file X
Return the hash of the file
Compare returned hash with hash in ledger


Verifier
Keepers
System is online
Request to retrieve file with ID Y
Lookup ID Y in ledger and retrieve its metadata
Request file Y from swarm
Query the swarm & retrieve file Y
Return file Y
Return file Y

3.2 IMPLEMENTATION

The system is implemented in Rust. The main reason for this is that Rust is a systems programming language, which means that it is fast and has a low memory footprint. It also provides a lot of safety guarantees, which is important for a system that needs to be resilient to malicious peers.

The common modules of the project containing constants and errors are separated in a separate library crate. The custom errors are implemented using the error_chain crate. It provides a useful macro that allows to define custom errors with a description and a display message.

```
error_chain! {
    errors {
        ConfigErr(e: ConfigError) {
            description("loading config failed"),
            display("loading config failed: {}", e),
        }
    }
}
```

This allows the custom errors to encapsulate any other errors from other crates.

Both the Keeper and the Verifier follow the same code architecture - asynchronous main with dependency injection relying on yaml settings.

The main function looks similarly to:

```rust
async fn main() {
    match run().await {
        Ok(()) => info!("shutting down"),
        Err(err) => die(err), // prints the error and exits
    }
}
async fn run() -> Res<()> {
    env_logger::init(); // initialize the logger
    // initialize the dependency injector
    let injector = dependency_injector()?;
    let grpc_handler: Svc<dyn IGrpcHandler> = injector.get();
    let kad: Svc<dyn ISwarm> = injector.get();
    // start the services asynchronously
    try_join!(grpc_handler.start(), kad.start())?;
}
```

The logger has to be initialized before any other code is executed, because the other code might use the logger. The dependency injector is initialized next. It lazily initializes the modules when one is requested for the first time, and caches the result. For example, GrpcHandler depends on the Settings module, so Settings will be initialized and then passed to GrpcHandler. Finally, we start all modules and wait for them to error out. The start methods are pretty much infinite loops that act as event listeners.

```rust
pub fn dependency_injector() -> Res<Injector> {
    let mut injector = Injector::builder();
    injector.add_module(p2p::module());
    injector.provide(
        SettingsProvider
            .singleton()
            .with_interface::<dyn ISettings>(),
            // Settings is an interface
    );
    injector.provide(
        KeeperGatewayProvider
            .singleton()
            .with_interface::<Mutex<KeeperGateway>>(),
            // No interface and no good concurrency :(
    );
    ...
}
```

The dependency injector adds all dependencies as singletons. This means that only one instance of each dependency will be created. This is good because we ensure no different instances will try to access the same resource and cause a race condition. But it also causes a huge pain to initialize some dependencies. For example, the KeeperGateway module in the Verifier, which is responsible for communicating with the Keepers over gRPC, contains a Mutex<KeeperGrpcClient<_> >. This is needed because the gRPC client does not implement the necessary traits to be thread-safe and mutable. Rust is very pedantic about having mutable variables being accessed from different threads, so it disallows the gRPC client to be modified without a mutex. So we have to wrap the gRPC client in a mutex, so we can provide the KeeperGateway as a singleton dependency. But, if we want to take control of a mutex and modify the data inside, we need a mutable reference to it. This means that the whole KeeperGateway needs to be mutable, i.e., provided in a mutex. However, providing a module surrounded in a mutex breaks the idea of providing an interface, because the mutex does not implement the KeeperGateway's interface. We also cannot provide mutex surrounding an interface, because the interface does not have a size known at compile time.

tl;dr; Rust is very pedantic about mutability and thread-safety, which is good, but it makes it very difficult to use dependency injection in a multithreaded (async) environment. We have to encapsulate modules, that are not implemented as thread-safe, into mutexes, which makes them not implement the necessary interfaces, and that breaks the dependency injection idea.

Switching to something simpler - the Settings module reads off the settings from a YAML config file. The Settings utilize the serde crate to deserialize the YAML file into a struct. The config file specifies any variables that change between instances - for example the port number and any secrets. Nothing fancy happens here.

The storage is pretty simple as well. It uses the object_store crate, which provides the necessary APIs to work with HDD storage or S3 storage.

The gRPC module is implemented using the tonic crate. It is very well documented and explains in details how to implement a gRPC server and client. It boils down to writing a protobuf definition and then tonic generates all the boiler-plate code, leaving the developer to implement only the interface methods for the server and the client.

Another pretty hard to implement module is the Kademlia module. The module itself is not hard to implement, but any interaction with the module is painful to say the least. Kademlia is implemented with 1 field - Mutex<Swarm<CombinedBehaviour> >. It has to be a mutex again, because this is the only way to provide it as a singleton, and we need to have mutable access to the Swarm, so we can read events from it. Where's the problem? Kademlia is initialized as an infinite loop that listens for events from the Swarm. This means that we have to take a mutable reference to the Swarm and then pass it to the infinite loop. Yes. The mutex is now locked, and we cannot access it from anywhere else. The solution was to make a separate module, that - SwarmController, which initializes a tunnel between itself and the Kademlia module, that it uses to send messages to the Kademlia module. i.e., These messages are the getters and setters of the Kademlia module. And they are asynchronous, because we do not know when the Swarm will be unlocked or will not be processing Kademlia events and will be ready to be used. Here is how this looks in code:

```
async fn start(&self) -> Res<()> {
    let mut swarm = self.inner.lock().await;
    let mut receiver = self.swarm_controller.lock().await;
    loop {
        select! {
            instruction = receiver.recv() => {
                // handle controller (getter/setter) event
            },
            event = swarm.select_next_some() => {
                // handle kademlia event and
            }
        }
    }
}
```

The select! macro allows us to wait for 2 blocking events and whenever 1 happens to execute the corresponding code. Since this happens inside the Kademlia module, we can safely take ownership of the swarm (make it mutable). This allows us to use the swarm and handle any Kademlia events at the same time.

The most excruciating part of the communication is how exactly the SwarmController communicates with the Kademlia module. I will try to put it into words, but it is very difficult to wrap one's head around it. Here goes.

The SwarmController shares a two-way channel with the Kademlia module. When someone calls the SwarmController getter a message is sent to the Kademlia module indicating that a getter was called. Kademlia does its p2p magic and whenever it receives a response from the Swarm it has to send back a message. In order to achieve that in a non-blocking way the Kademlia module keeps a hash table with the IDs of the requests made to the swarm together with the way to send back a response.

Here's what the code in the SwarmController looks like for a getter:

```
async fn get(&self, key: String) -> Res<Bytes> {
    // Create a channel<channel>
    let (sender, receiver) = oneshot::channel::
        <OneReceiver<Res<Bytes>>>();
    self.swarm_api .send(SwarmInstruction::Get { key, resp: sender });
    // Get the channel where the response will be sent
    let receiving_channel = receiver.await.unwrap();
    // Get the actual response
    let result = receiving_channel.await.unwrap();
    result
}
```

We send a channel containing a channel to the Kademlia module. Next, the Kademlia module accepts the request and sends back a channel where it will send the response when it receives it from the Swarm. Kademlia also saves the channel where the response will be sent to the SwarmController together with the ID of the request sent to the swarm in its hash table. This happens in this piece of code:

```
async fn handle_controller_get<'t>(...) {
    let key = Key::new(&key);
    let (sender, receiver) = oneshot::channel::<Res<Bytes>>();
    // Send the channel receiver where the response will be
    // sent to the SwarmController
    resp.send(receiver).unwrap();

    let query_id = swarm.behaviour_mut().kademlia.get_record(key);
    // Add ID:sender-channel to the hash table
    self.queries.insert(query_id, QueryResponse::Get { sender });
}
```

Finally, when the Kademlia module receives a response from the Swarm it sends it back to the SwarmController over the channel, which was saved in the hash table in the previous code snippet. Here's what the code looks like:

```
async fn handle_get_record(&self, message: GetRecordResult, id: QueryId) {
    let response_channel = self.queries.remove(&id);

    match message {
        Ok(GetRecordOk::FoundRecord(PeerRecord {
            record: Record { value, .. },
            ..
        })) => response_channel
            .send(Ok(value))
            .expect("swarm response channel closed"),
        ...
    };
}
```

I felt the need to put in code snippets, even if they are mostly pseudocode, because it is very difficult to explain the communication between the modules in words. We send a channel, containing a channel, over a channel. This is the only way to ensure we won't deadlock and keep the whole communication asynchronous.

4 DISCUSSION

The aim in this project is to build resilience against malicious peers, and not invent a new decentralized storage system. Since we want to build a network to withstand disruptions, we build this project on top of Kademlia. This means that in terms of performance of the storage operations, the system in this project will perform the same as Kademlia.

In this version of the KISS system we will not focus on anonymity of peers or node authentication. Hence, we will not compare the system to Tarzan or S/Kademlia. This will be a future work.

We can compare the approach in this project and the ARA proposal [3]. Both KISS and ARA rely on auditing to detect malicious peers or degradation of the network. Peers in ARA share information about the "credits" they have given to other peers. These "credits" are used to determine if a peer is behaving correctly, by requesting the "credits" from other peers that have interacted with it. An issue with this approach would be if a subnet is composed entirely of malicious peers. Then a peer that has only malicious peers can freely adjust its credit score. Another problem would be generation of fake requests in order to increase the score of malicious peers, that store data for these requests. Peers in the KISS network are not as "smart" and do not have such responsibility. Instead, the audit is performed by an outside entity. This entity might be another decentralized network or a centralized authority. This delegates the complexity of keeping the network in check and shifts the problem elsewhere. Currently, KISS uses a centralized Verifier, but in the future it will be possible to use a decentralized network. In this case it won't suffer from malicious subnets, because the Verifiers will be rotated and are not necessarily peers that have recently interacted with a given Keeper. Also, since answering requests doesn't contribute to a peer's reputation there is no reason to flood the network with fake requests. It doesn't mean that a DoS attack against the network is impossible, but it will not affect the reputation/trust of the peers. A strategy to prevent a DoS attack can be deployed separately from the reputation system, and it can work independently without taking into account what is the underlying network.

5 EVALUATION & CONCLUSION

Let's first discuss the language choice - Rust. Rust is a compiled language that produces small statically linked binaries. It claims to be as fast as C/C++, memory safe, and thread-safe without a garbage collector. Performance and size are important for the following reasons:

- A small compiled binary means it can run on a wide range of devices, such as a Raspberry Pi or mobile devices.
- A good performance is important so that the system doesn't become a burden on the user's machine.
- Compiled language means no external runtimes, so the user doesn't have to install anything else.

Rust is a memory safe language, which means that it is very difficult to have memory leaks, buffer overflows, race conditions, etc. This means that the system will be more resilient to attacks.

To give the readers some numbers about the binary size - compiling the Keeper module into a binary produces a 9 MB binary. This is a very small size for a binary that can run a decentralized storage system and is statically linked. That means it has no external dependencies and can run on any machine that has a CPU. In comparison, a simple Hello-World Go program would compile to less than 100 KB, but it would require a Go runtime, i.e. it will be dynamically linked to libgo.so, which is around 47 MB. And this is without any other dependencies. The Keeper binary, on the other hand, uses approximately 450 crates (Rust libraries), which are statically linked and is only 9 MB.

TODO ... write more about the evaluation

A
AN APPENDIX

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