This is the Project Title

Your Name

Master of Science

Cyber Security, Privacy and Trust

School of Informatics

University of Edinburgh

2022

Abstract

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Declaration

I declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification except as specified.

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Acknowledgements

Any acknowledgements go here.

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Chapter 1

Introduction

The predawn of the 21st century was marked by unprecedented growth in the information technology field, especially after the commercialisation of the World Wide Web. Every household got plugged into the internet, and every person could navigate through web pages, shop online, send emails and communicate with others across the globe. During that era, the internet was a safe place predominantly used by academics and hobbyists. However, once everyone became a potential user, crime shifted from the analogue to the digital world.

Many hacker groups have different reasons for attacking private communication channels, targeting personal information, such as passwords, credit card numbers, and government emails. Hackers can be (a) cybercriminals who want to exploit users' data for profit, (b) governments targeting private messages for national interest or (c) security researchers challenging and enhancing systems.

Nowadays, we overcome most of the vulnerabilities related to plain-data transfers over the wire/air using the notion of cryptography. Even though this mechanism seems to provide adequate security, it fails to encapsulate metadata concealment. Metadata such as the message size, the communication duration, the message origin and destination leak information of an encrypted, "secure" transmission. A global adversary passively eavesdropping on every network node can statistically observe a message's sender and receiver with a certain probability. Characteristically, the former National Security Agency (NSA) and Central Intelligence Agency (CIA) director General Michael Hayden said that "we kill people based on metadata". Hence, researchers have been steering towards new means of communication that respect users' privacy and improve anonymity.

Mix Networks (Mixnets) provide a solution to the metadata anonymity issue by

routing equal-sized messages through a chain of nodes (Mixes). Mixes shuffle messages using different techniques to obliterate any link between the sender and the receiver.

The Mixnets pioneer David Chaum proposed Cascade networks as a tool for a hard-to-trace electronic mail exchange system back in 1981. Nevertheless, his idea did not succeed due to (a) the high computational requirements of such a system, (b) the significant network latency and (c) the lack of quality implementations[]. Soon, researchers realised the potential of Mixnets and their applications to many domains. Such applications include remailers[], instant messaging apps[], or even more recently, blockchain transaction routing apps that provide anonymity[]. In addition, researchers have developed two simulators[] - Simulator and MiXiM - to empirically evaluate Mix Networks' performance and anonymity. When designing a Mixnet, we can have several design configurations. With the term configurations, we refer to different mixing techniques and topologies, which we will explain later in this study.

Within the context of this project, we are interested in experimenting with the existing Mix Network simulators, trying to answer the following questions:

1. Which simulator is better to adopt for future research and development?
2. How do simulators are compared in terms of performance (time required to run a simulation and memory used)?
3. What features do simulators implement?
4. How do simulators score in terms of their realisation?

Additionally, according to published related work[], both simulators support static scenarios assuming a network is operational as initialised. This fact raises the following questions:

1. What happens in a situation where Mixes fail arbitrarily, forming an imbalanced network?
2. If Mixes fail, can we achieve the same or worse anonymity?
3. How is the network latency affected?

The two hypotheses of the current dissertation have been motivated by these questions. The existing literature does not elaborate on these matters, yielding a research opportunity. In more detail, our first hypothesis assumes that both simulators perform

equally and can contribute to future research. Our second hypothesis focuses on the behaviour of imbalanced stratified Mixnets, assuming that anonymity downgrades since some Mixes receive less traffic. To test our hypotheses, we run a series of experiments and propose a framework that enables us to compare both simulators to a certain degree.

The contribution of this project is threefold. We initially assess both simulators quantitatively and qualitatively to find their potential. Secondly, we perform a short replication study regarding previous work. Thirdly, we extend one of the simulators to support a Stratified network where nodes crash arbitrarily during the transmission rounds.

The conducted analysis suggests that the MiXiM simulator offers a plethora of features; however, the code seems to be buggy and not entirely functional. On the other hand, Simulator[] (Piotrowska's project has not an official name and is called "Simulator") has fewer features but works appropriately, has cleaner code, and therefore can be trusted for further development. Nonetheless, it is worth mentioning that Simulator is a high memory demand software. Remarkably, increasing the number of users in a simulation requires lots of memory. At the same time, the simulation runtime sharply increases.

In addition, we observe that a dynamically imbalanced Stratified Mixnet is not compromised in terms of anonymity since all mixes will receive the same amount of traffic in the long term. Similarly, a Stratified Mixnet with a constantly different number of nodes on each layer - statically imbalanced - achieves the same levels of anonymity. As noticed, the number of mixes in the middle, first, and last layers are not significantly affecting anonymity. In other words, all layers affect anonymity equally. Furthermore, assuming the same traffic while increasing the number of mixes per layer indicates a decline in anonymity. Also, we find out that the number of users sending and receiving messages over the network significantly impacts anonymity. In other words, anonymity sharply increases when a network facilitates thousands of users. Finally, the current realisation of Stratified networks seems not to affect the average end-to-end transmission latency.

The following chapters are organised as follows. Chapter 2 briefly introduces background knowledge, including Mixnets fundamentals and the anonymity metric used. Chapter 3 focuses on comparing the provided simulators, qualitatively and quantitatively. Chapter 4 covers the replication and comment of existing literature using both simulators. Chapter 5 presents our analysis and experiment conducted to bring conclusiveness to our research questions. Finally, chapter 6 summarises the key points

and lessons learned from this project and discusses future directions on this topic.

Chapter 2

Background

This chapter focuses on essential information and background knowledge needed to understand Mix Networks. Next, we describe the structure of a Mixnet and how it operates, as well as various system arrangements regarding network topologies and mixing techniques. Also, we introduce and define the metric of entropy, which we will use to measure anonymity in subsequent chapters.

2.1 Mix Networks Fundamentals

Mix Network is a communication system which enables us to exchange messages from one end to another, hiding metadata. In more detail, metadata includes but is not limited to geographical location, message sender and receiver, transmission time and frequency, size of the message and the message sequence. Mixnets remove time and sequence-related correlation factors between a message sender and receiver as they route same-size messages through a chain of nodes called Mixes. Mixes can be arranged into specific formations called topologies, defining how they are interconnected. Whenever a Mix receives a message m, it is permuted within a set of other messages M. The messages' permutation is called mixing and can be conducted using various techniques. Mixing aims to hinder an adversary from linking input and output messages of a Mix. Still, a global adversary can observe a sender initiating a message transmission and a receiver acquiring a message. For this reason, Mixnets use decoy/cover traffic to confuse an adversary, determining a real from a fake message.

Furthermore, each topology and mixing technique has advantages and disadvantages, yielding scalability and performance versus anonymity tradeoffs. In the following sections (... ..), we thoroughly analyse available topologies and mixing techniques,

distinguishing their differences.

2.2 Mix Network Topologies

2.2.1 Cascade

This topology defines a simplified version of Mixnets, where all messages pass through a predetermined chain of nodes[6]. However, Cascade topology has many limitations in terms of scalability. Notably, its maximum throughput is caped to the throughput of a single Mix; thus, network latency is high as well. Besides that, If we have any malicious node on the chain, the whole system can be compromised or fail to deliver any messages, turning the Mix into a single point of failure. We can comprehend what a cascade topology looks like in Figure 2.1a

2.2.2 Multi-Cascade

This topology removes the Cascade topology limitations of scalability and single point of failure by deploying multiple parallel Cascades. Figure 2.1b depicts this topology. As we understand, the main advantage of this formation is the greater availability and scalability. The user can select a different Cascade to transmit a message. Also, having multiple Cascades allows the network to process more messages simultaneously. However, if a Mix on a Cascade is malicious, we will get less anonymity since there is no way of routing traffic between the different Cascades.

2.2.3 Stratified

This topology comprises a set of layers. On each layer, we can have a fixed number of mixes. Every Mix that belongs to layer l is bonded to every node that belongs to layers $l-1$ and $l+1$[8]. Variations of this topology are (a) fully connected nodes as described above and (b) semi-connected nodes where each node in layer l communicates with only a set of nodes on layers $l-1$ and $l+1$[7]. Stratified topology is flexible regarding scalability and latency because we can handle more traffic by adding more mixes in each layer. Also, having many mixes in each layer makes the network crash and fault tolerant. However, we must note that if a stratified topology gets too large and the traffic for some reason is reduced, anonymity is also reduced. This occurs because messages split to more nodes, and therefore we have less mixing. We can overcome this issue

by generating decoy traffic, but we must recognise that an extra computational cost is accompanied too. Figure 2.1c illustrates a fully connected stratified topology.

2.2.4 Mesh

In this topology, Mixes are loosely arranged. Specifically, there is a link between every Mix in the network. A mixing route can start and finish at any node. Nevertheless, the muddled paths, a message can take on this topology, make it hard for researchers to measure anonymity. Hence, it is not widely realised and used. Figure 2.1d depicts a mesh topology.

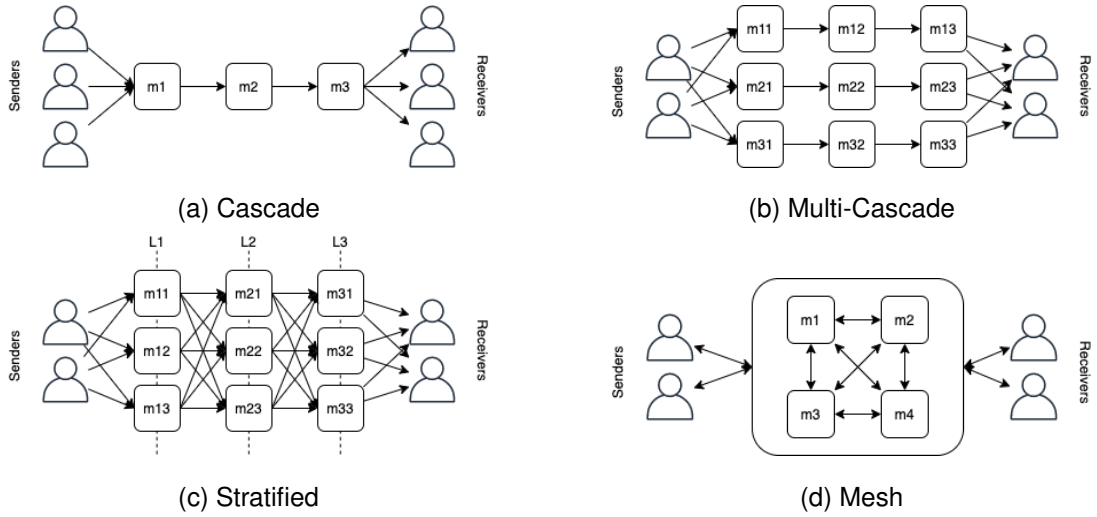


Figure 2.1: Mixnets Topologies

2.3 Mixing Techniques

2.3.1 Time-Based

The time-based mixing technique aims to collect incoming messages and permute and forward them every t seconds, where t is a system-defined variable. Figure 2.2a illustrates how time-based Mixes work. The advantage of this mixing technique is the control of the message transfer delay. Nonetheless, on the downside, we do not know and govern how many messages we mix. This is because a different number of messages may be received in separate rounds. As a result, the number of messages shuffled each time is not the same; therefore, the anonymity set can sometimes be either large or smaller. A small set of messages infers reduced anonymity. To keep anonymity

above a baseline, we must incorporate complementary cover traffic, which comes with an extra computational expense.

2.3.2 Threshold-Based

Similar to time-based mixes, a threshold Mix buffers messages into a queue until a predefined threshold is reached. Then, we shuffle and forward messages to the next hop[]. We observe a threshold Mix in Figure 2.2b. In contrast with timed Mixes, threshold Mixes allow us to control the anonymity set of messages being processed. Nonetheless, this technique has some disadvantages as well. Primarily, the problem arises when the network does not have much traffic, and the receiving buffer does not reach its limit shortly. As a result, message delivery will be delayed significantly, which is not ideal for the user's experience. The solution to this pitfall is to integrate cover traffic in order to fill a Mix with messages more frequently. As mentioned earlier, this comes with a computational overhead.

2.3.3 Pool-Mix

This hybrid mixing technique[25] derives features from timed and threshold mixing approaches. We release a fraction of the messages every t seconds if a threshold is reached. The bright side of this realisation is that a message leaving the Mix can be either a new message which just entered the pool or an old one which was not picked during the last emission. There is no way of knowing which one was picked. Consequently, anonymity is improved. At the same time, one could assume this feature is a bug. In other words, a message can stack in the pool for quite some time before arriving at its destination. We observe that this fact yields unexpected delays. Besides that, a pool Mix requires many messages to work optimally. Therefore, this solution might need to include cover traffic to increase the network's capacity. Figure 2.2c illustrates a Pool Mix.

2.3.4 Continues

This mixing technique depends on a delay given by the message sender[26]. The main advantage of this approach is that messages are not shuffled together, and therefore, there is no statistical inference. As described in the literature, it has a memory-less property[]. Each message is treated individually, and the dispatch timestamp is not

affected by the arrival of any other message. Figure 2.2d illustrates a Continues Mix.

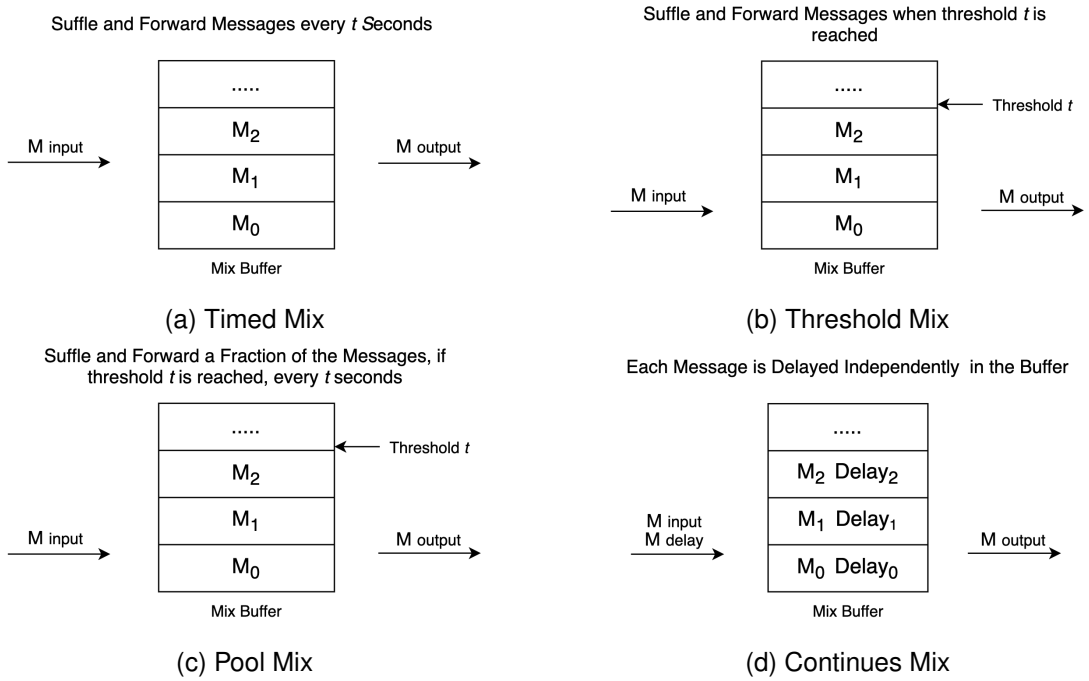


Figure 2.2: Mixnets Mixing Techniques

2.4 Measuring Anonymity

As many scientists stated in the past, ”Entropy is the natural order of the universe”, meaning natural chaos. One way to measure anonymity in Mixnets is entropy. In other words, we try to measure the chaos among message transmissions. Hence, we use the Shannon entropy formula (the result is in bits) to achieve the desired results. Equation 2.1 describes that formula. High entropy values imply better anonymity than lower values. There is no way of identifying acceptable entropy levels since this depends on the network size and adversary capabilities. In the following formula, we denote as $p(x)$ the probability that an attacker can assign to a user being the message sender. For instance, if we have an anonymity set of 1000 indistinguishable messages within a Mix buffer, we have 9.96 bits of entropy. ($Entropy = -\sum_{i=1}^{1000} p(\frac{1}{1000}) \log_2 p(\frac{1}{1000}) = 9.96 bits$).

$$H(X) = -\sum_{x \in X} p(x) \log_2 p(x) \tag{2.1}$$

Chapter 3

A Deep Dive Into The Simulators

This chapter describes MiXiM and Simulator, criticising both projects qualitatively and quantitatively. Next, we provide information about the simulators' realisation, development decisions, execution workflow and supported features. We also conduct a baseline experiment, measuring their needs for computational resources. Finally, we aggregate this information on a competitive grid to decide which software is potentially the best to adopt for future research and development.

3.1 Simulator

Piotrowska's work[] focuses on creating a simulator for evaluating the anonymity, latency, bandwidth overhead and scalability of Mix Networks over different design configurations. Her study mainly used the Simulator to compare existing projects - Elixxir, HOPR and Nym - deployed on Mix Network infrastructure with different layouts.

The developed software realises many features that capture real-world use cases of Mix Networks, but it is not limited to it. Even though the simulator can handle peer-to-peer (P2P) network simulations, we are not interested in such network formations within the context of this project. Next, we will look deeper into the Simulator's intrinsics, reporting on its core functionality, available features and input parameters. Additionally, we will run the simulator against a baseline configuration file using profiling tools[] and capture useful information about the simulation execution. This type of information will subsequently enable us to comment on simulation bottlenecks.

After analysing Piotrowska's simulator, we understood the code intrinsics and captured its approach when simulating a network. The project is well-designed, with

the main simulation entities abstracted into classes. In particular, there are abstractions for the following entities: (a) Network, (b) Mix Node, (c) Client, (d) Message and (e) Packet. Even though it appears to exist a provision for splitting messages into packages, it seems that this part of the code is incomplete, and consequently, all messages are of one packet size.

Furthermore, this simulator allows users to run experiments given many options. Specifically, there is support for many topologies, such as (a) Cascade, (b) Multi-Cascade, (c) Stratified and (d) P2P. In addition, there is an option for two mixing techniques (a) batch and reorder - threshold - and (b) poisson mixing -continues. The current implementation has default-enabled cover traffic generation for both clients and Mixes. Finally, the Simulator outputs the anonymity metrics of entropy and unlinkability.

3.1.1 Execution Workflow

The workflow of executing a standard simulation scenario is as follows:

1. Read user-generated configuration file.
2. Initialize global/environment variables.
3. Initialize loggers.
4. Create and initialize a Network object comprising a set of clients and Mix Nodes.
5. Randomly select two message senders and one recipient from the clients' set.
6. All clients begin generating cover traffic, while the initially elected senders will also generate real traffic. The message routing is selected randomly on every packet hop. The current step is simulated for three phases, burnin, execution, and cool down. During the burnin step, clients and Mixes generate only cover traffic, and no logging is performed. On the other hand, logging is enabled during the execution stage. During that phase, clients and Mixes send both real and cover traffic. We log entropy for every real message on every hop. Lastly, we stop sending real messages during the cool-down phase while we continue sending dummy messages.
7. Ultimately, the Simulator presents results to the user after inspecting the execution logs.

3.1.2 Input Parameters and Configuration File

To begin with, the Simulator takes as input some command-line arguments, defining the simulation mode and necessary configuration and log directories. There follows a list of the accepted command-line arguments and their descriptions:

> `-mode` **(required)** *(string)*: This describes the mode in which we run the simulator. The accepted modes are *test*, *test_diff*, *transcript*, *synthetic traces*, and *anon*; however, only the *test* mode is entirely realised. We have no clue about the functionality or purpose of the other modes.
>
> `-exp_dir` **(required)** *(string)*: This argument declares the directory's path, where the Simulator will dump any experiment logging files.
>
> `-config_file` **(required)** *(string)*: This is the path to the configuration file, describing the simulation settings.

The following command-line arguments are declared but never actually used in the Simulator. We assume that a future continuation of this project will frame their purpose. These arguments are `-test`, `-datadir`, `-hour`, `-12hour`, `-minute`, `-day`.

Moving to the configuration file, we can observe nine sections describing different simulation aspects. We present a sample configuration file in Appendix

Section 1 - *Experiment Id*: In this section, we provide a simple label to help keep different simulations in order.

Section 2 - *Logging*: This section allows us to enable or disable logging. The attribute `dir` extends the logging directory path specified in the command-line arguments. The attributes `client_log` and `mix_log` shown in the configuration sample are never used throughout the simulation.

Section 3 - *Simulation Phases*: This section is related to simulation phases - burnin, execution and cool down. Mainly we can define the duration of each stage.

Section 4 - *Network Topologies*: This part of the file describes the supported network topologies of the simulator - Cascade, Stratified, Multi-Cascade and P2P - and their properties, such as the number of layers and layer size for stratified topologies or length and wideness for Cascade/Multi-Cascade topologies.

Section 5 - *Packets*: This section defines the packet size (feature not realised).

Section 6 - *Messages*: This section defines the message size (feature not realised, all messages are of length one packet).

Section 7 - *Mixing Configurations*: This section describes, Mixes' settings like the average delay before sending a packet (continues mixing) and the batching of messages according to specific batch size (threshold mixing).

Section 8 - *Clients Information*: This section specifies information about clients such as the number of participating clients, how often the client adds a real message to the send buffer, the send rate, and if the client is generating cover traffic, and if so, at what rate. It is important to note that the attributes `rate_ack`, `ACK`, `retransmit`, `dummies_acks`, and `max_retransmissions` are never used.

Section 9 - *miscellaneous*: This section keeps information denoting the length of a message-id and the number of total real messages we want to send during the simulation.

3.1.3 Baseline Simulation and Profiling Measurements

In our endeavour to assess Simulator, we run a series of experiments to identify its performance and quality of results. In particular, the baseline simulation examines the Simulator's behaviour in terms of space, memory, time complexity, and the network's entropy. We run the same experiment for the three established topologies - Cascade(10 Mixes), Multi-Cascade (3x10 Mixes) and Stratified (3x10 Mixes) - while increasing the simulation duration from 100 to 10000 time ticks. We also configured the mixing technique to Poisson (i.e. Continues), the number of clients to 100, and set the number of real messages under transfer to 1000.

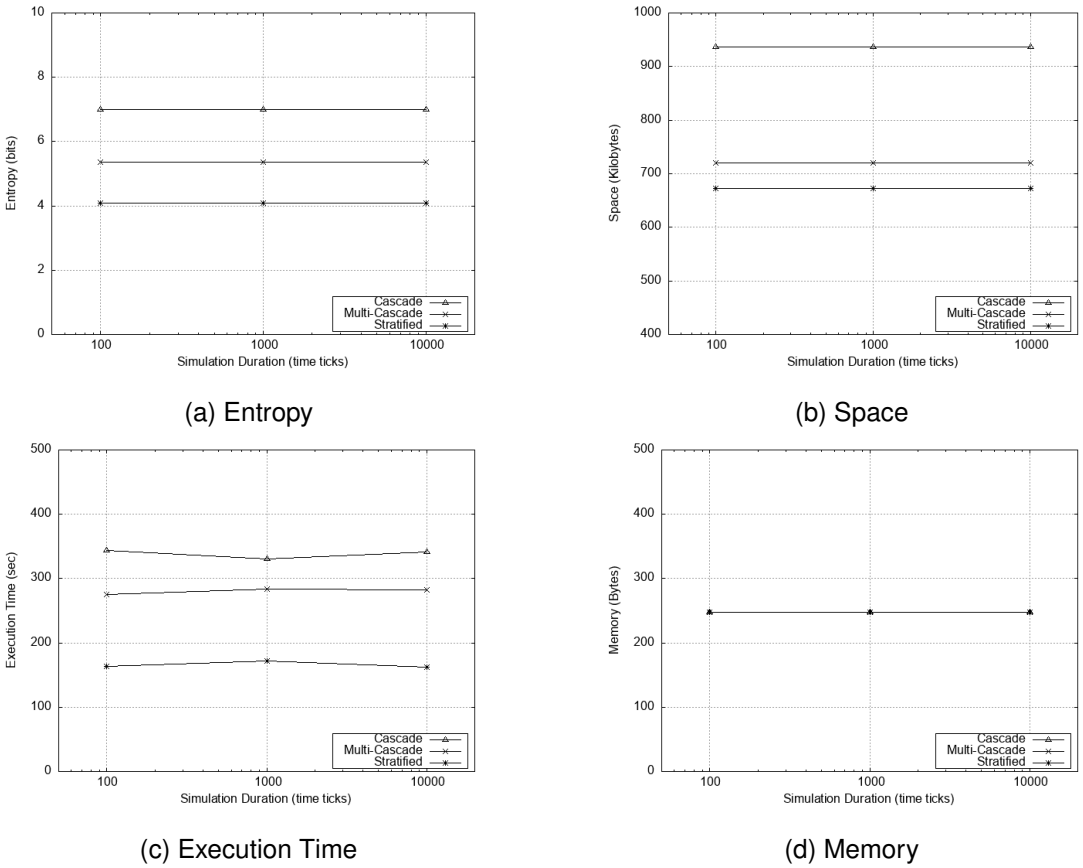
Our anticipation regarding memory usage assumes all experiments will deliver the same results for all topologies except Cascade. We establish our assumption on the fact that a single Cascade topology has fewer Mixes than the other topologies described earlier. However, according to Figure 3.1d, our hypothesis fails since the Simulator uses the same amount of memory - roughly 247 megabytes - in all experiments. In a later chapter, we will point out that memory usage solely depends on the number of users we are simulating.

In regards to space complexity, we expect to have differences among topologies. Specifically, a Cascade Mixnet needs to route traffic through a chain of nodes. The network's capacity aligns with a single mix's capacity. Therefore, every time we dump each Mix's logs, we observe log lines to repeat because messages stall there for a long time. A Multi-Cascade Mixnet performs better since there are parallel chains of Mixes. The Stratified topology should be the best since messages continually move from one Mix to another and do not repeat in the log files. Indeed, our hypothesis is accurate, and

we can notice the results in Figure 3.1b

Execution time should follow the same pattern as space complexity, given the same reason concerning the nature of each topology, as noted previously. We observe in Figure 3.1c that this is mostly true, except for the Simulation duration of 1000 time ticks. This negligible time offset, on Figure 3.1c, could be caused by other processes running on our workstation at that moment.

Further, we need to check if Piotrowska's simulator reasonably captures the notion of entropy for each topology. According to our measurements in Figure 3.1a Simulator reports higher entropy for Cascade topology. There follows Multi Cascade and Stratified. These results are acceptable since aggregating more messages on each hop increases Mix's anonymity set, so entropy is higher.



(a) Entropy

(b) Space

(c) Execution Time

(d) Memory

Figure 3.1: Simulator Baseline Experiments

Finally, we run Piotrowska's project using a *cProfiler*[] to get visual information and statistics about its execution tree (sequence of functions called). We get a detailed representation of the execution tree in Appendix. We also analyze the project using *SonarQube* to get information about the quality of the code. In the first place, *cProfiler*

reveals that 59.75% of the CPU usage was for processing packets, while the heaviest task running under the *packet processing* branch was *entropy_update()*. *entropy_update()* took 38.76% of the total CPU usage, indicating a possible bottleneck to the whole execution. Regarding *SonarQube* results, we found out that 2.7% of the code is duplicated, and there are 57 *code smells*, 2 *bugs* and 5 *security issues* of no great importance.

3.2 MiXiM

Guirat et al. carried out a similar attempt to develop an event-driven Mix Network simulator. In particular, Guirat et al., in their study[], present MiXiM, a simulation framework that helps academics and industry professionals assess various Mix Networks design options. Next, we will delve into the simulator implementation, reporting on its functionality, available features and input parameters. Besides that, we aim to run the simulator against a baseline scenario, reporting on its outputs and execution statistics. This information will help us decide if MiXiM is a well-built and feature-proof tool that brings out the most.

After we analysed MiXiM, we understood the code intrinsics and captured its approach when simulating a network. Likewise, Piotrowska's work is well-designed and abstracted into similar entities: (a)Simulation, (b) Network, (c) Mix Node - Poisson Mix, Pool, Timed Mix, Threshold Mix - (d) Client, (e) Relay - abstraction of an attacker - and (f) Message.

Moreover, the simulator allows users to run experiments given various configurations. In more detail, there is support for many topologies, such as (a) Cascade, (b) Multi-Cascade, and (c) Ctratified. Additionally, there is an option for three mixing techniques (a) Timed mixing and (b) Poisson mixing, (c) Threshold Mixing and (c) stop-and-go mixing[] (i.e. Continues). Besides that, the users can enable dummy traffic generation, giving a specific generation rate. Another outstanding feature is the introduction of corrupted mix nodes during the simulation. Finally, the Simulator outputs the anonymity metric of entropy.

3.2.1 Execution Workflow

The workflow of executing a standard simulation scenario is as follows:

1. Read user-generated configuration file.

2. Create and initialize a simulation object passing all the input parameters found in step 1.

3. Call the run function of the simulation object.

4. Create and initialize a Network object comprising a set of Clients and Mix Nodes, including possible corrupted nodes. Connect nodes with their neighbours.

5. All clients begin generating traffic according to the given λ generation variable. In the meantime, dummy traffic is generated as well.

6. The simulation is executed in a single phase lasting for several time ticks declared in the configuration file. During each message transmission from one node to another, entropy is updated.

7. After inspecting the execution logs, MiXiM presents the entropy to the user.

3.2.2 Input Parameters and Configuration File

MiXiM, compared to Simulator, does not take any command-line arguments. We only observe a single configuration file with six different sections. We present a sample configuration file in Appendix .... Following, we provide a thorough description of the aforementioned file.

Section 1 - *DEFAULT*: Under the DEFAULT section, we recognise the number of clients sending and receiving messages in a network and a parameter called lambda_c representing the rate of generating messages per time tick.

Section 2 - *TOPOLOGY*: In this section, we describe settings for all three supported topologies - Stratified, Cascade and Free Route. The parameter fully_connected enables us to have a complete or a semi-connected Stratified topology. Also, in this section we define the routing strategy by choosing between the source - users choose the route - or hop_by_hop - random selection. Other parameters in this section include E2E, the minimum end-to-end transmission delay, and n_layers, l_mixes_per_layer and n_cascades, which describe the number of layers and their corresponding number of mixes.

Section 3 - *MIXING*: This section is related to the available mixing techniques. We have the mix_type, which can be Poisson, Time, or Pool and mu, which is the delay on each mix node. For each of the aforementioned mixing techniques, the variables timeout, threshold, and flush_percent, match each case accordingly.

Section 4 - *DUMMIES*: This section regards dummy data generation. The user sets the variables client_dummies to enable or disable dummy messages, rate_client_dummies to control the dummy data generation, link_based_dummies to send dummies dropped on the next hop, multiple_hop_dummies to send dummies that last for many hops, and rate_mix_dummies to generate dummy messages on the Mix.

Section 5 - *NODE_SELECTION*: All attributes in this section are not required during the simulation and might be the fragments of older software versions.

Section 6 - *THREAT_MODEL*: In this section we define the number of corrupted nodes and if we want them uniformly distributed across the network layers.

3.2.3 Baseline Simulation and Profiling Measurements

Section 3.1.3 described our attempt to evaluate the Simulator according to a baseline scenario. We make the same assumptions for MiXiM, running the same experiments. Unfortunately, our expectations did not match the results since we could not reproduce every simulation.

Mainly, we managed to simulate Stratified topologies for 100 and 1000 time ticks. Attempting to run experiments for Cascade and Multi-Cascade network arrangements failed due to run-time errors. Simulating a Stratified topology for 10000 time ticks resulted in a crash too. We were hesitant about the failure causes, so we decided to probe the software code-base to uncover potential issues.

Indeed, skimming the source code, we managed to spot four bugs we present in the following list:

1. The parsing section of the code accepts as valid topologies ”cascade”, ”multi-cascade”, and ”stratified”. Nevertheless, this is not the case for some files - Network.py, Simulation.py and Client.py - where the code expects a topology called ”XDR”. This contradiction causes MiXiM to crash, given the topologies ”cascade” and ”multi-cascade”.

2. The variable n_cascade, which describes the number of parallel Cascades in Network.py, is hard coded. Hence, the simulation is not assuming the user’s configuration.

3. In file Simulation.py, a variable is declared as *otherClient*, while the software developer used the name *other_client* when initialising the variable. Consequently, the initialisation is meaningless, and *otherClient* has no value.

4. The initial parsing of boolean parameters from the configuration file is incorrect since the code used is a Python2 command which, when using Python3 - which other project libraries require - always returns True. Therefore, all boolean parameters in the configuration file are True, no matter their actual value.

The purpose of this project is not to fix someone else's work but to assess it. Consequently, we did not proceed with further code reviews or repairs.

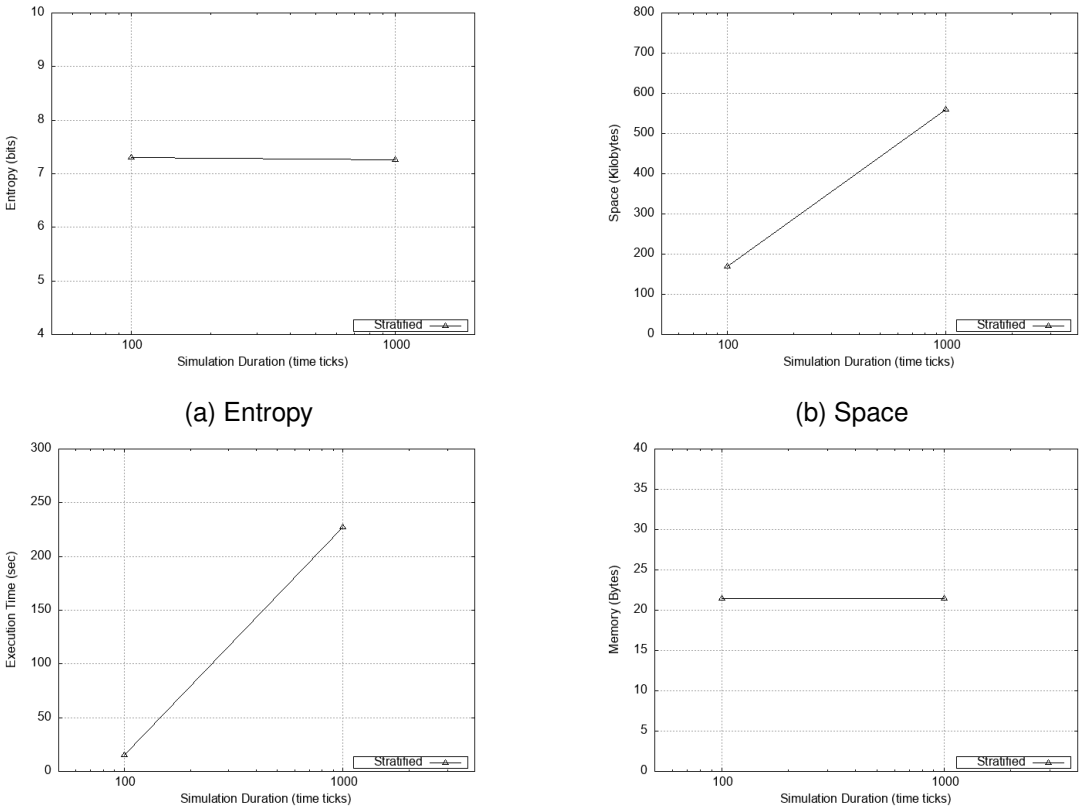
In regards to the successful experiments, we can observe the results in Figure 3.2. Surprisingly, the execution time and space used to dump log files increase linearly for different simulation time-frames. According to our previous code analysis, this is justifiable since clients in MiXiM generate messages based on predefined λ rate. The longer the simulation, the more messages are generated. Hence, more processing time and storage space are required.

On the other hand, Simulator uses only the number of specified target messages regardless of the duration. Furthermore, it is notable that in terms of memory usage, MiXiM is sufficient, requiring only 21.4 MB of RAM for all our successful trials. Lastly, we cannot deduce further valuable insights from these graphs because, as we mentioned earlier, we failed to perform all baseline experiments.

3.3 Compasisson Framework

To bring conclusiveness to our simulators analysis, we present in this section a comparison framework. Our ultimate goal is to find out which simulator is better to adopt for further development in the future. A comprehensive comparison framework needs to evaluate multiple factors. Therefore, we assumed the following KPIs (key performance indicators) (a) Topologies, (b) Mixing Techniques, (c) Routing Methods for Stratified topology, (d) Cover Traffic, (e) Corrupt Relays, and (f) SonarQube Code analysis insights.

Table ... illustrates how MiXiM and Simulator are compared in each aspect. We notice that MiXiM realises 13 features, while Simulator has only 9. Nonetheless, it is essential to prompt that most of MiXiM's features do not work, crashing on runtime. Also, both software achieve high scores in object abstraction, while code readability for MiXiM seems to be poor. Further, MiXiM has 81 *code smells* compared to Simulator, which has only 57 *code smells*. Moreover, MiXiM has double the *bugs* and *security issues* compared to Simulator, which has 2 and 5, respectively. Eventually, both projects



(a) Entropy

(b) Space

(c) Execution Time

(d) Memory

Figure 3.2: MiXiM Baseline Experiments

have negligible amounts of *code duplication*.

Ultimately, we decided that the best simulator, so far, is Piotrowska's Simulator. We justify our decision mainly based on the usability aspect. Even though MiXiM advertises a large set of features, it fails to deliver a working code-base. We are confident that Simulator is a well-designed software and can be improved by supporting a complete set of features, in the future. Besides, Simulator justified our reasoning for valid and quality entropy and network latency results.

		Simulator	MiXiM
Topologies	Cascade	✓	✓
	Multi-Cascade	✓	✓
	Stratified - Fully Connected	✓	✓
	Stratified - Semi Connected		✓
	P2P	✓	
Mixing Techniques	Timed		✓
	Threshold	✓	✓
	Pool		✓
	Continues	✓	✓
Routing	Random Choice	✓	✓
Cover Traffic	On Client	✓	✓
	On Mix	✓	✓
	Multi-hop Dummies		✓
Relays	Corrupt Mixes		✓
Code Analysis	Code Readability	4/5	2/5
	Object Abstraction	5/5	5/5
	Code Smells	57	81
	Bugs	2	4
	Security Issues	5	10
	Duplicate Code	2.7%	0%
	Runtime Crashes		✓

Table 3.1: Simulators Comparisson Table

Chapter 4

Replication Study

This chapter is dedicated to replicating existing literature[], reasoning about its outcomes. Minutely, a replication study frames the process of reproducing and analysing the experiments of other researchers under similar conditions. The purpose of a replication study is primarily to discover if current findings provide a valid basis for deciding future research paths.

Within the context of this dissertation, we conduct a short replication study, considering previous works[]. Our goal is to realise how existing topologies, mixing techniques, cover/decoy traffic and the appearance of corrupter Mixes affect the latency and anonymity of a Mixnet. This analysis will help us reason about Mixnets' behaviour, further extending recent research in chapter 5.

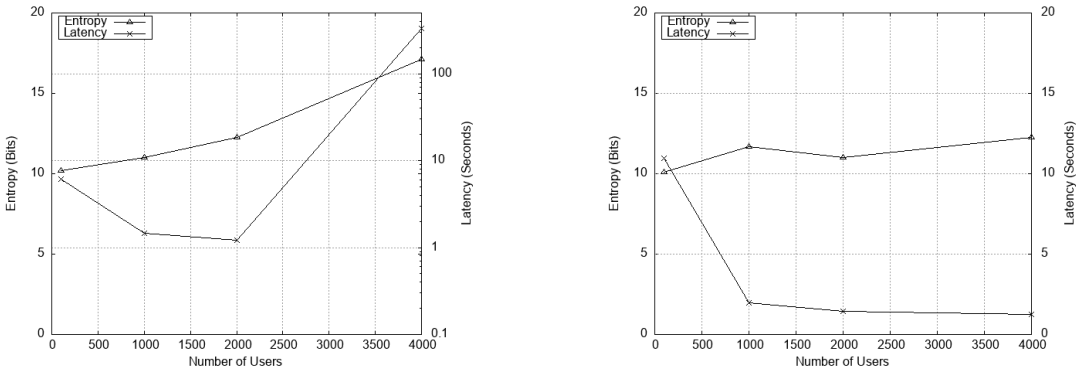
Replicating previous work was challenging for many reasons. For our part, the experimental set-up was not clearly described, and some parameters were missing. Consequently, we had to make assumptions on a few occasions. Another essential aspect when replicating studies is to use similar environments. Nonetheless, none of the previous research had references to the employed hardware. For this reason, we used our personal computer, comprising an Ubuntu machine facilitating a 6-core Intel core i5-8600K and 16 GB of RAM. The experiments conducted throughout chapters 4 and 5 use exclusively this equipment. At this point, it is worth mentioning that simulating more than 4000 clients on Piotrowska's Simulator required more than 16 GB of RAM, which was out of our practical limit. Therefore, we managed to replicate most of the experiments partially.

4.1 Studying the Effect of Mix Network Topologies and Mixing Techniques

Indubitably, different topologies and mixing techniques, as described in chapter 2, can impact the anonymity and latency of a Mix Network. Piotrowska saught the same questions when writing her study on the anonymity trilemma[]. The conducted experiments evaluated and compared three Mixnets implementations - Nym, Elixxir Network, and HOPR. Each one of these projects is designed using a different topology.

Nym integrates a stratified topology based on three layers with three Mixes each. Also, the mixing technique used is Continues, where the delay is randomly picked from the exponential distribution. On the other hand, Elixxir is a Chaumian cascade network based on the cMix protocol[]. Elixxir can be configured to run on a single Cascade, like cMix, or use multiple Cascades. Compared to Nym, Elixxir uses the batch and reorder mixing technique (for Elixxir Network, we assumed a 1000 message threshold). Lastly, HOPR uses a P2P topology, and for this reason, we did not include it in this work.

In the first place, we are going to compare Single-Cascade and Multi-Cascade network topologies. Intuitively, we expect that a Single-Cascade formation will have higher anonymity levels since all traffic is routed through a chain of Nodes. Shuffling the whole anonymity set of messages on each stop can provide greater anonymity. Nonetheless, we assume that latency can be high because the network's capacity is caped to the Mix's throughput. The latency can be low for a negligible number of clients, but it will be higher if we increase the user base.



(a) Single-Cascade Elixxir Network

(b) Multi-Cascade Elixxir Network

Figure 4.1: MiXiM Baseline Experiments

Indeed, Figure 4.1 portray the expected results. Assuming Cascades of length three and by increasing the number of users, we observe an increase in entropy as well. Also,

we remark that the entropy's increase rate is much more extensive for a Single-Cascade (1x3) than for a Multi-Cascade(2x3) topology. Nonetheless, there is evidence of poor latency in Figure 4.1a when the system facilitates more than 2000 users. Latency sharply increases from just above 1 second to almost 350 seconds. On the other hand, a Multi-Cascade design allows very low latency by sacrificing a bit of anonymity. From the above analysis, we can deduce that for Cascade and Multi-Cascade topologies, we have to choose between scalability and anonymity. We can not have both.

In contrast to Cascade topologies, a Stratified topology should scale better. This is intuitive since we can add more Mixes to each layer, distributing traffic into distinct routes. At the same time, we deem it is possible to achieve lower latency since not many messages get congested into a Mix.

As we notice in Figure 4.2, Nym's Stratified implementation - three layers of three Mixes each - can achieve greater anonymity with very low latency. We presume that latency is at the level of 0.3 seconds because Nym realises a Continues mixing technique, while earlier, Elixxir used a batch and reorder technique, meaning that batch size can affect latency. Moreover, entropy is in an uptrend, showing that by increasing the number of users, anonymity increases as well. Therefore, Nym's Stratified configuration can handle significant traffic with increasing anonymity and low latency.

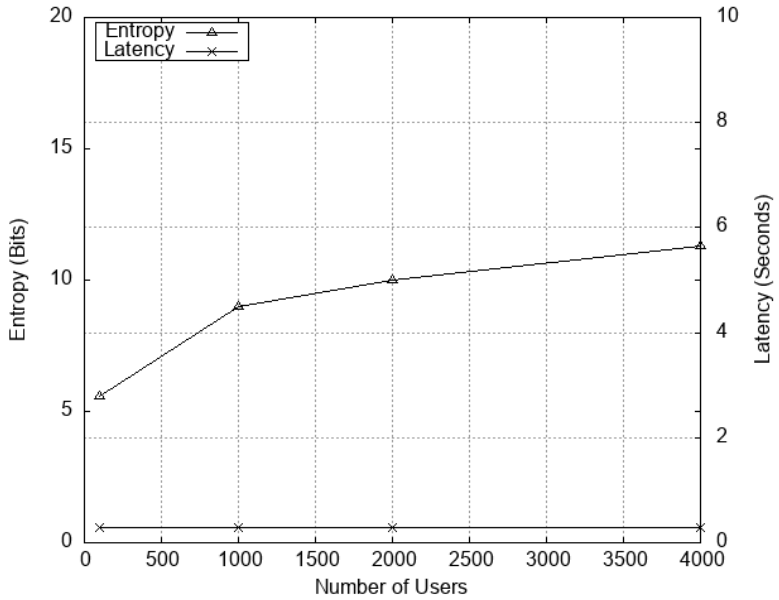
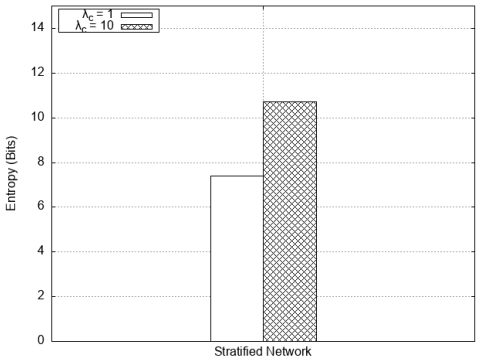


Figure 4.2: Stratified Nym Network

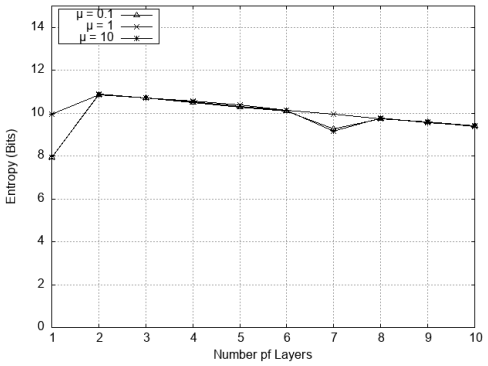
Using MiXiM, we get similar results. In particular, Figure 4.3a depicts the anonymity of a Stratified topology of three layers comprising ten Mixes each, simulated by setting

the λ message generation factor to 1 and 10, respectively. We observe that entropy increases when traffic rises, conforming to the previous experiment's results.

Also, Figure 4.3b shows us the impact on entropy when increasing the number of layers, assuming different average delays on mixing - presuming Continuous mixing. We observe anonymity growing between one and two layers; however, there is a steady decline afterwards. We are not sure why this happens. Intuitively, the longer the route a message takes, the bigger should be the entropy. Besides, assuming various mixing delays, the entropy should have been higher for more extended time frames. According to the simulation results, this is not true, as the drawn curves seem primarily identical. Nonetheless, we are not confident about the quality of the results since, as we have studied in chapter 3, MiXiM has many bugs and unrealised features.



(a) Impact of different messages generation rates on entropy



(b) Impact of different number of layers and average delay on Entropy

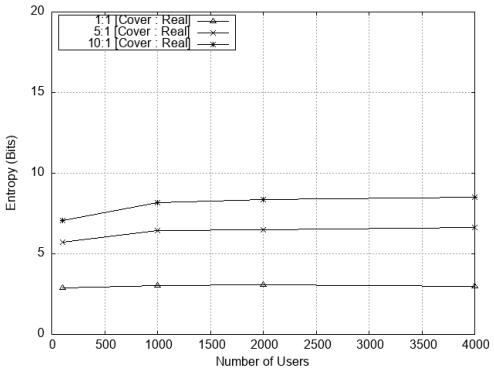
4.2 Studying the Effect of Traffic

Cover traffic is an essential tool that both MiXiM and Simulator incorporate. Notably, using dummy messages, we increase the anonymity set during the mixing stage. Allegedly, we anticipate greater anonymity when having more traffic. Also, cover traffic enables us to aim for the same anonymity levels while reducing latency. Theoretically, we achieve that by increasing traffic and keeping the average delay low - assuming the Continuous mixing technique.

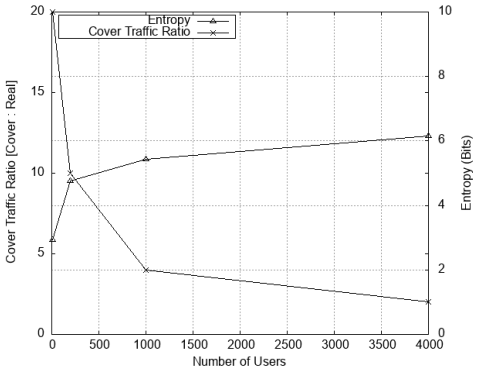
4.2.1 Cover Traffic

Figure 4.4a illustrates the effect of cover traffic on anonymity, assuming different cover traffic ratios. We observe that for higher ratios, anonymity is greater. Also, increasing

the number of users contributes to anonymity. Notably, in Figure 4.4b we notice that decreasing the cover traffic ratio from 10:1, to 2:1 [Cover:Real] yields acceptable levels of entropy, which is further boosted by the increasing number of users.



(a) Impact of Cover Traffic on Entropy



(b) Impact of Cover Traffic on Entropy

4.2.2 Real Traffic

Real traffic is generated according to the number of users in our network. Therefore, more users imply higher anonymity levels. In fact, as noted by [simulator] and [mixim], increasing the average delay of Continues mixing offers greater anonymity. Nevertheless, what if we want to keep latency down? As we notice in Figure 4.5 this can be achieved by keeping the average delay down. As more and more users join a Stratified network, the anonymity increases; thus, we can employ low mixing delays. As a result, we have a network with low latency yet constant anonymity.

4.3 Studying the Effect of Corrupt Relays

Another exciting subject investigated by Guirat et al.[] is the appearance of corrupted Mixes within a Stratified network. The notion of a corrupt node implies that the adversary knows all input and output messages on a Mix with complete certainty.

The results illustrated in Figure 4.6 refer to a Stratified network of three layers comprising ten mixes each. The mixing technique used is Continues, with an average delay of 0.1 seconds. Also, we facilitate 100 clients, each generating 10 messages per second. For this experimental set-up, we anticipate declining anonymity by increasing the percentage of corrupted mixes.

Indeed, Figure 4.6 depicts rigid results. There is a steady decrease in anonymity each time we increase the fraction of corrupt nodes. Moreover, it is interesting to

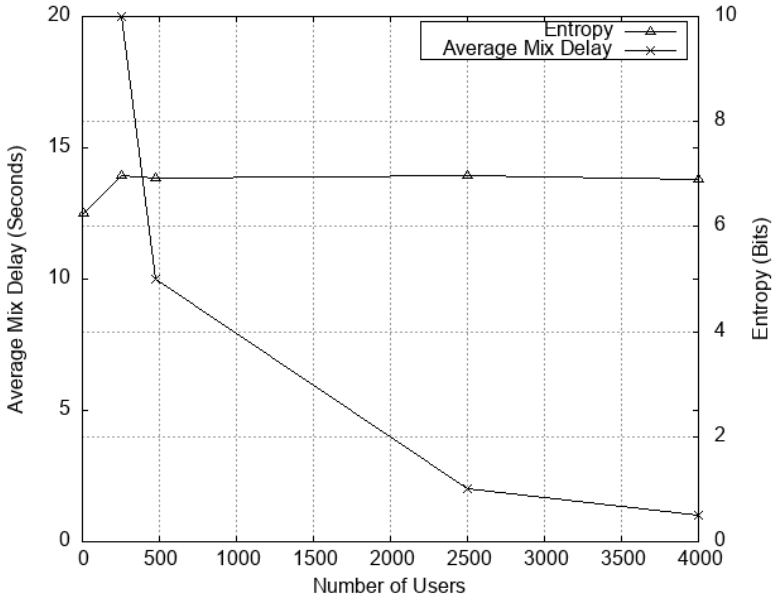


Figure 4.5: Constant Entropy with reduced Latency

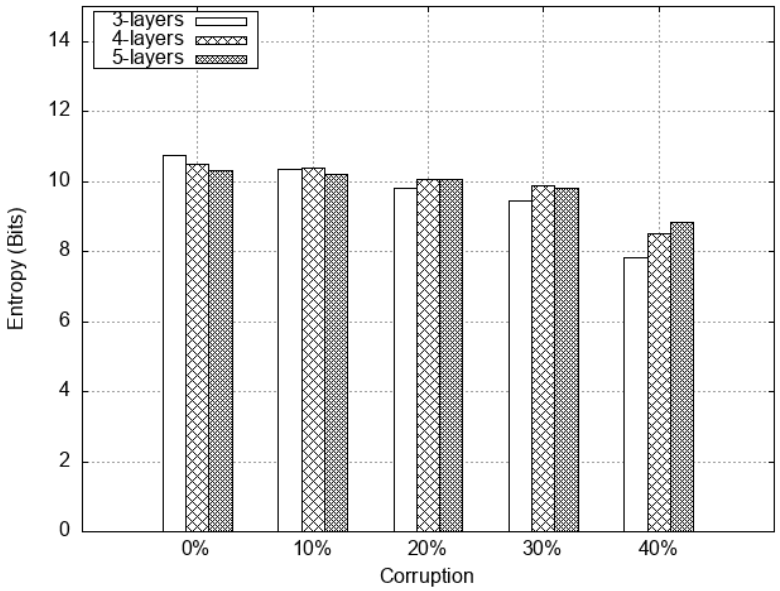


Figure 4.6: Impact of Corrupted Mixes on Entropy

observe that for 0% and 10% of corruption, the three-layer scheme provides better anonymity, while this is not true for 20%, 30% and 40% of corruption. Instead, we notice that the higher the corruption fraction, the lower the entropy is for the three-layer and four-layer Stratified Mixnet. In contrast, the entropy of a five-layer design seems to perform better. Intuitively, this is reasonable because a network with more layers provides the possibility of having less interference by an adversary. On the other side, a network with fewer layers but more adversarial mixes implies a greater possibility of

maliciously influencing the communication between mixes.

Ultimately, considering the effect of the number of layers on the network's anonymity according to [mixim], and the results of our experiment in Figure 4.6, we deduce that it is challenging to design a Mixnet. In the first place, we observe that increasing the number of layers does not much contribute to the anonymity while introducing corrupt relays appears to make more extensive networks necessary. Nevertheless, augmenting a Mixnet implies computational and hardware expenses. It is beyond question that there are some apparent tradeoffs between anonymity and scalability when adversaries emerge.

Chapter 5

Exteding Current Research Using Simulator

Chapter 5 discusses our main contribution to the Mixnets field, which is the simulation and evaluation of arbitrarily formed Stratified networks. Particularly, we assumed that a Stratified Mix Network might have imbalanced layers due to crashing Mixes. Within the context of this chapter, we study two different types of imbalanced Mixnets, which are (a) dynamically imbalanced and (b) statically imbalanced. Additionally, we examine the impact on anonymity caused by increasing the number of Mixes per layer. Lastly, any experiments in this chapter operated on our modified version of Piotrowska's Simulator[].

5.1 Stratified Networks with Increasing Number of Mixes

In previous research, Guirat et al. investigated the topic of increasing the number of layers in a Stratified network. In this section of chapter 5, we are experimenting with the number of Mixes per layer regarding Stratified networks.

Our experimental setup is relatively straightforward. We are using a Stratified topology and the Continues mixing technique, with an average mixing delay of 0.1 seconds. Also, we are running many iterations of the experiment using a different number of Mixes per layer. Intuitively, we expect designs with more Mixes to yield worse anonymity. We justify our supposition, assuming that each Mix will eventually receive less traffic. It is a matter of fact that less traffic implies a smaller anonymity set; hence, a global adversary might be able to identify message senders and receivers smoothly. Still, assuming that we are using the Continues mixing technique, which has

a memory-less property[], the network's entropy should fluctuate in a tight range.

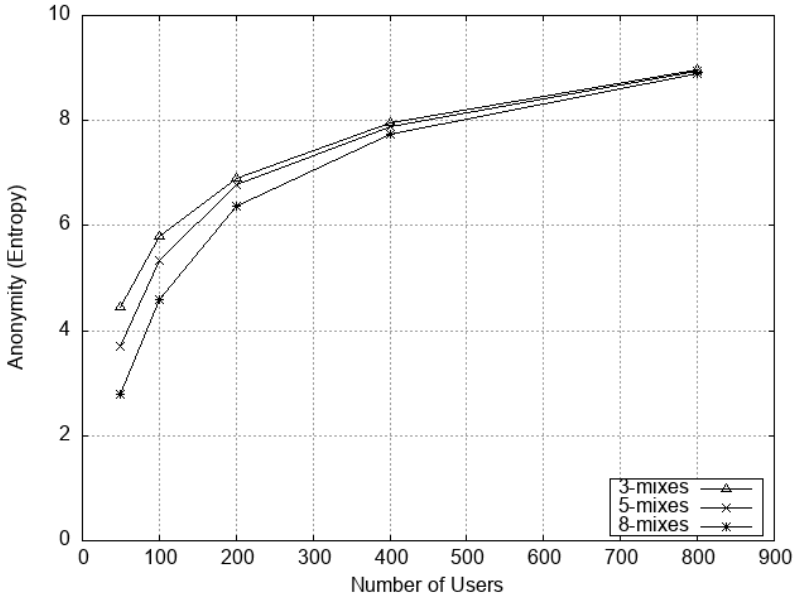


Figure 5.1: Effect of Increasing the Number of Mixes per Layer

Indeed, observing Figure 5.1 we deduce that entropy is initially different, but as we increase the network's user base, it converges. Potentially, we can declare that the three interpolations are logarithmic-like for a low number of users. Nonetheless, we are not sure if entropy diverges for a more extensive user base. Also, we notice that netowrks with more Mixes in each layer have lower entropy for 10 to 400 users. This is reasonable because, as mentioned earlier, less traffic is routed through mixes. Regarding the increased number of users, it is evident that larger user bases yield better anonymity overall.

5.2 Dynamically Imbalanced Stratified Network

The notion of a dynamically imbalanced Stratified network revolves around the idea of having random Mixes crashing arbitrarily through different message transmission rounds. Our goal is to make each Mix crash according to a given probability. Mainly, we extended Simulator to handle this feature by tossing a coin. In other words, before we sample a random route for a potential message, we call a function producing a Real number between 0 and 1. A value less than 0.2 implies that a Mix crashes successfully, with a probability of 20%. Also, in the provision of a non-live route (i.e. the subsequent layer has only malfunctioning Mixes and, therefore, we can not determine a valid path),

we increase the message queue delay by 1 second. Our decision was natural since there is wasted time when a Mix tries to find the next live destination.

In our experimental setup, we assumed a Stratified network with three layers comprising ten Mixes. Also, we set the mixing techniques to Continues, with an average delay of 0.1 seconds. Then, we ran our simulation for 20%, 40% and 60% probability of failure for each Mix individually.

Our initial theory considered that increasing the failure probability would decrease anonymity because a considerable amount of Mixes receive less traffic. This hypothesis is invalidated since anonymity seems to remain persistent for different failure probabilities. According to Figure 5.2, for a 20% crash probability, we get slightly higher entropy, assuming 100 clients in the network. Nonetheless, once we scale up the user base and crash probabilities, the anonymity ranges in equivalent levels. Besides that, our initial assumption for higher latency is false since, as we notice in Figure 5.2, latency remains constant.

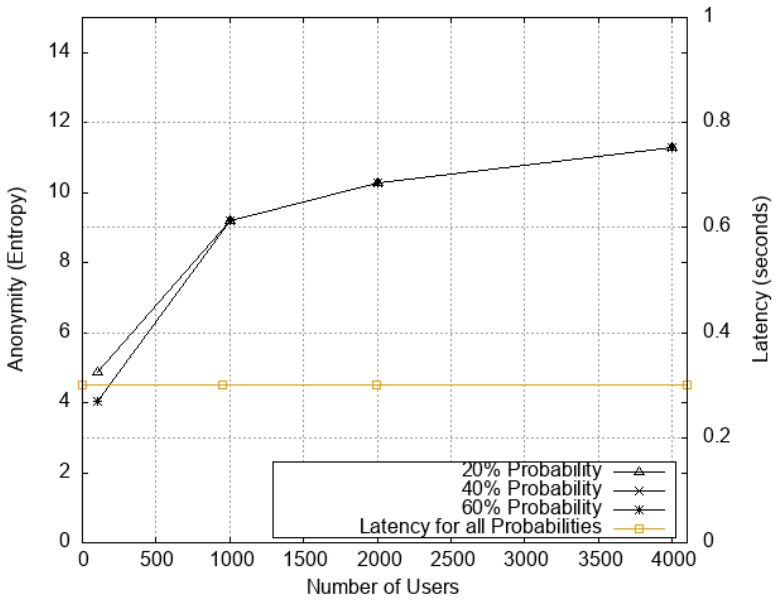


Figure 5.2: Effect of Different the Crash Probabilities on Entropy

The results illustrated in the above Figure 5.2 are reasonable and justified through the simulation logs. In more detail, skimming the log files, we revealed that invalid paths occur sporadically; hence the increased latency of a few messages does not affect the average network latency. Moreover, anonymity is not affected because entropy fluctuations seem to cancel out each other after simulating many messages for many users. In other words, a route of Mixes might not appear many times in the short term,

but after sampling routes for 1000 messages, all possible paths seem to be selected an equal number of times. Therefore, anonymity converges to a single value.

5.3 Statically Imbalanced Stratified Network

Examining the case study of a dynamically imbalanced stratified network was fascinating. A parallel idea arose to investigate statically imbalanced Stratified networks as well. Our perception of ”static” describes a formation where each layer has a fixed number of Mixes, yet this number is different. In particular, we seek to study the effect on anonymity when deploying more or fewer Mixes on the first, middle and last layer of a Stratified Mixnet. This concept seems to be more realistic than dynamically imbalanced networks since, when a portion of the network is down, it can be for quite some time. Hence, statically imbalanced Mixnets might be formed for short time frames.

Our experimental setup comprises a three-layer Stratified topology enabling Continues mixing with an average delay of 0.1 seconds. We also employ coverer traffic of 1:1 ratio. Initially, we assess the impact on anonymity based on a variable number of Mixes in the middle layer, testing one, two, and three Mixes setups. Next, we repeat the same trial starting with 1 Mix and steadily increase this number to 3 Mixes per layer for the first and last layer, respectively.

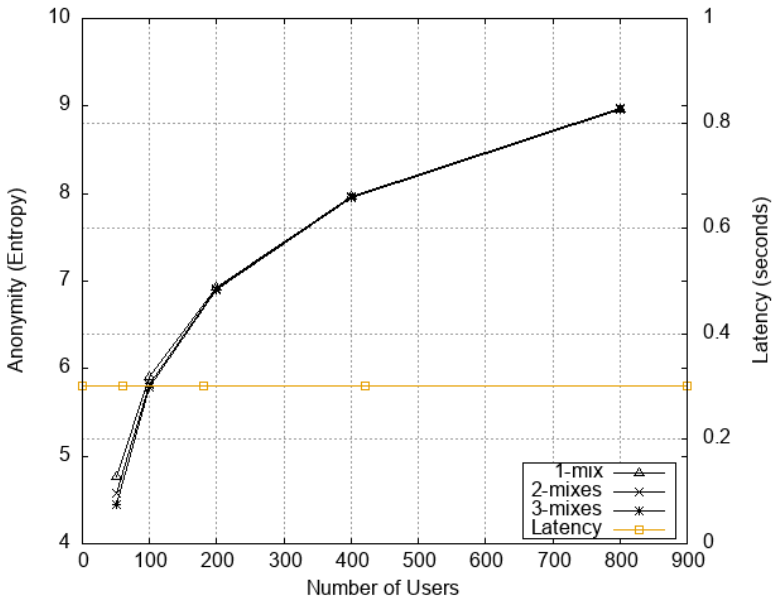


Figure 5.3: need to add caption

According to our analysis in Figures 5.3, 5.4, and 5.5, increasing the number of

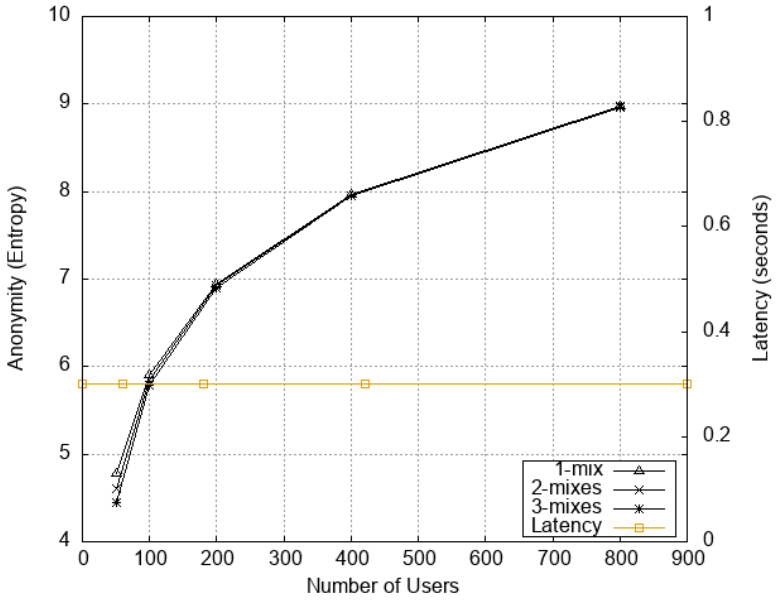


Figure 5.4: need to add caption

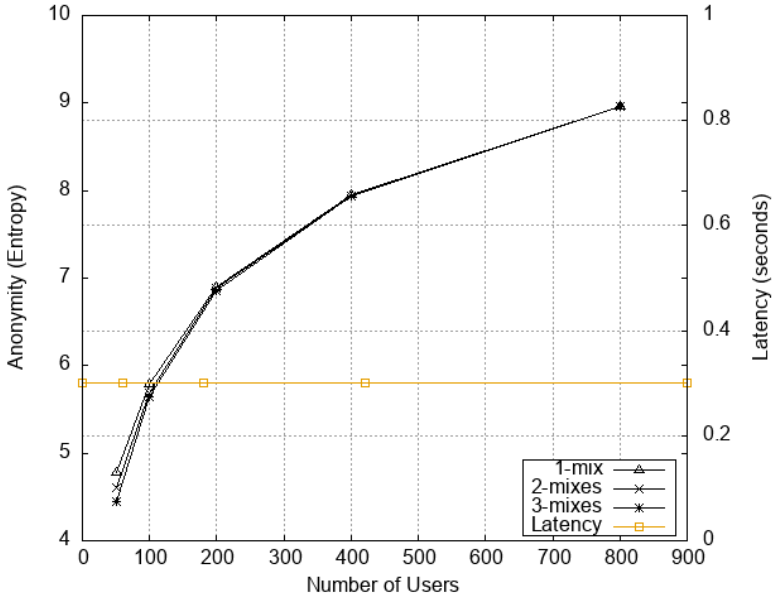


Figure 5.5: need to add caption

layers regardless of the layer position impacts anonymity likewise. This is caused because all mixes repeat the same process in all layers and traffic flows continuously from senders to Mixes and from Mixes to recipients. Nonetheless, something different occurs assuming a smaller user base. Notably, a three Mix per layer configuration yields slightly higher entropy compared to two Mix layers. Likewise, a two Mix per layer network has narrowly taller entropy than a one Mix per layer design. The results of this Figure are credible since, by definition, routing more traffic into a Mix results in better

anonymity.

Finally, we observe latency at a constant level of 0.3. The exact value was reported in the previous section of chapter 5, where we simulated a dynamically imbalanced network. This was expected since latency, as realised earlier, is not mainly affected in network designs utilising the Continues mixing technique.

Chapter 6

Conclusion

Mix Networks provide anonymous communication against global adversaries passively eavesdropping on network transmissions. Mixnets designs might vary according to their topological structure, mixing algorithms and other parameters such as cover/decoy traffic generation. Researchers developed two event-driven simulators to assess different network designs in terms of performance and anonymity.

Within the context of this MSc dissertation project, we report on the existing simulators[code] - Simulator and MiXiM - shedding light on which one should be trusted and further developed. To bring conclusiveness to this matter, we performed a qualitative and quantitative analysis. Mainly, we found out that MiXiM furnishes a plethora of simulation features compared to Simulator. Nonetheless, our study highlighted that we could not trust MiXiM since many unrealised functions exist in the codebase. On the other hand, Simulator offers a limited number of features, yet it is functional, generating justifiable results. In addition, we crafted a baseline simulation scenario to test the performance of both projects. MiXiM baseline simulations remain incomplete due to runtime crashes. Regarding Simulator, we observe poor performance and extended execution timeframes when increasing the number of users in a network. Particularly, a large user base requires immense amounts of RAM (4000 users mandate roughly 16GB of RAM).

Further, we conducted a short replication study attempting to validate previous research[] and reason about their results. We manage to partially replicate experiments because of hardware limitations. As mentioned in chapter 4, our environment's RAM was caped to 16GB. Nonetheless, our analysis revealed that, indeed anonymity of a Mixnet can be affected by the network's topology, mixing technique and the generation of cover/decoy traffic. Notably, a Cascade network might achieve greater anonymity

than a Multi-Cascade and a Stratified network. Also, Continues mixing yields low latency overheads and increased anonymity due to their memory-less property. Another intriguing highlight is that a large network user base positively impacts its anonymity. Also, cover traffic and mixing delay are vital for networks with small userbases as they keep anonymity to acceptable levels. Furthermore, it is worth mentioning that in the presence of corrupted relays, assuming a Stratified network, the anonymity decreases.

The last contribution of our project is the investigation of dynamically and statically imbalanced Stratified Mix Networks. As of writing this dissertation, we are unaware of similar work in this field; hence, our research on imbalanced networks can provide valuable insights. A dynamically imbalanced network assumes that each Mix fails with a certain probability on each transmission round. Anonymity and latency on such networks are not affected since after sending and receiving numerous messages; the traffic passed through all Mixes converges, cancelling temporal anonymity issues. On the other hand, statically imbalanced networks consider that a layer might have more or less Mixes for longer timeframes. Notably, we found out that the number of Mixes per layer does not affect anonymity, especially on networks with large user bases. However, for a limited number of users, we observed a negligible difference. Deploying fewer Mixes, regardless of the layer, will equally favour and improve anonymity. Finally, static and dynamic imbalanced networks' latency is low, considering the tested Stratifed topology and Continues mixing.

In the future, we suggest exploring imbalanced Stratified Mix Networks further. Particularly, it is worth experimenting with all mixing techniques since threshold and timed Mixes might behave differently in an imbalanced network. Besides that, we can adapt the dynamically imbalanced concept for Cascade and Multi-Cascade topologies. Essentially, in Cascade networks, each Mix is a potential point of failure. Therefore, simulating imbalanced Cascades will allow us to evaluate the actual overhead in latency and anonymity when a Mix frankly goes down. To frame all of our recommendations, we propose the development of an efficient and modular event-driven simulator, which will support all types of topologies, mixing techniques and cover traffic functionalities. In addition, as reported in the literature [], there are several methods to encrypt messages flowing through Mixes. The new simulator should allow users to explicitly define any delays that occur due to encryption and decryption of messages. Further, a new simulator should be developed carefully to use a few computational resources. For this reason, we propose using Go language, a statically typed compiled language similar to C but with a low memory footprint.

To conclude, it is essential to highlight that Mix Networks enable people to form liberal societies where respect for privacy and anonymity prevails. Certainly, current research provides robust knowledge on this topic. In my opinion, we need to practically develop more applications that will benefit from using an underline Mixnet. Finally, there is always room for improvement.

Bibliography

Appendix A

Sample Configuration Files

A.1 Simulator Configuration File

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```
        "id_len": 32,
        "num_target_packets": 1000
    }
}
```

A.2 MiXiM Configuration File

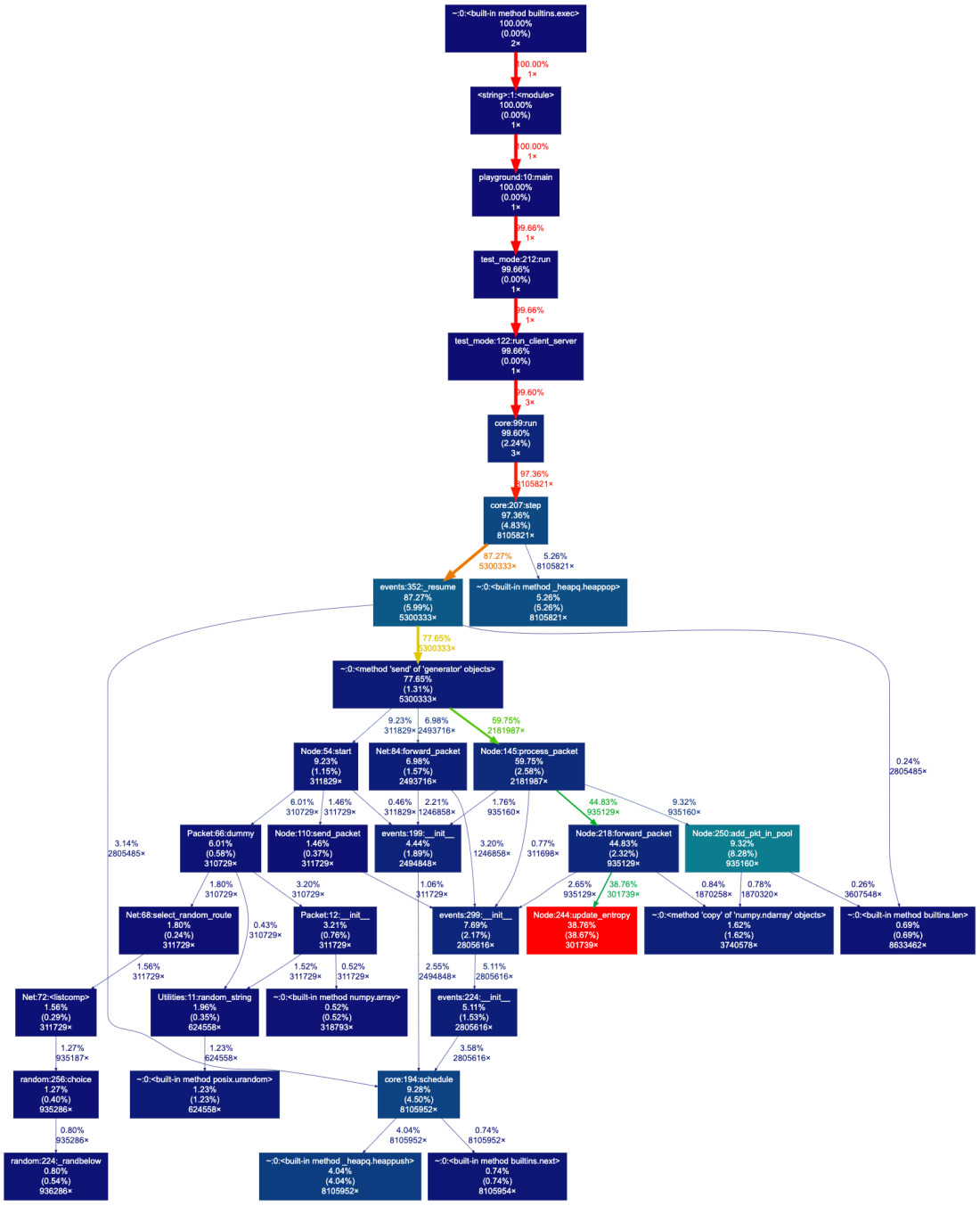
```
[DEFAULT]
n_clients= 100
lambda_c = 1

[TOPOLOGY]
#Topology can take stratified, cascade, free route
type = stratified
fully_connected = True
routing = source
E2E = 1
n_layers = 1
#If stratified
l_mixes_per_layer = 10
#If Cascades
n_cascades = 3
[MIXING]
#mix_type takes poisson, time, or pool
mix_type = poisson
mu = 1
timeout = 2
threshold = 100
flush_percent = 0.1
[DUMMIES]
client_dummies = False
rate_client_dummies = 1
link_based_dummies = True
multiple_hop_dummies = False
```

```
28 rate_mix_dummies = 1
29 [NODES_SELETION]
30 #Probability over nodes selection: uniform, specific
31 probability = Uniform
32 #if specific
33     #if topology = stratified
34 w_mix_l1 = [0.5]
35 w_mix_l2 = [0.3]
36 w_mix_l3 = [0.1]
37     #if topology = cascade
38 w_cascades = [0.8, 0.1, 0.1]
39
40 [THREATMODEL]
41 corrupt_mixes = 0
42 balanced_corruption = True
```

Appendix B

cProfile Execution Trees

B.1 Simulator Execution Tree



B.2 MiXiM Execution Tree