



MessageVortex

Transport Independent Messaging anonymous to 3rd Parties

Inauguraldissertation
zur
Erlangung der Würde eines Doktors der Philosophie
vorgelegt der
Philosophisch-Naturwissenschaftlichen Fakultät
der Universität Basel
von
Martin Gwerder (06-073-787)
von Glarus GL

November 25, 2016

Original document available on the edoc sever of the university of Basel edoc.unibas.ch.



Genehmigt von der Philosophisch-Naturwissenschaftlichen Fakultät

Auf Antrag von

Prof. Dr. Christian F. Tschudin

Prof. Dr. Heiko Schuldt

Basel, FIXME datum der fakultätsversammlung FIXME Signature line with Name of Dean of Faculty below

Contents

1. Introduction	1
1.1. Contributions	2
1.2. Notation	2
1.2.1. Cryptography	2
1.2.2. Code and commands	2
1.2.3. Hyperlinking	3
2. Main Research Question	5
2.1. RQ1: Sending messages maintaining unlinkability against an adversary	5
2.2. RQ2: Attacking unlinkability and circumvention	5
2.3. RQ3: Attack Mitigation by design	5
I. Methodes	7
3. Requirements for an anonymising Protocol	11
3.1. Anonymizing and Unlinking	11
3.2. Censorship Resistant	11
3.3. Controllable trust	12
3.4. Reliable	12
3.5. Diagnosable	12
3.6. Available	12
3.7. Rough draft of Protocol Layers	12
3.8. Rough Draft of Messages	13
4. Existing Transport Layer Protocols	15
4.1. HTTP	15
4.2. FTP	15
4.3. TFTP	16
4.4. MQTT	16
4.5. Advanced Message Queuing Protocol	16
4.6. Constrained Application Protocol (CoAP)	16
4.7. Web Application Messaging Protocol	16
4.8. XMPP (jabber)	16
4.9. SMTP	17
4.10. SMS	17
4.11. MMS	17
4.12. Roundup for Transport Protocols	17
5. Existing Research and Implementations on the Topic	19
5.1. Anonymity	19
5.1.1. k -Anonymity	19
5.1.2. ℓ -Diversity	19
5.1.3. t -Closeness	19
5.2. Zero Trust	19
5.3. Pseudonymity	20
5.4. Undetectability	20
5.5. Unobservability	20
5.5.1. Ephemeral Identity	20
5.6. Single Use Reply Blocks and Multi Use Reply Blocks	20
5.7. Censorship	20
5.7.1. Censorship Resistant	21
5.7.2. Parrot Circumvention	21
5.7.3. Censorship Circumvention	21
5.7.3.1. Covert Channel and Channel Exploitations	21
5.7.3.2. Spread Spectrum	21
5.7.3.3. Steganography	21
5.7.3.4. Timing Channels	21

5.8.	Cryptography	21
5.8.1.	Symmetric Encryption	21
5.8.1.1.	AES	21
5.8.1.2.	Camelia	22
5.8.2.	Asymmetric Encryption	22
5.8.2.1.	RSA	22
5.8.2.2.	Elliptic Curve Cryptography	22
5.8.3.	Homomorphic encryption	22
5.8.4.	Deniable Encryption and Deniable Steganography	22
5.8.5.	Key Sizes	22
5.9.	Routing	22
5.9.1.	Mixing	23
5.9.2.	Onion Routing	23
5.9.3.	Crowds	23
5.9.4.	Mimic routes	23
5.9.4.1.	DC Networks	24
5.9.4.2.	Anonymous Remailer	24
5.10.	System Implementations	24
5.10.1.	Pseudonymous Remailer	24
5.10.2.	Babel	24
5.10.3.	Cypherpunk-Remailer	25
5.10.4.	Mixmaster-Remailer	25
5.10.5.	Mixminion-Remailer	25
5.10.6.	Crowds	25
5.10.7.	Tarzan	25
5.10.8.	Tor	25
5.10.9.	I^2P	25
5.10.10.	Freenet	26
5.10.11.	Herbivore	26
5.10.12.	Dissent	26
5.10.13.	P5	26
5.10.14.	Gnutella	26
5.10.15.	Gnutella2	26
5.10.16.	Darknet	26
5.10.17.	Sneakernet	26
5.10.18.	Hordes	26
5.10.19.	Salsa	26
5.10.20.	AP3	26
5.10.21.	Hydra-Onion	26
5.10.22.	DUO-Onion	26
5.10.23.	Cashmere	26
5.10.24.	SMTP	26
5.10.25.	Mail Endpoints	27
5.10.25.1.	Fat clients	28
5.10.25.2.	Server located clients	28
5.10.25.3.	Web clients	28
5.10.26.	Interfaces of Mail Endpoints	28
5.10.27.	S/MIME	28
5.10.28.	PGP/MIME	29
5.10.29.	XMMP	29
5.11.	Proof of work	29
5.11.1.	CPU-Bound Proof of work	29
5.11.1.1.	Hash based puzzle by Juels and Brainard	29
5.11.1.2.	Hash based puzzle by Aura, Nikander and Leiwo	29
5.11.1.3.	Modified Repeated Squaring Puzzle	30
5.11.1.4.	Hinted Hash Puzzle	30
5.11.1.5.	Chained Hash Puzzle	30
5.11.1.6.	Targeted Hash Puzzle	30
5.11.1.7.	Repeated Squaring Puzzle	30
5.11.1.8.	Discrete Logarithm Puzzle	30
5.11.1.9.	Subset sum puzzle	30

5.11.2.	Memory-Bound Proof of work	30
5.11.2.1.	Moderately hard, memory-bound functions	30
5.11.2.2.	Memory bound puzzle based on pattern databases	30
5.11.2.3.	Argon2	30
5.11.2.4.	Scrypt	31
5.11.3.	Summary for Proof of Work Algorithms	31
5.12.	Known Attacks	31
5.12.1.	Broken Encryption Algorithms	31
5.12.2.	Attacks Targeting Anonymity	31
5.12.2.1.	Probing Attacks	31
5.12.2.2.	Hotspot Attacks	32
5.12.2.3.	Message Tagging and Tracing	32
5.12.2.4.	Side Channel Attacks	32
5.12.2.5.	Timing Attacks	32
5.12.2.6.	Sizing Attacks	32
5.12.2.7.	Bugging Attacks	32
	Bugging through certificate or identity lookup:	32
	Bugging through DNS traffic:	32
	Bugging through external resources:	32
5.12.3.	Denial of Service Attacks	33
5.12.3.1.	Censorship	33
5.12.3.2.	Credibility Attack	33
6.	Applied Methodes	35
6.1.	Problem Hotspots	35
6.1.1.	Zero Trust Philosophy	35
6.1.2.	Information leakage	35
6.1.2.1.	P2P design	35
6.1.2.2.	Decoy traffic generation	35
6.1.2.3.	Message tagging or bugging protection	36
6.1.2.4.	Message replay protection	36
6.1.2.5.	No Dedicated Infrastructure Philosophy	36
6.1.3.	Accounting	36
6.1.4.	Anonymisation	36
6.1.5.	Initial Bootstrapping	36
6.1.6.	Cypher selection	37
6.1.6.1.	Cypher Mode	37
	ECB (Electronic Code Book):	37
	CBC (Cypher Block Chaining):	37
	PCBC (Propagation Cypher Block Chaining):	37
	EAX:	37
	CFB (Cypher Feedback):	38
	OFB:	38
	OCB (Offset Codebook Mode):	38
	CCM:	38
	CTR:	38
	GCM (Galois Counter Mode):	38
6.1.6.2.	Padding	38
	PKCS1:	38
	PKCS7:	38
	OAEP with SHA and MGF1 padding:	38
6.1.7.	Usability	38
6.2.	Protocol outline	38
6.2.1.	Protocol Terminology	39
6.2.2.	Vortex Communication model	39
6.2.3.	Transport Layer	39
6.2.4.	Blending Layer	39
6.2.5.	Routing Layer	40
6.2.5.1.	Block Structure	40
6.2.5.2.	MURBs	40

6.3.	Protocol design	40
6.3.1.	Header block	41
6.3.1.1.	Ephemeral Identity	41
6.3.1.2.	Requests	41
	newIdentity request:	41
	queryPeer request:	41
	queryCapability request:	41
	messageQuota request:	42
	transferQuota request:	42
	queryQuota request:	42
6.3.1.3.	Replies to Clear Text Requests	42
6.3.2.	Main block	42
6.3.2.1.	Routing Blocks	42
6.3.2.2.	Payload Building Instructions	42
	splitMessage:	42
	joinMessage:	42
	forkMessage:	42
	unforkMessage:	43
	encryptMessage:	43
	decryptMessage:	43
6.3.2.3.	Reply Block	43
	replyCapability block:	43
	replyPuzzleRequired block:	43
	replyStatus block:	43
	ctxlessNewidentity block:	43
6.3.2.4.	payload Block	43
6.3.3.	Accounting	44
6.3.3.1.	Accounting Data of an Identity	44
6.3.3.2.	Accounting Data of a Header Block	44
6.3.3.3.	Accounting Data of a Payload Block	44
6.4.	Protocol handling	44
6.4.1.	Received Block Processing	44
6.4.2.	Transmission Block Processing	44
II.	Results	47
6.5.	Vortex Client	49
6.6.	Vortex Addresses	49
6.6.1.	Vortex Accounts	49
6.6.2.	Vortex node types	49
6.6.2.1.	Public vortex node	49
6.6.2.2.	Stealth vortex node	49
6.6.2.3.	Hidden vortex node	50
7.	MessageVortex - Transport Independent Messaging anonymous to 3 rd Parties	51
7.1.	Protocol Implementation	51
7.2.	Block Structure	51
7.3.	Message Building	51
7.4.	Accounting	52
7.5.	Blending layer	52
7.6.	Message Flows	52
7.7.	Considerations for Building Messages	52
7.7.1.	Ephemeral identities	52
7.7.2.	Timing of messages	52
7.7.3.	Building Diagnostic Paths	52
7.7.3.1.	Implicit Diagnostic	52
7.7.3.2.	Automatic Explicit Diagnostic	52
7.7.3.3.	On-Demand Explicit Diagnostic	52
7.8.	Verification of requirements	52
	RQ1 (Zero Trust):	52
	RQ2 (P2P):	52
	RQ3 (untagable):	53
	RQ4 (unbugable):	53
	RQ5 (replay):	53

RQ6 (accounting):	53
RQ7 (anonymisation):	53
RQ8 (bootstrapping):	53
RQ9 (encryption variety):	53
RQ10 (easy handleable):	53
7.9. Considerations for Routing Messages	53
7.9.1. Time of sending	53
7.10. Real World Considerations	53
7.10.1. No Routing Log	53
7.10.2. Message Content	54
8. Security Analysis	55
8.0.1. Attack on Users Identity	55
8.0.1.1. Frequency and Bandwidth Analysis	55
8.0.2. Attack on Message content	55
8.0.2.1. Attacking Routing Blocks	55
8.0.3. Attack on Message size	55
9. Additional Considerations	57
9.1. Man in the Middle Attacks to Conversations	57
9.2. Identification of participating account	57
9.2.1. Identification by content	57
9.2.2. Identification by Query	57
9.2.3. Identification by Traffic Type	57
9.2.4. Identification by Bandwidth	57
9.2.5. Identification by Behavioural analysis	57
9.3. Storage of Messages and queues	57
9.4. Economy of transfer	57
III. Discussion	59
10. Recommendations on using the Vortex Protocol	63
10.1. Message content	63
11. Anonymity	65
11.1. Effects of anonymous communication on behaviour	65
IV. Appendix	A1
ASN.1 representation of the protocol	A3
Glossary	A7
Bibliography	A9

[

List of Tables

4.1. comparison of protocols in terms of the suitability criteria as transport layer	17
7.1. Requests and the applicable criteria for replies	53

List of Figures

3.1. A traceroute to the host www.ietf.org	11
3.2. A first rough overview for the protocol	12
5.1. Mail Agents	27
6.1. flow diagram showing processing of incoming messages	45
7.1. Overview of the Vortex modules	51

List of Requirements

RQ1 No infrastructure should be trusted unless it is the senders or the recipients infrastructure.	35
RQ2 Mixes and peers must be undistinguishable.	35
RQ3 The message should be untagable (neither by a sender, or by an intermediate party such as a mixer).	36
RQ4 The message should be unbugable (neither by a sender, or by an intermediate party such as a mixer).	36
RQ5 A message must not be replayable	36
RQ6 The system must be able to do accounting without being linked to a real identity.	36
RQ7 System must be able to anonymise sender and recipient at any point of the transport layer and at any point of mixing unless it is the sender or the recipient itself.	36
RQ8 The system must allow to boot strap from a zero knowledge or near zero knowledge point and extend the network on its own.	36
RQ9 The system must be able to use multiple symmetric, asymmetric, and hashing algorithms.	37
RQ10 The system must be usable without cryptographic know-how and with well known tools.	38

1. Introduction

Almon Brown Strowger was owner of a funeral parlour in St. Petersburg. He filed a patent in March 10th 1891 for an “Automatic Telephone Exchange” [73]. This patent built the base for modern automated telephone systems. According to several sources, he was annoyed by the fact that the local telephone operator was married to another undertaker. She diverted potential customers of Mr. Strowger to her husband instead, which caused Almon B. Strowger to lose business. In 1922, this telephone dialing system which is nowadays called pulse dialing became the standard dialing technology for more than 70 years until it was replaced by tone dialing.

This dialing technology enabled automatic messaging for voice and text messages (e.g. telex) up until today and built the base technology for today's routed networks.

These networks are building the base for our communication-based society today. We are using these networks today as a common communication meaning for all purposes and do spend very little thoughts on the possible consequences arising if someone is able to put hands on this communication. This is not only a question if someone wants to hide something. The main problem is that the broad availability of data enabled our society to judge on peoples not only on what they are doing but as well, on what they did. While this is nothing bad people seem to be unable to differentiate that things that might have been common and normal in the past might be judged differently in present.

Numerous events in present and past show that multiple actors, some of which are state sponsored, collected data on a broad base in the internet. Whether this is a problem or not may be a disputable fact. Undisputed is however that if data is not handled with care peoples are accused with numerous “facts” that are more than questionable. To show that this may happen even under complete democratic control we might refer to events such as the “secret files scandal” (or “Fichenskandal”) in Switzerland. In the years from 1900 to 1990 Swiss government collected 900'000 files in a secret archive (covering roughly 10% of the natural and juristic entities within Switzerland at that time). More about the Fichenskandal may be found in the Swiss Federal Archives (<https://www.bar.admin.ch>)

A series of similar attempts to attack privacy on a global scale have been discovered by whistle blower Edward Snowden. The documents leaked in 2009 by him claim that there was a data collection starting in 2010. Since these documents are not publicly available, it is

hard to prove claims based on these documents. However – because the documents were screened by a significant number of journalists spanning multiple countries, the information seems credible.

According to these documents (verified by NRC) NSA infiltrated more than 50k computers with malware to collect classified, or personal information. They furthermore infiltrated Telecom-Operators (mainly executed by british GCHQ) such as Belgacom to collect data and targeted high member of governments even in associated states (such as the Germans president mobile phone). A later published shortened list of “selectors” in Germany showed 68 telephone and fax numbers targeting economy, finance and agricultural parts of the German government.

This list of events shows that big players are collecting and storing vast amounts of data for analysis or possibly future use. The list of events shows also that the use of this data has in the past been at least partially questionable. As a part of possible counter measures this work analyses the possibility of using state of the art technology to minimize the information footprint of a person on the internet.

We leave a vast information footprint in our daily communication. On a regular email we disclose everything in an “postcard” to any entity on its way. Even when encrypting a message perfectly with today's technology (S/MIME[32] or PGP[25]) leaves at least the originating and the receiving entity disclosed or we rely on the promises of a third party provider which offers a proprietary solution. Even in those cases we leak informations such as “message subject”, “frequency of exchanged messages”, “size of messages”, or “client being used”. A good anonymity protocol has therefore far more attributes to cover than the message itself. It includes beside the message itself, all metadata, and all the traffic flows. Furthermore a protocol anonymising messages should not rely on the trust of infrastructure other than the infrastructure under control of the sending or receiving entity as a trust in any third party might be misleading.

Furthermore – Any central infrastructure is bound to be of special interest to anyone gathering data concerning the using entities of such a protocol. It furthermore may be manipulated in order to attack the messages or their flow. So central infrastructure has to be avoided.

In this work a new protocol is designed to allow message transfer through existing communication channels. These messages should be unobservable to any third party. This unobservability does not only cover the message itself but all metadata and flows associ-

1. Introduction

ated with it. We called this protocol “Message Vortex” or in short just “Vortex”. The protocol is designed in such a way so that it is capable to use a wide variety of transfer protocols. It is even possible to switch protocols while the messages are in transfer. This allows media breaches (at least on a protocol level) and makes analysis even harder.

The new protocol should allow safe communication without the need of trusting the underlying transport media. Furthermore it is desirable that the usage of the protocol itself is possible without altering the immediate behaviour of the transport layer. That way it is possible to use the transport layers normal traffic to increase the noise in which information has to be searched.

This work splits into multiple parts. In the first part we are collecting available researches and technologies. We emphasize in all technologies on the strength and weaknesses relevant to this work. In the second part we reassemble the parts to a new protocol. In the third part we analyse the protocol for fitness of the purpose. We try to find weaknesses and work out recommendations for the protocol usage. In the last part we discuss the results and try to summarize the findings. Try to elaborate to what extend the protocol fulfils the requirements of this work.



1.1. Contributions

This thesis contributes to the topic in the following senses:

- It introduces a consistent model for message delivery which includes all endpoints and involved parties.
- It shows an approach based on existing protocols for anonymous communication which gives full control of the anonymity to the sender while controlling the costs.
- It offers a client application implementing the proposed Protocol as IMAPv4 cache daemon and as SMTP relay.

1.2. Notation

1.2.1. Cryptography

The theory in this document is heavily based on symmetric encryption, asymmetric encryption and hashing. In order to use a uniformed notation I use $E^{K_a}(M)$ (where a is an index to distinguish multiple keys) resulting in M^{K_a} as the encrypted message. If we are reflecting a tuple of information we write it in

boldface. to express the tuples content we use angular brackets $\mathbf{L}(\text{normalAddress}, \text{vortexAddress})$. If we want Messages encrypted with multiple keys do list the used keys as a comma separated list in superscript $E^{K_b}(E^{K_a}(M)) = M^{K_a, K_b}$.

For a symmetric encryption of a message M with a key K_a resulting in M^{K_a} where a is an index to distinguish different keys. Decryption uses therefore $D^{K_a}(M^{K_a}) = M$.

As notation for asymmetric encryption we use $E^{K_a^1}(M)$ where as K_a^{-1} is the private key and K_a^1 is the public key of a key pair K_a^p . The asymmetric decryption is noted as $D^{K_a^{-1}}(M)$.

For hashing we do use $H(M)$ if unsalted and H^{S_a} if using a salted hash with salt S_a . The generated hash is shown as H_M if unsalted and $H_M^{S_a}$ if salted.

If we want to express what details contained in a tuple we use the notation $M(t, \text{MURB}, \text{serial})$ respectively if encrypted $M^{K_a}(t, \text{MURB}, \text{serial})$.

$$\begin{aligned} \text{asymmetric} : E^{K_a^{-1}}(M) &= M^{K_a^{-1}} \\ D^{K_a^1}(E^{K_a^{-1}}(M)) &= M \\ D^{K_a^{-1}}(E^{K_a^1}(M)) &= M \\ \text{symmetric} : E^{K_a}(M) &= M^{K_a} \\ D^{K_a}(E^{K_a}(M)) &= M \\ \text{hashing}(\text{unsalted}) : H(M) &= H_M \\ \text{hashing}(\text{salted}) : H^{S_a}(M) &= H_M^{S_a} \end{aligned}$$

In general Subscripts denote selectors to differentiate values of the same type and superscript denote relevant parameters to operations expressed.

1.2.2. Code and commands

Code blocks are always displayed as light grey block with line numbers:

```
1 public class Hello {
2   public static void main(String args[]) {
3     System.println("Hello_"+args[1]);
4   }
5 }
```

Commands entered at the command line are in a grey box with top and bottom line. Whenever root rights are required the command line is prefixed with a “#”. Commands not requiring specific rights are prefixed with a “\$”. Lines without a trailing “\$” or “#” are output lines of the previous command. If long lines have to be broken to fit into the paper a “↵” is inserted to indicate that the line break has been introduced for readability.

```
~ su -
# javac Hello.java
# exit
$ java Hello
Hello.
$ java Hello "This is a very long command-line that had to be broken to fit into the code box displayed
on this page." ↵
Hello. This is a very long command-line that had to be broken to fit into the code box displayed on this
page. ↵
```


1.2.3. Hyperlinking

The electronic version of this document is hyperlinked. This means that references to the glossary or the literature may be clicked to find the respective entry. Chapter or table references are clickable too.

2. Main Research Question

The main topic of this thesis was defined as follows:

- Is it possible to have specialized messaging protocol used in the internet based on “state of the science” technologies offering a high level of unlinkability (sender and receiver anonymity) towards an adversary with a high budget and privileged access to internet infrastructure?

Based on this main question there are several sub questions grouped around various topics:

1. What technologies and methods may be used to provide sender and receiver anonymity and unlinkability when sending messages against a potential adversary? (RQ1)
2. How can entities utilizing these technologies and methods be attacked and what measures are available to circumvent such attacks? (RQ2)
3. How can attacks targeting anonymity of a sending or receiving entity be mitigated by design? (RQ3)

2.1. RQ1: Sending messages maintaining unlinkability against an adversary

This question covers the principal part of the work. We try to elaborate first rough criterias for the protocol. We then create a list of suitable technologies. Based on this list we define a protocol combining these technologies and researches to a solution. This solution will be implemented and analysed for suitability based on the criteria defined.

2.2. RQ2: Attacking unlinkability and circumvention

Within this questions we look at common attacks and test resistance of the protocol based on the definition of the protocol. We do this by first collecting well known attacks (either generic or specific to a technology used in the protocol). We then try to elaborate if these attacks might be successful (and if so under what circumstances).

2.3. RQ3: Attack Mitigation by design

Within this question we define baselines in order to mitigate attacks by defining guidelines for using the protocol. We analyse the effectiveness of the guidelines and try to elaborate the general achievement level of the protocol by looking at the criteria defined in RQ1.

Part I.

Methodes

In this part of the thesis we collect requirements, definitions, methods, and existing research relevant to the topic of this thesis. We start with collecting requirements for the protocol.

Having the requirements we collect numerous existing technologies on research and implementation level. Each of the technologies is quickly categorized and either further studied or rejected naming the reasons for rejection.

The list of technologies and research collected is big in this chapter. All relevant technologies either widely adopted or thoroughly researched should be included in this chapter. All Technologies and research are categorized.

Technologies are always referenced through their respective standard. If applicable multiple standards may be part of the analysis. A very quick introduction into the protocol is given and then analysed for suitability for a specific problem addressed in this work.

Research are referenced by a paper. If applicable multiple related researches and papers are collected together into a bigger picture and then analysed for suitability concerning specific problem. If related to a standard technology links to that technology are provided where relevant.

3. Requirements for an anonymising Protocol

In the following sections we try to elaborate the main characteristics of the anonymising protocol.

The main goal of the protocol is to enable Freedom of speech as defined in Article 19 of the International Covenant on Civil and Political Rights (ICCPR)[76].

everyone shall have the right to hold opinions without interference

and

everyone shall have the right to freedom of expression; this right shall include freedom to seek, receive and impart information and ideas of all kinds, regardless of frontiers, either orally, in writing or in print, in the form of art, or through any other media of his choice.

We imply that not all participants in the internet share this value. As of September 1st 2016 Countries such as China (signatory), Cuba (signatory), Qatar, Saudi Arabia, Singapore, United Arab Emirates, or Myanmar did not ratify the ICCPR. Other countries such as United States or Russia did either put local laws in place superseding the ICCPR or made reservations rendering parts of it ineffective. We may therefore safely assume that freedom of speech is not given in the internet as a lot of countries explicitly supersede them.

We always have to keep in mind that we have no control over the flow of data packets in the internet. Packets may pass though any point of the world. It is not even possible to detect what way has a packet taken. The common network diagnostic tool `tracert` respectively `traceroute` tries to figure that out. But neither can a route of a packet beeing sent forseen nor can it be measured while or after sending. This is due to the fact that all routers along the way only decide for the next hop of a packet.

As an example of the problems analysing a packet route we may look at `traceroute`. The manpage of `traceroute` of Linux tells us that `traceroute` uses UDP, TCP, or ICMP packets with a short TTL and analyses the IP of the peer sending an `TIME_EXCEEDED` (message of the ICMP protocol). This information is then collected and shown as a route. This route may be completely wrong. Some of the possible cases are described in the manpage.

The output of `traceroute` is therefore not a reliable indication of route. Since routes do not have to be static and may be changed or even be alternating the output represents in the best case a snapshot of the current routing situation. We cannot be sure that data packets we are sending are passing only through

countries accepting the ICCPR to the full extend.

```
$ traceroute www.ietf.org
traceroute to www.ietf.org (104.20.0.85), 64 hops max
 1  147.86.8.253  0.418ms  0.593ms  0.421ms
 2  10.19.0.253  1.177ms  0.829ms  0.782ms
 3  10.19.0.253  0.620ms  0.427ms  0.402ms
 4  193.73.125.35  1.121ms  0.828ms  0.905ms
 5  193.73.125.81  2.991ms  2.450ms  2.414ms
 6  193.73.125.81  2.264ms  1.961ms  1.959ms
 7  192.43.192.196  6.472ms  199.543ms  201.152ms
 8  130.59.37.105  3.465ms  3.138ms  3.121ms
 9  130.59.36.34  3.904ms  3.897ms  4.989ms
10  130.59.38.110  3.625ms  3.333ms  3.379ms
11  130.59.36.93  7.518ms  7.232ms  7.246ms
12  130.59.38.82  7.155ms  17.166ms  7.034ms
13  80.249.211.140  22.749ms  22.415ms  22.467ms
14  104.20.0.85  22.398ms  22.222ms  22.146ms
```

Figure 3.1.: A traceroute to the host `www.ietf.org`

3.1. Anonymizing and Unlinking

If we are unable to limit the route of our packets through named jurisdictions we must protect ourselves from unintentionally breaking the law of a foreign country. Therefore we need to be anonymous when sending or receiving messages. Unfortunately most transport protocols (in fact almost all of them such as SMTP, SMS, XMPP or IP) use a globally unique identifier for senders and receivers which are readable by any party which is capable of reading the packets.

As a result anonymisation of a sender or a receiver is not simple. If messages are being sent through a relay at least the original sender might be concealed (Sender anonymity). By combining it with encryption we may even achieve a very simple form of sender and receiver pseudonymity. If cascading more relay like infrastructures and combining it with cryptography we might even achieve sender and receiver anonymity. This approach has however several downsides (see 5.9.4.2 and 5.9.1 for details) and is easily attackable.

3.2. Censorship Resistant

In our scenario in 3 we defined the adverser as someone with superior access to the internet and its infrastructure. Such an adverser might attack a message flow in several ways:

- Identify sender
- Identify recipient
- Read messages passed or extract meta information
- Disrupt communication fully or partially

3. Requirements for an anonymising Protocol

We furthermore have to assume that all actions taken by a potential adversary are not subject to legal prosecution. This is due to the fact that an adversary trying to establish censorship may be part of a jurisdictions government. We may safely assume that there are legal exceptions in some jurisdiction for such entities.

In order to be able to withstand an adversary outlined above the protocol needs certain attributes. The message content needs to be unidentifiable by attributes or content. Whereas “Attributes” include meta information such as frequency, timing, message size, sender, protocol, ports, or recipient (list not conclusive).

3.3. Controllable trust

If we want to control trust we have to conclude that

1. trust in an infrastructure is given due to the fact that it is under full control of either the sender or the recipient.
2. trust in an infrastructure may not be necessary as the infrastructure is ideally unable to misuse data passed through it.

In this thesis we work with both cases. We will however never trust a third party apart from sender and recipient (no even their providers of infrastructures).

3.4. Reliable

Any message sending protocol needs to be reliable in its functionality. If means of message transport are unreliable users tend to use different means for communication.

3.5. Diagnosable

Reliability is somehow linked to transparent behaviour. This due to the fact that if something is generating a constant behaviour but we are unable to determine the reason for it (i.e. if we are expecting a different behaviour) we normally assume a malfunction. Therefore “Reliable” means not only stable by its behaviour. It means also diagnosable. User perception will not be “Reliable” if he is not able to determine causes for differences in observed and expected behaviour.

3.6. Available

Availability has two meanings in this context which do differ. A technology is available if . .

1. a sender and a recipient have (or may have) the means of using it.
2. the infrastructure is providing the service (as opposed to: “is running in a degraded/faulty state unable to provide a service).

The first meaning tells us that a protocol must run independently from infrastructure the user has commonly ready.

The second meaning tells us that messages must always be capable of flowing from the sender to the recipient. As infrastructure may fail at any time the protocol must offer the possibilities to send messages through alternate routes. This sounds easy and many protocols implement such redundancies already. However, taking into account that sender and recipient is not known to a routing node this is a goal hard to achieve.

3.7. Rough draft of Protocol Layers

In order to fulfil the criteria given above we define a very rough idea of the protocol and its layers. The rough overview is given in figure 3.2. The protocol should work on the base of onion routing. Unlike Tor (see 5.10.8) it should not rely on central infrastructures. It furthermore should not be limited to onionize messages. It should be capable of splitting and reassemble messages at any layer

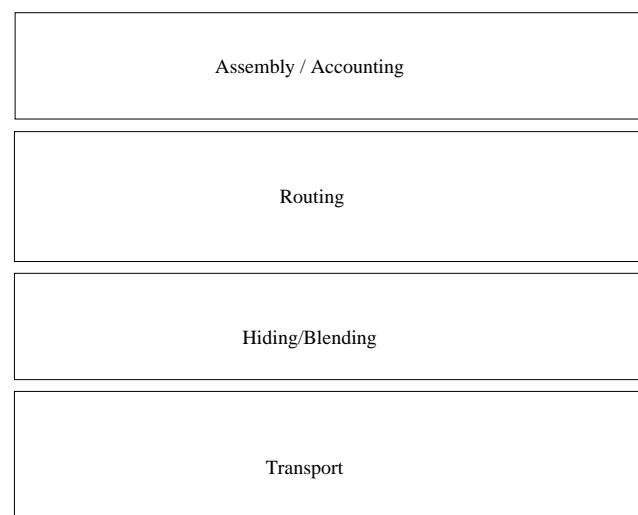


Figure 3.2.: A first rough overview for the protocol

The protocol itself should send messages through a well known transport protocol (“Transport”) which will be used for our messages.

The messages will be hidden within regular messages already using that transport layer. In an ideal implementation messages sent by our protocol should be

indistinguishable from regular messages (by computers and humans). In order to achieve this particular task we introduce a "Hiding / Blending" layer. This layer is normally specific to the underlying transport layer and may vary.

The "Routing" layer is the layer that receives and sends messages. It parses only the core protocol and the data processed here is completely independent from the underlying transport layer.

The "Assembly / Accounting" layer disassembles the received messages into its parts. It then recomposes and stores the messages for further routing. In order to avoid spamming over this media some kind of accounting will be involved.

The messages passed through such a protocol stack are onionised to offer anonymity from evil nodes. Furthermore a node should be unable to tell whether a message was intended for a specific node or not (so all nodes including sender and recipient should handle identically).

In order to mitigate size based attacks (an onionised packet loses permanently data on its way) we introduce operations which may be applied to a valid message as well as to decoy traffic. The operations should be able to increase and decrease in size without being able to tell if this message is destined to a target or not. Operations not carried out due to missing data might be either intentionally or a malfunction.

The defined message operations are as follows:

- Split a message block into two parts of variable size.
This operation may be used to fan out decoy traffic, to cut off decoy data, or to send multiple parts of a message through different routing nodes.
- Join two data blocks to a bigger block using an xor operation.
This operation may be used to minimise decoy traffic or to rejoin data which has been split earlier.
- Fork off xor'ed data from a data block by applying an xor operation to a received block with a block of random data.
With this operation we may create decoy traffic, or split a message into two parts.
- Encrypt a block with a given key.
- Decrypt a block with a given key.

To avoid making this system attractive to UBE an accounting system is introduced. The system works as follows:

- Routing nodes may offer their services at a cost. These "costs" are typically paid by solving crypto puzzles.
- The following operations may be cost effective:
 - Getting a discardable identity on a node (prerequisite for accounting).

- Allowance to route a number of messages through the node (cost per outgoing message) in a specified interval. This allowance is always linked to a discardable identity.
- Allowance to route a specific size of bytes through the node (cost per outgoing byte) in a specified time interval. This allowance is always linked to a discardable identity.
- Offer information about the known routing network by the node.
- Offer information about the identities current quota.

All quotas require accounting. In order to minimise accounting all these quotas must be assigned a time interval in which they are effective. This guarantees that quota data is not growing indefinitely. It is up to the node to decide what time duration is still acceptable.

In order to limit the possibility to Denial of Service (DoS) a node by overloading it the following precautions are taken:

- The message is built in such a way that message building is far more complex than message routing.
- Messages may be decrypted in parts to minimize the amount of work required to decide whether the full processing of the message will be done or the message is discarded anyway.
- The usage of inefficient operations (e.g. asymmetric encryption) is minimized.
- The server may limit specific operations.

3.8. Rough Draft of Messages

For our protocol we assume the following outline for a message:

- Header block
This block contains an ephemeral identity of the sender on the message processing host. It allows the host to decide whether he is willing to process the rest of the message or not. It is important to know that the identity block contains a symmetric key for decryption of the main block and a secret repeated in the main block. This prevents that a malicious node may exchange the main block.
- Main block
This block contains all information regarding routing and processing data. It furthermore contains the payload data which may or may not contain messages.
 - Routing Blocks
This block contains information of which data block should be sent to what recipient. It furthermore may contain instruction for pro-

3. Requirements for an anonymising Protocol

cessing the data blocks and routing/reply blocks for subsequent processing. Another important thing to note is that routing blocks and payload data may arrive on two different paths to the target node.

- Routing Log Block
This Block contains information about the already occurred routing in onionised form. It may be regarded as the onionised pendant of received header in an SMTP header.
- Reply Block
This Block contains a Routing block which may be used to contact the original sender of a message (e.g. for an error message)
- payload Block
These Blocks form the payload data. It might contain a message, parts of a message or decoy material.

The message is picked up from the transport layer and extracted in the blending layer. Processing is then split. First the Assembly/accounting layer is extracting the identity block and authorises further processing. The message building instructions are put into a identity specific list (with the expiration dates of the message). and the payload blocks are stored (again with the expiration date).

After having prepared the message in such a way the routing layer gets the routing blocks. Every routing block is then processed after a final approval by the accounting layer (he is in charge to keep the quotas for this identity in sync). The routing layer assembles the new messages according to the (no authorized) instructions in the routing block and sends it to the next hop where the processing restarts with the new instructions.

4. Existing Transport Layer Protocols

In this chapter we have a look at various available transport layer protocols. The main goal is to identify strong candidates as a transport layer. Main focus lies on the following criteria:

- Widely adopted (Ct1)
The more widely adopted and used a protocol is the harder it is for an adversary to monitor (due to the sheer mass), filter or block the protocol (censorship resistance).
- Reliable (Ct2)
Message transport between peers should be reliable. As messages may arrive anytime from everywhere we do not have means to synchronize the peer partners on a higher level without investing a considerable effort. In order to avoid this effort we do look for inherently reliable protocols.
- Symmetrical built (Ct3)
The transport layer should be built on a peer to peer base. All servers implement a generic routing which requires no prior knowledge of possible targets. This criteria neglects centralised infrastructures.

4.1. HTTP

The HTTP protocol allows message transfer from and to a server and is specified in RFC2616 [54]. It is not suitable as a communication protocol for messages due to the lack of notifications. There are some extensions which would allow such communications (such as WebDAV) but in general even those are not suitable as they require a continuous connection to the server in order to get notifications. Having a “rollup” of notifications when connecting is not there by default but could be implemented on top of it.

HTTP servers listen on standard ports 80 or 443 for incoming connects. The port 443 is equivalent to the port 80 except for the fact that it has a wrapping encryption layer (usually TLS). The incoming connects (requests) must offer a header part and may contain a body part which would be suitable for transferring messages to the server. The reply onto this request is transferred over the same TCP connection containing the same two sections.

HTTP0.9-HTTP/1.1 are clear text protocols which are human readable (except for the data part which might contain binary data). The HTTP/2 (as specified in [10]) is using the same ports and default behaviour. Unlike HTTP/0.9-HTTP/1.1 it is not a clear text but a binary protocol. Headers and bodies of messages are sent

as binaries.



The protocol does definitely satisfy the first two main criteria (Ct1: Widely Adopted and Ct2: Reliable).

The main disadvantage in terms as message transport protocol is that this protocol is not symmetrically. This means that a server is always just “serving requests” and not sending actively information to peers. This Request-Reply violates criteria (Ct1: Symmetrically built) and makes the protocol not a primary choice for message transport.

4.2. FTP

FTP is defined in RFC959[59]. This Protocol is intended for authenticated file transfer only. There is an account available for general access (“anonymous”). This account does for security reasons normally not offer upload rights.

It is possible to use FTP as message transfer endpoint. The configuration would work as follows: “anonymous” has upload rights only. It is unable to download or list a directory. A node may upload a message with a random name. If there is a collision the node retries with another random name.

The blending layer picks messages up using an authenticated user.

This has multiple downsides. At first, handling FTP that way is very uncommon and usually requires an own dedicated infrastructure. Secondly passwords are within FTP always in plain text. This is considered as a very bad practice nowadays. Encryption as a wrapping layer (FTPS) is not common and SFTP (actually a subsystem of SSH) has nothing in common with FTP except for the fact that it may transfer files as well.

Furthermore FTP may be problematic when used in active mode for firewalls. All these problems make FTP not very suitable as transport layer protocol.

Like HTTP a main disadvantage of FTP in terms as a message transport protocol is that this protocol is not symmetrically. This means that a server is always just “serving requests” and not sending actively information to peers. This Request-Reply violates criteria (Ct3: Symmetrically built) and makes the protocol not a primary choice for message transport. The Protocol however satisfies the first two criteria (Ct1: Widely Adopted and Ct2: Reliable).

4.3. TFTP

TFTP has despite its naming similarities to FTP very little in common with it. TFTP is a UDP based file transfer protocol without any authentication scheme. This makes it not suitable as transport layer as it would leave messages open to anyone. The protocol is due to the use of UDP in a meshed network with redundant routes. Since the internet has a lot of these redundant routes this neglects the use of this protocol.

TFTP is rarely ever used in the internet (it is quite commonly used in labs for booting over a network connection). This violates Criteria one (Ct1: Widely Adopted). TFTP is not symmetrically. This means that a server is always just “serving requests” and not sending actively information to peers. This Request-Reply violates criteria (Ct3: Symmetrically built) and makes the protocol not a primary choice for message transport. The Protocol furthermore violates Ct2 (Ct2: Reliable) as it is based on UDP without any additional error correction.

4.4. MQTT

MQTT is an ISO standard (ISO/IEC PRF 20922:2016) and was formerly called MQ Telemetry Transport. The current standard as the time of writing this document was 3.1.1 [5].

The protocol runs by default on the two ports 1883 and 8883 and may be encrypted with TLS. MQTT is a publish/subscribe based message passing protocol which is mainly targeted to m2m communication. This Protocol requires the receiving party to be subscribed in a central infrastructure in order to be able to receive messages. This makes it very hard to be used in a system without centralistic infrastructure and having no static routes between senders and recipients.

The protocol does definitely satisfy the second criteria (Ct2: Reliable). It is in the area of enduser (i.e. Internet) not widely adopted thus violating Criteria 1 (Ct1: Widely Adopted). In terms of decentralistic design the protocol fails as well (Ct3: Symmetrically built).

4.5. Advanced Message Queuing Protocol

The Advanced Message Queuing Protocol (AMQP) was originally initiated by numerous exponents based mainly in finance related industries. The AMQP-Protocol is either used for communication between two message brokers, or between a message broker and a client[4].

It is designed to be interoperable, stable, reliable and safe. It supports either SASL or TLS secured commu-

nication. The usage of such a tunnel is controlled by the immediate sender of a message. In its current version 1.0 it does however not support a dynamic routing between brokers[4].

Due to the lack of a generic routing capability this protocol is therefore not suitable for message transport in a global generic environment.

The protocol satisfies partially the first criteria (Ct1: Widely Adopted), and fully satisfies the second criteria (Ct2: Reliable). However the third criteria is violated due to the lack of routing capabilities between message brokers (Ct3: Symmetrically built).

4.6. Constrained Application Protocol (CoAP)

The Constrained Application Protocol (CoAP) is a communication Protocol which is primarily destined to m2m communication. It is defined in RFC7252[14]. It is Defined as lightweight replacement for HTTP in IoT devices and is based on UDP.

The protocol does partially satisfy the first criteria (Ct1: Widely Adopted). The second criteria (Ct2: Reliable) is only partially fulfilled as it is based on UDP and does only add limited session control on its own.

The main disadvantage in terms as message transport protocol is that this protocol is not (like HTTP) symmetrically. This means that a server is always just “serving requests” and not sending actively information to peers. This Request-Reply violates criteria (Ct3: Symmetrically built) and makes the protocol not a primary choice for message transport.

4.7. Web Application Messaging Protocol

WAMP is a websockets based protocol destined to enable M2M communication. Like MQTT it is publish/-subscribe oriented. Unlike MQTT it allows remote procedure calls (RPC).

The WAMP protocol is not widely adopted (Ct1: Widely Adopted) but it is definitely reliable on a per node base (Ct2: Reliable). Due to its RPC based capability unlike MQTT a routing like capability could be implemented. Symmetrical protocol behaviour is therefore not available but could be built in relatively easy.

4.8. XMPP (jabber)

XMPP (originally named Jabber) is a synchronous message protocol used in the internet. It is speci-

fied in the documents RFC6120[69], RFC6121[69], RFC3922[68], and RFC3923[67]. The protocol is a very advanced chat protocol featuring numerous levels of security including end-to-end signing and object encryption[67]. There is also a stream initiation extension for transferring files between endpoints [74].

It has generic routing capabilities spanning between known and unknown servers.

The protocol itself seems to be a strong candidate as a transport layer as it is being used actively in the internet.



4.9. SMTP

The SMTP protocol is currently specified in [44]. It specifies a method to deliver reliably asynchronous mail objects thru a specific transport medium (most of the time the internet). The document splits a mail object into a mail envelope and its content. The envelope contains the routing information which is the sender (one) and the recipient (one or more) in 7-Bit ASCII. The envelope may additionally contain optional protocol extension material.

The content should be in 7-Bit-ASCII (8-Bit ASCII may be requested but this feature is not widely adopted). It is split into two parts. These parts are the header (which does contain meta information about the message such as subject, reply address or a comprehensive list of all recipients), and the body which contains the message itself. All lines of the content must be terminated with a CRLF and must not be longer than 998 characters excluding CRLF.

The header consists of a collection of header fields. Each of them is built by a header name, a colon and the data. Exact outline of the header is specified in [63] and is separated with a blank line from the body.

It [44] furthermore introduces a simplistic model for smtp message based communication. A more comprehensive model is introduced in the section ?? . As the proposed model is not sufficient for a comprehensive end-to-end analysis.

Traditionally the message itself is mime encoded. The MIME messages are mainly specified in [32], and [33]. MIME allows to send messages in multiple representations (alternates), and attach additional information (such as possibly inlined images or attached documents).

SMTP is one of the most common messaging protocols in the internet (Ct1: Widely Adopted) and it would be devastating for business of a country if for censoring reasons this protocol would be cut off. The protocol is furthermore very reliable as it has built in support for redundancy and a throughout message design making it relatively easy to diagnose problems (Ct2: Re-

liable). All SMTP servers are normally capable of routing and and receiving messages. Messages going over serveral servers are common (Ct3: Symmetrically built) so the third criteria may be considered as fulfilled as well

SMTP is considered a strong candidate as transport layer.

4.10. SMS

SMS capability was introduced in the SS7 protocol. This protocol allows the message transfer of messages not bigger than 144 character. Due to this restriction in size it is unlikely to be suitable for this type of communication as the keys being required are already sized similarly leaving no space for Messages or routing information.

Secondly the protocol is not widely adopted within the internet domain. There are gateways providing bridging functionalities to the SMS service. However – the protocol itself is insignificant in the internet itself.



4.11. MMS

The Multimedia Messaging Service (MMS) is maintained by 3GPP (3rd Generation Partnership Project). This protocol is manly a mobile protocol based on telephone networks.



4.12. Roundup for Transport Protocols

Criteria Protocol	Ct1: Widely adopted	Ct2: Reliable	Ct3: Symmetrically built
HTTP	✓	✓	x
FTP	✓	✓	x
TFTP	x	x	x
MQTT	~	✓	x
AMQP	~	✓	x
CoAP	~	~	x
WAMP	x	✓	~
XMPP	✓	✓	✓
SMTP	✓	✓	✓
SMS ¹			
MMS	✓	✓	x

Table 4.1.: comparison of protocols in terms of the suitability criteria as transport layer

In table 4.1 we sum up all previously analysed protocols. We use “✓” for a fulfilled criteria, “~” for a partially fulfilled criteria, and “x” for a not fulfilled criteria. This overview shows in compact form which protocols have been identified as strong candidates for use as a transport layer in terms of an anonymising protocol.

4. Existing Transport Layer Protocols

This table shows that strong identified candidates are SMTP (being already a message sending protocol on asynchronous base) and XMPP (a real time chat protocol able to attach files. This protocol features furthermore end-to-end encryption and signing). Both have the advantages that they are really wide adopted in the internet and do support additionally advanced content (such as alternatives or attachments).

¹omitted due to message size being too small

5. Existing Research and Implementations on the Topic

5.1. Anonymity

As Anonymity we take the definition as specified in [58].

Anonymity of a subject means that the subject is not identifiable within a set of subjects, the anonymity set.¹

and

Anonymity of a subject from an attacker's perspective means that the attacker cannot sufficiently identify the subject within a set of subjects, the anonymity set.¹

Whereas the anonymity set is defined as the set of all possible subjects.

Especially the anonymity of a subject from an attacker's is very important to this paper.

5.1.1. k -Anonymity

k -anonymity is a term introduced in [2]. This work claims that no one might be held responsible for an action if the action itself can only be identified as an action which has been taken by one unidentifiable entity out of k entities.

The Document distinguishes between *Sender k -anonymity* where the sending entity can only be narrowed down to a set of k entities and *Receiver k -anonymity*



5.1.2. ℓ -Diversity

In [49] an extended model of k -anonymity is introduced. In this paper the authors emphasize that it is possible to break a k -anonymity set if there is additional Information available which may be merged into a data set so that a special entity can be filtered from the k -anonymity set. In other words if an anonymity set is to tightly specified a single additional background information might be sufficient to identify a specific entity in an anonymity set.

While it might be arguable that a k -anonymity in which a member is not implicitly k -anonymous still is sufficient for k -anonymity in its sense the point made in

this work is definitely right and should be taken into account.

Their approach is to introduce an amount of invisible diversity into k -anonymous sets so that simple background knowledge is no longer sufficient to isolate a single member.

5.1.3. t -Closeness

While ℓ -diversity protects the identity of an entity it does not prevent information gain. A subject which is in a class has the same attributes. This is where t -closeness[56] comes into play. t -closeness is defined as follows:

An equivalence class is said to have t -closeness if the distance between the distribution of a sensitive attribute in this class and the distribution of the attribute in the whole table is no more than a threshold. A table is said to have t -closeness if all equivalence classes have t -closeness.

5.2. Zero Trust

Zero trust is not a truly researched model in systems engineering. It is however widely adopted.

We refer in this work to the zero trust model when denying the trust in any infrastructure not directly controlled by the sending or receiving entity. This distrust extends especially but not exclusively to the network transporting the message, the nodes storing and forwarding messages, the backup taken from any system except the client machines of the sending and receiving parties, and software, hardware, and operators of all systems not explicitly trusted.

As explicitly trusted in our model we do regard the user sending a message (and his immediate hardware used for sending the message), and the users receiving the messages. Trust in between the receiving parties (if more than one) of a message is not necessarily given.

¹footnotes omitted in quote

5.3. Pseudonymity

As Pseudonymity we take the definition as specified in [58].

A pseudonym is an identifier of a subject other than one of the subject's real names. The subject which the pseudonym refers to is the holder of the pseudonym. A subject is pseudonymous if a pseudonym is used as identifier instead of one of its real names.²

5.4. Undetectability

As undetectability we take the definition as specified in [58].

Undetectability of an item of interest (IOI) from an attacker's perspective means that the attacker cannot sufficiently distinguish whether it exists or not.²

5.5. Unobservability

As unobservability we take the definition as specified in [58].

Unobservability of an item of interest (IOI) means

- undetectability of the IOI against all subjects uninvolved in it and
- anonymity of the subject(s) involved in the IOI even against the other subject(s) involved in that IOI.

This part is very important. As we are heading for a censorship resistant solution unobservability is a key. As mentioned in this paper unobservability raises the bar of required attributes again (\Rightarrow reads "implies"):

censorship resistance \Rightarrow *unobservability*
unobservability \Rightarrow *undetectability*
undetectability \Rightarrow *anonymity*

So this means that we have to use an undetectable data channel in order to achieve censorship resistance.

5.5.1. Ephemeral Identity

In this work we use accounting on various levels. While we are dealing with anonymity accounting has still to be linked to some kind of identity for this reason we are introducing a term called "ephemeral identity".

²footnotes omitted in quote

A Ephemeral identity is a temporary identity which is defined by the following attributes:

- It is an artificial identity
- It is only used for a short timespan
- It is not linkable to another identity

The key in this definition is the last point is crucial and at the same time hard to achieve.

5.6. Single Use Reply Blocks and Multi Use Reply Blocks

The use of single use reply blocks were first introduced by Chaum in [17]. A routing block in general is a structure allowing to send a message to someone without knowing the targets true address. It might be differentiated into "Single Use Reply Blocks" (SURBs) which may be used once and "Multi Use Reply Blocks" (MURBs) which may be used a limited number of times.

The concept is that we have in our case a routing block which might be used up to n times ($0 < n < 127$). The number has been chosen for practical reasons. It is easily representable in a byte integer (signed or unsigned) on any system. It is big enough to support human communication in a sensible way and is big enough to add not too much overhead when rerequesting more MURBs. The number should not be too big because if a MURB is reused the same pattern of traffic is generated thus making the system susceptible to statistical attacks.

5.7. Censorship

As definition for censorship we take

Censorship: the cyclical suppression, banning, expurgation, or editing by an individual, institution, group or government that enforce or influence its decision against members of the public – of any written or pictorial materials which that individual, institution, group or government deems obscene and "utterly without redeeming social value," as determined by "contemporary community standards."

Which is attributed to Chuck Stone Professor at the School of Journalism and Mass Communication, University of North Carolina. Please note that "Self Censorship" (not expressing something in fear of consequences) is a form of censorship too.

In our more technical subsystem this means

A systematic suppression, modification, or banning of data in the internet by either removal, or modification of the data, or syste-

matic influencing of entities involved in the processing (e.g. by writing, routing, storing or reading) of this data.

5.7.1. Censorship Resistant

A censorship resistant system is a system which allows the users of the system and the data itself to be unaffected from censorship. Please note that this does not deny the possibility of censorship per se. It still exists outside the system. But it has some consequences for the system itself.

- The system must be either undetectable or out of reach for an entity censoring.
The possibility of identifying a protocol or data allows a censoring entity to suppress the use of the protocol itself.
- The entities involved in a system must be untraceable.
Traceable entities would result in means of suppressing real world entities participating in the system.

5.7.2. Parrot Circumvention

In [39] Houmansadr, Brubaker, and Shmatikov express that it is easy for a human to determine decoy traffic as the content is easily identifiable as automated content. While this is absolutely true there is a possibility here to generate “human like” data traffic to a certain extent. In our design this is the job covered by the blending layer.

5.7.3. Censorship Circumvention

Several technical ways have been explored to circumvent censorship. All seem to boil down to two main ideas:

- Hide data.
- Copy data to a vast amount of places in order to improve the lifespan of data.

In the following section we look at technologies and ideas dealing with these circumvention technologies.

5.7.3.1. Covert Channel and Channel Exploitations

The original term of covert channels was defined by Lampson[46] as

not intended for information transfer at all, such as the service program's effect on system load.

This was defined in such a way to distinguish the message flow from

legitimate channels used by the confined service, such as the bill.

The use of a legitimate channel such as SMTP and hide information in this specific channel is not a usage of covert channel. This method is commonly referenced as channel exploitation. In the following section we analyse technologies for suitability in a P2P network construct as data channel.

5.7.3.2. Spread Spectrum



5.7.3.3. Steganography



5.7.3.4. Timing Channels



5.8. Cryptography

Whenever dealing with hiding data and maintaining integrity of data cryptography is the first tool in the hand of an implementer. A vast amount of research in this area does already exist. For this work we did not collect a lot of information. We focussed on algorithms either well researched and implemented or research which seem very valuable when putting this work into place.

5.8.1. Symmetric Encryption

Symmetric encryption in this paper assumes always that

$$D^{K_a}(E^{K_a}(M)) = M \quad (5.1)$$

For a key $K_b \neq K_a$ this means

$$D^{K_a}(E^{K_b}(M)) \neq M \quad (5.2)$$

$$D^{K_b}(E^{K_a}(M)) \neq M \quad (5.3)$$

5.8.1.1. AES



5.8.1.2. Camelia



5.8.2. Asymmetric Encryption

For all asymmetric encryption algorithm in this paper we may assume that

$$D^{K_a^{-1}}(E^{K_a^1}(M)) = M \quad (5.4)$$

$$D^{K_a^1}(E^{K_a^{-1}}(M)) = M \quad (5.5)$$

It is important that

$$D^{K_a^{-1}}(E^{K_a^{-1}}(M)) \neq M \quad (5.6)$$

$$D^{K_a^1}(E^{K_a^1}(M)) \neq M \quad (5.7)$$

And for any other Keypair $K_a^p \neq K_b^p$

$$D^{K_b^{-1}}(E^{K_a^1}(M)) \neq M \quad (5.8)$$

$$D^{K_b^1}(E^{K_a^{-1}}(M)) \neq M \quad (5.9)$$

$$D^{K_b^{-1}}(E^{K_a^{-1}}(M)) \neq M \quad (5.10)$$

$$D^{K_b^1}(E^{K_a^1}(M)) \neq M \quad (5.11)$$

5.8.2.1. RSA

In 1978 the authors Rivest, Shamir, and Adleman published with [64] a paper which did revolutionize cryptography for years. In their paper the authors described an encryption method later to be called RSA which required a key pair (K_a) referenced as public (K_a^1) and private keys (K_a^{-1}). The novelty of this system was that anything encrypted with the public key was only decryptable with the private key and vice versa.

RSA is up until the day of writing this paper not publicly known to be broken (unless a too small key size is used). However – Shor described in 1997 an algorithm which should enable quantum computers to break RSA far faster than done with common computers. In the section 5.8.5 we do elaborate this effects further.

5.8.2.2. Elliptic Curve Cryptography

The elliptic curves were independently suggested by [50] and [45] in 1986. Elliptic curve Cryptography started to be widely deployed in the public space about in 2006. Since then it seems to compete very well with the well established RSA algorithm. While being similarly well researched ECC has the advantage of far shorter key sizes for the same grade of security.

5.8.3. Homomorphic encryption



5.8.4. Deniable Encryption and Deniable Steganography



5.8.5. Key Sizes

The question of key sizes is a hard to answer as it depends on the current and future possibilities of an adversary which is again depending on not foreseeable research. We tried to collect a couple of recommendations.

Encrypt II (<http://www.ecrypt.eu.org/>) recommends currently for a “foreseeable future” 256 Bits for symmetric encryption and for asymmetric encryption based on factoring modulus 15424 Bits. Elliptic Curve Cryptography and Hashing should be sufficient if used with at least 512 Bits. If the focus is reduced to the next \approx 20 years then the key size recommendations is reduced to 128 Bit for symmetric encryption, 3248 Bits for factoring modulus operations and 256 Bits for elliptic curves and hashing.

According to the equations proposed by Lenstra in [47] an asymmetric key size of 2644 Bits respectively a symmetric key length of 95 Bits, or 190 Bits for elliptic curves and hashing should be sufficient for security up to the year 2048.

According to [28] data classified up to “top secret” should be secured asymmetric encryption based on factoring modulus (no proposed encryption standard). For symmetric encryption they recommend 256 Bits, for Hashing at least SHA-384 and for Elliptic curves a 384 Bit sized key.

As it might seem not a wise idea to consider the recommendation of a potential state sponsored adversary and the Formulas proposed by Lenstra do not explicitly take quantum computers into account we therefore follow the recommendations of ENCRYPT II.

Furthermore taking all recommendations together it seems that all involved parties assume the biggest trust into elliptic curves rather than asymmetric encryption based on factoring modulus.

5.9. Routing

If we can follow data from a source to a destination we may safely assume that the participants of this data exchange are no longer anonymous. So special care should be taken to this aspect. In the past several approaches have been made in order to avoid detection

of data while routing. In the following sections we will look at some basic concepts which have been proposed up until today. We describe their concept and have a look at their weaknesses discovered so far.

In System Implementations we analyze some related real world systems regarding how they work and how they have been attacked in the past.

5.9.1. Mixing

Mixes have been first introduced by “Untraceable Electronic Mail, Return, Addresses, and Digital Pseudonyms” [17] in 1981. The basic concept in a mix goes as follows. We do not send a message directly from the source to the target. Instead we use a kind of proxy server or router in between which picks up the packet, anonymizes it, and forwards it either to the recipient or another mix. If we assume that we have at least 3 mixes cascaded we then can conclude that:

- Only the first mix knows the true sender
- All intermediate mixes know neither the true sender nor the true recipient (as the data comes from mixes and is forwarded to other mixes)
- Only the last mix knows the final recipient.

This approach (in this simple form) has several downsides and weaknesses.

- In a low latency network the message may be traced by analysing the timing of a message.
- We can emphasize a path by replaying the same message multiple times (assuming we control an evil node) thus discovering at least the final recipient.
- If we can “tag” a message (with a content or an attribute) we then may be able to follow the message.

In 2003 Rennhard and Plattner analyzed the suitability for mixes as a anonymizing network for masses. They concluded that there are three possibilities to run mixes.

- Commercial Static MixNetworks
- Static MixNetworks Operated by Volunteers
- Dynamic MixNetworks

They concluded that in an ideal implementation a dynamic mix network where every user is operating a mix is the most promising solution as static mixes always might be hunted by an adversary.

5.9.2. Onion Routing

Onion routing is a further development of the concept of mixes. In onion routers every mix gets a message which is asymmetrically encrypted. By decrypting the

message he gets the name of the next hop and the content which he has to forward. The main difference in this approach is that in traditional mix cascades the mix decides about the next hop. In an onionised routing system the message decides about the route it is taking.

While tagging attacks are far harder (if we exclude side channel attacks to break sender anonymity) the traditional attacks on mixes are still possible. So when adversaries are operating entry and/or exit nodes it is very easy for them to match the respective traffic.

One very well known of onion routing networks is Tor (<https://www.torproject.org>). For more information about tor see section 5.10.8.



5.9.3. Crowds

Crowds is a network which offers anonymity within a local group. It works as follows:

- All users add themselves to a group by registering on a so called “blender”.
- All users start a service (called jondo).
- Every Jondo takes any received message (might be from him as well) and sends it with a 50% chance either to the correct recipient or to a randomly chosen destination

While crowds do anonymize the sender from the recipient rather well the system offers no protection from someone capable of monitoring crowds traffic. The system may however be easily attacked from within by introducing collaborating jondos.



5.9.4. Mimic routes

Mimics are a set of static mixes which maintain a constant message flow between the static routes. If legitimate traffic arrives the pseudo traffic is replaced by the legitimate traffic an outstanding observer is thus incapable of telling the difference between real traffic and dummy traffic.

If centralized mixes are used the system lacks the same vulnerabilities of sizing and observing the exit nodes as all previously mentioned systems. If we assume that sender and receiver operate a mixer by themselves the system would be no longer susceptible to timing or sizing analyses. The mimic routes put a constant load onto the network. This bandwidth is lost and may not be reclaimed. It does not scale well as every new participant increases the need for mimic routes and creates (in the case of user mixes) new mimic load.

5.9.4.1. DC Networks

DC networks are based on the work “The Dining Cryptographers Problem: Unconditional Sender and Recipient Untraceability” by Chaum[18]. In this work Chaum describes a system allowing a one bit transfer (The specific paper talks about the payment of a meal). Although all participants of the DC net are known the system makes it unable to determine who has been sending a message. The message in a DC-Net is readable for anyone. This network has the downside that a cheating player may disrupt communication without being traceable.

Several attempts have been made to strengthen the proposal of Chaum[36][77]. But no one succeeded without introducing significant downsides on the privacy side.

5.9.4.2. Anonymous Remailer

Remailers have been in use for quite some time. There are several classes of remailers and all of them are somehow related to Mixnets. There are “types” of remailers defined. Although these “types” offer some kind of hierarchy none of the more advanced “types” seem to have more than one implementation in the wild.



Pseudonymous Remailers (also called Nym Servers) take a message and replace all information pointing to the original sender with a pseudonym. This pseudonym may be used as an answer address. The most well known pseudonymous remailer possibly was anon.penet.fi run by Johan Helsingius. This service has been forced several times to reveal a pseudonym's true identity before Johan Helsingius decided to shut it down. For a more in depth discussion of Pseudonymous Remailers see 5.10.1

Cyberpunk remailers forward messages like pseudonymous remailers. Unlike pseudonymous remailers Cyberpunk remailers decrypt a received message and its content is forwarded without adding a pseudonym. A reply to such a message is not possible. They may therefore be regarded as an “decrypting reflector” or a “decrypting mix” and may be used to build an onion routing network for messages. For a more in depth discussion of Type I Remailers see 5.10.3.

Mixmaster remailers are very similar to Cyberpunk remailers. Unlike them Mixmaster remailers hide the messages not in an own protocol but use SMTP instead for it. While using SMTP as a transport layer Cyberpunk remailers are custom (non traditional mail) servers listening on port 25. For a more in depth discussion of type II remailers see 5.10.4.

Mixminion remailers extend the model of Mixmaster remailers. They still use SMTP but introduce new con-

cepts. New concepts in Mixminion remailers are:

- Single Use Reply Blocks (SURBs)
- Replay prevention
- Key rotation
- Exit policies
- Dummy traffic

For a more in depth discussion of Mixminion remailers see 5.10.5.



5.10. System Implementations

The following sections emphasize on implementations of anonymising (and related) protocols regardless of their usage in the domain of messaging. It is a list of system classes or their specific implementations together with a short analysis of strength and weaknesses. Wherever possible we try to refer to original sources. This is however not always possible since some of these systems are no longer in use.

If a system shows strong similarities in parts then we emphasize on this parts and analyse the findings.

5.10.1. Pseudonymous Remailer

The basic idea of remailers were discussed in [17]. The most well known remailer was probably anon.penet.fi which operated from 1993 to 1996.

In principle an anonymous remailer works as an ordinary forwarding SMTP server. The only difference is that it strips off all header fields except for “from”, “to”, and “subject” and then replaces the sender and recipient address with pseudonyms (if any).

As the example shows this kind of remailer is easily attackable by an authority. Since the remailer knows tuples of pseudonyms and their respective real identity it may be forced to reveal true identities. Furthermore message may be monitored at the server or on its way and then due to the content a matching or even tagging is possible.

This remailer offers therefore no protection against an adversary defined in our problem.

5.10.2. Babel

Babel was an academic system defined in a paper by Güllü and Tsudik in 1996[38].



5.10.3. Cypherpunk-Remailer



5.10.4. Mixmaster-Remailer



5.10.5. Mixminion-Remailer



5.10.6. Crowds

Crowds is an implementation of the crowds protocol.



5.10.7. Tarzan



5.10.8. Tor

Tor is one of the most common onion router networks these days. It is specified in [23]. It might be considered one of the most advanced networks since a lot of research has been done here.

In short tor is a network consisting of multiple onion routers. Each client first picks an entry node. Then it establishes an identity, gets a listing of relay servers, and chooses a path through multiple onion routers. This path is linked to the temporary identity. This identity (and the path connected to it) should be changed at least once a day.

There is centrally organized directory in the tor network knowing all tor relay servers. Any Tor relay server may be a directory server as well.

Many attacks involving the Tor networks have been discussed in the academic world such as [57, 8, 9, 12, 13, 22, 27] and some have even been exploited actively. In the best case the people discovering the attacks did propose mitigation to the attack and took care that these mitigations flowed back into the protocol. Some general thoughts of the attacks should be emphasized here for treatment in our protocol.

Being an exit node may be a problem in some jurisdictions. In general it seems to be accepted that routing traffic with unknown content (to the routing node) seems to be accepted as one might argue that users of Tor are not regarded bad in general. So by being unable to tell malicious or illegal traffic apart from legitimate traffic this is not a problem. However – being

an exit node can mean that unencrypted and illegal traffic is leaving the routing traffic. In this specific case operators of a relay node might fear legal prosecution. This is why tor nodes may be listed as “non exit nodes”

Furthermore several DoS-Attacks have been carried out in order to overload parts of the Tor network. Most of them do a bandwidth drain on the network layer.

Attacking anonymisation has been done by several ways. First of all the most common attack is a time wise correlation of packets if in control of an entry and an exit node. A huge attack of this kind was published in 2014 and has been published on the tor website (relay early traffic confirmation attack). This has been possible because tor is a low latency network. Another attack is to identify routes through tor by statistically analyse the traffic density in the network between nodes. More theoretical attacks focus on the possibility of controlling the directory servers to guarantee that an entity may be deanonymised because it is using compromised routers.

Generally the effectiveness of monitoring of single or multiple networks is disputed. According to a study by Johnson et al. in 2013[42] a system in the scale of PRISM should be able to correlate traffic of 95% of the users within a few days. Other sources based on the Snowden Papers claim that NSA was unable so far to De-Anonymize Tor users. However since these papers referenced to “manual analysis” the statement may be disputed when looking at automated attacks as well.



5.10.9. I^2P

The name I^2P is derived from “Invisible Internet Project” according to geti2p.net. The system itself is comparable to Tor for its capabilities. Major differences are:

- P2P based
- Packet switched routing (tor is “circuit switched”)
- Different forward and backward routes (called tunnels)
- Works pseudonymously
- Supports TCP and UDP

I^2P has not attracted as much attention as Tor so far. So it is hard to judge upon its real qualities.



5.10.10. Freenet

Freenet was originally designed to be a fully distributed data store[19]. Exactly as I^2P it is not analysed thoroughly by the scientific world. unlike I^2P Freenet is based on crowds.



5.10.11. Herbivore

Herbivore is a network protocol designed by Goel et al in [35].



5.10.12. Dissent



5.10.13. P5



5.10.14. Gnutella

Gnutella is not a protocol to the anonymity world in special. It is a file sharing protocol on a Peer to peer base. This is the most interesting aspect of gnutella in this context. Gnutella has proven to be working with a large number of clients.

The current protocol specification may be found under <http://rfc-gnutella.sourceforge.net/>

extension: [6]



5.10.15. Gnutella2

Despite its name Gnutella2 is not the next generation of Gnutella. It was a fork in 2002 from the original Gnutella and has been developed in a different direction. The specification may be found on <http://g2.doxu.org>.



5.10.16. Darknet



5.10.17. Sneakernet



5.10.18. Hordes



5.10.19. Salsa

[55]

Related: [53]



5.10.20. AP3



5.10.21. Hydra-Onion



5.10.22. DUO-Onion



5.10.23. Cashmere



5.10.24. SMTP

As SMTP is our transport prototype we focus in depth onto this topic.

Today's mail transport is mostly done via SMTP protocol as specified in [44]. This protocol has proven to be stable and reliable. Most of the messages are passed from a MUA to a SMTP relay of a provider. From there the message is directly sent to the SMTP server of the recipient and from there to a server based storage of the recipient. The recipient may at any time connect to his server based storage and may optionally relocate

the message to a client based (local) storage. The delivery from the server storage to the MUA of the recipient may happen by message polling or by message push (where as the later is usually implemented by a push-pull mechanism).

To understand the routing of a mail it is essential to understand the whole chain starting from a user(-agent) until arriving at the target user (and being read!). To simplify this I used a consistent model which includes all components (server and clients). The figure 5.1 shows all involved parties of a typical Mail routing. It is important to understand that Mail routing remains the same regardless of the used client. However – Availability of a mail at its destination changes drastically depending on the type of client used. Furthermore control of the mail flow and control is different depending on the client.

The model has three main players storage (derfref-Storage), agent (derfrefAgent) and service (derfref-Service). Storages are endpoint storages storing mails. Not explicitly shown are temporary storages such as spooler queues or state storages. Agents are simple programs taking care of a specific job. Agents may be exchangeable by other similar agents. A service is a bundle of agents which is responsible for a specific task or task sets.

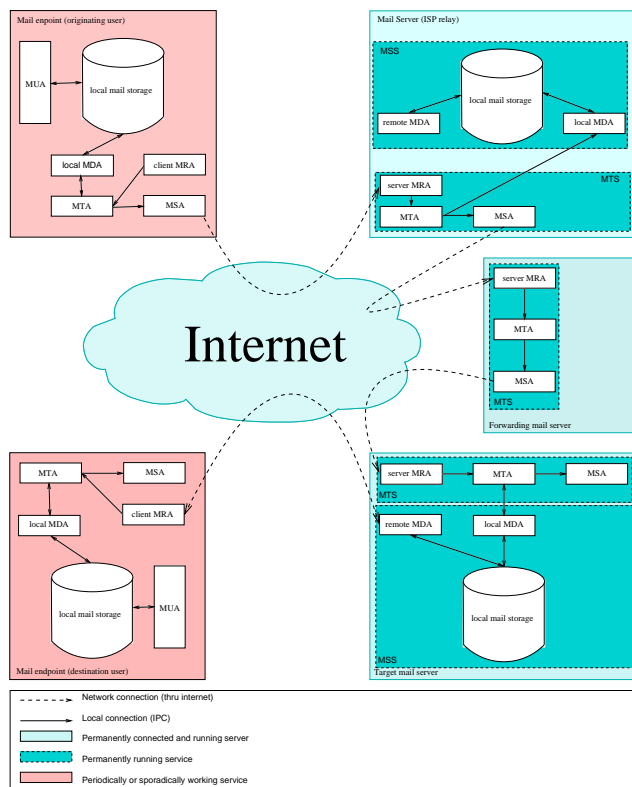


Figure 5.1.: Mail Agents

In the following paragraphs (for definitions) the term “Mail” is used synonymously to the term “Message”. The reason why “Mail” has been chosen over “Messages” that a lot of terms do already exist in standard documents. In these documents the term mail is com-

monly used.

Mails are typically initiated by a Mail User Agent (MUA). A MUA accesses a local mail storage which may be the server storage or a local copy. The local copy may be a cache only copy, the only existing storage (when mails are fetched and deleted from the server after retrieval) or a collected representation of multiple server storages (cache or authoritative).

Besides the MUA the only other component accessing a local mail storage is the Mail Delivery Agent (MDA). An MDA is responsible for storing and fetching mails from the local mail storage. Mails destined for other accounts than the current one are forwarded to the MTA. Mails destined to a User are persistently stored in the local mailstorage. It is important to understand that a mailstorage not necessarily reflects a simple mailbox. It may as well represent multiple mailboxes (eg. a rich client serving multiple IMAP accounts) or a combined view of multiple accounts (eg. a rich client collecting mail from multiple POP accounts). In the case of a rich client the local MDA is part of the software provided by the user agent. In the case of a mail server the local MDA is part of the local Mailstore (not necessarily of the mail transport service).

On the server side there are usually two components (services) at work. A “Mail Transport Service” (MTS) responsible for mail transfers and a “Mail Storage System” which offers the possibility to store received Mails in a local, persistent store.

A MTS consists generally out of three parts. For incoming connects there is a daemon called Mail Receiving Agent (Server MRA) is typically a SMTP listening daemon. A Mail Transfer Agent (MTA) which is responsible for routing, forwarding and rewriting mails. And a Mail Sending Agent (MSA) which is responsible for transmitting mails reliably to another Server MRA (usually sent via SMTP).

A MSS consists out of a local storage and delivery agents which do offer uniform interfaces to access the local store. They do also deal with replication issues and grant should take care of the atomicity of transactions committed to the storage. Typically there are two different kind of MDAs. Local MDAs offer possibilities to access the store via efficient (non network based) mechanisms (eg IPC or named sockets). This is usually done with a stripped down protocol (eg. LMTP). For remote agents there a publicly – network based – agent available. Common Protocols for this Remote MDA include POP, IMAP, or MS-OXMAPIHTTP.

5.10.25. Mail Endpoints

Mail endpoints consist typically of the following components:

- A Mail User agent (MUA)

5. Existing Research and Implementations on the Topic

- A Local Mail storage (MUA)
- A Local Mail Delivery Agent (Local MDA)
- A Mail Transfer Agent (MTA)
- A Mail Sending Agent (MSA)
- A Mail Receiving Agent (MRA)

Only two of these components do have external interfaces. These are MSA and MRA. MSA usually uses SMTP as transport protocol. When doing so there are a couple of specialities.

- Portnumber is 587 (specified in [34]).
Although port numbers 25 and 465 are valid and do have usually the same capabilities, they are for mail routing between servers only. Mail endpoints should no longer use them.
- Connections are authenticated.
Unlike a normal server-to-server (relay or final delivery) SMTP connections on port 25 clients should always be authenticated of some sort. This may be based on data provided by the user (eg. username/password or certificate) or data identifying the sending system (eg. IP address)[34]. Failure in doing authentication may result in this port beeing misused as an sender for UBE.

Mail User Agents (MUA) are the terminal endpoint of a mail delivery. Mail user agents may be implemented as fat clients on a desktop or mobile system or as an interface over a different generic protocol such as HTTP (Web Clients).

Server located clients are a special breed of fat clients. These clients share the properties of fat clients except for the fact that they do not connect to the server. The client application itself has to be run on the server where the mail storage persists. This makes delivery and communication with the server different. Instead of interfacing with a MSA and a client MDA they may directly access the local mail storage on the server. On these systems the local mail storage may be implemented as a database in a user specific directory structure.

5.10.25.1. Fat clients

The majority of mail clients are fat clients. These clients score over the more centralistic organized web clients in the way that they may offer mail availability even if an internet connection is not available (through a client specific local mail storage). They furthermore provide the possibility to collect mails from multiple sources and store them in the local storage. Unlike Mail servers, clients are assumed to be not always online. In fact they may be offline most of the time. To guarantee the availability of a certain email address a responsible mail server for a specific address collects all mails (this is done by the MSS) and provides

a consolidated view onto the database when a client connects through a local or remote MDA.

As these clients vary strongly it is absolutely mandatory for the MDA that they are well specified. Lack in doing so would result in heavy interoperability problems. Most commonly the Protocols IMAP, POP and EWS are being used these days. For mail delivery the SMTP protocol is used.

Fat clients are commonly used on mobile devices. According to [16] in Aug 2012 the most common fat email client was Apple Mail client on iOS devices (35.6%), followed by Outlook (20.14%), and Apple Mail (11%). *Email Client Market Share*[26] as a more recent source lists in February 2014 iOS devices with 37%, followed by Outlook (13%), and Google Android (9%).

5.10.25.2. Server located clients

server located clients build an absolute minority. This kind of clients have been used mainly in the days of centralized hosts. An example for a Server Located Client is the Unix command "mail". This client reads a mail storage from a file in the users home directory.

5.10.25.3. Web clients

Web clients are these days a common alternative to fat clients. Most big provider companies use their own proprietary web client. According to [26] the most common web clients are "Gmail", "Outlook.com", and "Yahoo! Mail". All these Interfaces do not offer a kind of public plug-in interface. However, they do offer IMAP-interfaces. This important for a future generalistic approach to the problem.

5.10.26. Interfaces of Mail Endpoints

There are two interfaces



5.10.27. S/MIME

S/MIME is an extension to the MIME standard. The MIME standard allows in simple text oriented mails an alternate representation of the same content (e.g. as text and as html), or it allows to split a message into multiple parts which may be encoded. It is important to note that MIME encoding is only effective in the body part of a mail.

S/MIME as described in [61] extends this standard with the possibility to encrypt mail content or to sign it. Practically this is achieved by either putting the encrypted part, or the signature into an attachment. It is

important to know, that this method leaks significant parts of the data.

As the mail travels directly from sender to recipient both involved parties are revealed. Neither message subject nor message size or frequency are hidden. This method does offer limited protection when assuming an adversary with interest in the message content only. It does not protect from the kind of adversary in our case.

The trust model is based on a centralistic approach involving generally trusted root certification authorities.

5.10.28. PGP/MIME

Exactly as S/MIME PGP[60] builds upon the base of MIME. Although the trust model in PGP is peer based. The encryption technology does not significantly differ (as seen from the security model).

A good thing to learn from PGP is that there are peer based approaches offering limited possibilities for trust. The trust in PGP is based on the peer review of users. This peer review may give an idea of how well verified the key of a user is.



5.10.29. XMMP



5.11. Proof of work

Proof of work is one possibility to limit resource exhaustion on locally controlled resources. Traditional proofs are either CPU- or memory-bound. This means that they have to prove that they assigned a certain amount of their own CPU time or memory bandwidth to a problem posed by the receiving node.

In [3] is a good summary of proposed proof of work methods. Although they are used there for the defence of DDoS-attacks (Distributed Denial of Service) they might as well be used for defence against misuse for UBE and (D)DoS of the Vortex system. The list has been shortened with irrelevant algorithms for this work and extended with newer research in that field.

In our case we are looking for a proof which imposes ideally the same amount of work to an attacker and a valid sender. Since an attacker needs a lot more resources than a normal sender the amount of work should be for him unbearable. A normal sender on the other hand should be able to cover the load imposed by the system easily.

5.11.1. CPU-Bound Proof of work

CPU bound proof of work tries to assign a task to a request. By presenting a result the sender proves that he solved a puzzle. Normally these puzzles may only be solved by brute force.

5.11.1.1. Hash based puzzle by Juels and Brainard

The hash puzzle by Juels and Brainard in [43] works as follows:

- The requester requests an operation.
- The service provider sends a block of data back with a known number of missing bits at the end and a cryptographic hash of the original block (including the missing bits)
- The requester then brute forces the missing bits until he finds the correct bit sequence to complete the hash puzzle and sends it to the service provider.

This puzzle has several downsides. One of the biggest downsides is that the puzzle may be solved by using multiple instances in parallel. This allows a specialised adversary to build an efficient infrastructure for solving this kind of puzzle.

5.11.1.2. Hash based puzzle by Aura, Nikander and Leiwo

The hash based puzzle by Aura, Nikander, and Leiwo in [7] is an improved variant of [43]. It works as follows:

- The requester requests an operation.
- The service provider sends a nonce block N_{sp} to the requester and a number k (this number represents the difficulty).
- The requester chooses a nonce N_r .
- The requester brute forces *puzzlesolution* by solving $hash(identity_r, N_{sp}, N_r, puzzlesolution) = hashValueStartingWithKBitsOfZeroes$.
- The requester sends N_r and X to the service provider.

The downsides of this puzzles are that it may be calculated in parallel. This allows a specialised adversary to build an efficient infrastructure for solving this kind of puzzle. Furthermore the client side nonce N_r must be stored as long as the server side nonce N_{sp} is not regenerated in order to avoid replay attacks.

5. Existing Research and Implementations on the Topic

5.11.1.3. Modified Repeated Squaring Puzzle

Jeckmans proposed in [41] a Squaring hash puzzle. The algorithm is described as follows:

- *Setup*(ℓ): the sever generates a new public parameter sp with length ℓ bits using a (pseudo)random number generator. It then selects two random large primes p, q and creates $n = p \times q$ out of this. The server also selects a difficulty for the puzzles, k . The algorithm then outputs $mk = 2^k \bmod \phi(n)$ and $params = \langle k, sp, n \rangle$.
- *PuzzleGen*(mk, req): $puz = \emptyset$ and $info = \emptyset$.
- *PuzzleSol*(puz): $g = H(\langle sp, id_C \rangle)$, $sol = g^{2^k} \bmod n$.
- *PuzzleVer*($info, mk, sol$): This algorithm computes the generator, $g = H(\langle sp, id_C \rangle)$. The solution is then verified $sol \stackrel{?}{=} g^{2^k \bmod \phi(n)} \bmod n$.
- *BatchVer*($info, mk, sol_i (1 \leq i \leq m)$): assume that the server has stored m solutions to check, $sol_i, 1 \leq i \leq m$. Compute the corresponding generators $g_i = H(\langle sp, id_{C_i} \rangle)$, $1 \leq i \leq m$. These solutions are then verified with batch verification using Equation $(\prod_{i=1}^m g_i)^{2^k} \bmod n \stackrel{?}{=} \prod_{i=1}^m sol_i \bmod n$.

This puzzle is a typical CPU bound puzzle compensating a lot of the drawbacks of [7] and [43] mentioned in the sections before. First it offers a potential verification in batches under the assumption that all solutions within the batch are correct. Secondly it is non-parallelizable. There is very little information to be stored on the server side and non of the information has a lifetime which is longer than the puzzle.

5.11.1.4. Hinted Hash Puzzle

In [29] the authors Feng, Kaiser, and Luu proposed a protocol and is closely related to [7]. The protocol itself is working as follows:

- The requester requests an operation and includes a nonce N_c .
- The service provider sends a chosen puzzle P and the hash answer $H(\langle A, N_s \rangle)$ to the requester.
- The requester brute forces A .
- The requester sends A to the service provider.

In the original protocols hashes and nonces are re-sent in order to verify if the requests do still match the originally sent data. As they have no impacts on the mathematical side of the operation they have been eliminated in this description.

From today's view this protocol is however not very secure. Solutions may be searched in parallel and the protocol is susceptible to replay attacks as found result A is replayed over the course of time to re-authenticate

5.11.1.5. Chained Hash Puzzle

[37] (CPU Bound)

5.11.1.6. Targeted Hash Puzzle

[30] (CPU Bound)

5.11.1.7. Repeated Squaring Puzzle

[65] (CPU Bound)

5.11.1.8. Discrete Logarithm Puzzle

The puzzle of Waters et al. in [78] are somewhat similar to a brute force attack in a DH key exchange. This puzzle is non-parallelizable and is related to the hint based puzzles.

5.11.1.9. Subset sum puzzle

[75] (CPU bound)

5.11.2. Memory-Bound Proof of work

5.11.2.1. Moderately hard, memory-bound functions

[1] (Memory hard)

5.11.2.2. Memory bound puzzle based on pattern databases

[24] (Memory hard)

5.11.2.3. Argon2

[11] (Memory hard)

5.11.2.4. Script



5.11.3. Summary for Proof of Work Algorithms



5.12. Known Attacks

In the following sections we emphasize on possible attacks to an anonymity preserving protocols. In the following sections we describe classes of attacks. These attacks may be used to attack the anonymity of any entity involved in the message channel. In a later stage we test the protocol for immunity against these classes of attacks.

5.12.1. Broken Encryption Algorithms

Encryption algorithms may become broken at any time. This either to new findings in attacking them, by more resources being available to an adversary, or by new technologies allowing new kind of attacks. A good protocol must be able to react to such threats in a timely manner. This reaction should not rely on a required update of the infrastructure. The grade of security should solely be controlled by the users.

We cannot do a lot for attacks of this kind to happen. However – we might introduce a choice of algorithms and key sizes to give the user a choice in the degree of security he wants to have.

5.12.2. Attacks Targeting Anonymity

All attacks targeting users anonymity is a main focus of this work. Many informations may be leaked and the main goal should therefore rely on the principles established in security.

- Prevent an attack
This can only be done for attacks which are already known and may not be realistic in all cases. In our protocol we have strict boundaries defined. A node under attack should at any time of a valid protocol usage (this excepts bandwidth depletion attacks) be able to block malicious identities. Since establishing new identities is costly an attacker should always require far more resources than the defender.
- Minimize attack surface
This part of the attack prevention is included by design in the protocol.
- Redirect an attack
Although this is not done by the implementation it is possible to handle suspected malicious nodes differently.
- Control damage
For us this means leaving as little information about identities or meta information as possible on untrusted infrastructures. If we leave traces (i.e. message flows, or accounting information) they should have the least possible information content and should expire within a reasonable amount of time.
- Discover an attack
The protocol is designed in such a way that discovering attacks (such as a query attack) may be done. However – we consider active attacks just as part of the ordinary message flow as an immediate result.
- Recover from an attack
An attack does always impose a load onto a systems resources regardless of its success. It is important that a system recovers almost immediately from an attack and is not covered in a non or only partial functional state either temporarily or permanently.

In the following subsections we list a couple of attack classes which have been used against systems listed in 5.10 or the respective academic works. We list the counter measures which have been taken to deflect these attacks.

5.12.2.1. Probing Attacks

Identifying a node by probing and check their reaction is commonly done when fingerprinting a service. As a node is participating in a network and relaying messages probing may not be evaded. However, it may be

5. Existing Research and Implementations on the Topic

made costly for an adversary to do systematic probing. This should be taken into account.

One strategy to avoid would be to put high costs onto clear text requests in such a way that a clear text request may have a long reply time (e.g. up to one day). An early retry of the same identity would lead to automatic blacklisting. This is however an insufficient strategy as a huge adversary may have lots identities in stock. Requesting a particularly long key as a plain text identity does not make sense either as these as well may be kept in stock. We may however force a plaintext request to have a hash following certain rules. We may for example put in a requirement that the first four bytes of the hash of a header block translates to the first four characters of the receiving address



5.12.2.2. Hotspot Attacks



5.12.2.3. Message Tagging and Tracing



5.12.2.4. Side Channel Attacks



5.12.2.5. Timing Attacks



5.12.2.6. Sizing Attacks



5.12.2.7. Bugging Attacks

Numerous attacks are available through bugging of a protocol. In this chapter we outline some of the possibilities and how they may be countered:

Bugging through certificate or identity lookup:

Almost all kind of proof of identities, such as certificates, offer some kind of revocation facility. While this is a perfect desirable property of these infrastructures they offer a flaw. Since the location of this revocation information is typically embedded in the proof of identity an evil attacker might use a falsified proof of identity with a recording revocation point.

There are multiple possibilities to counter such an attack. The easiest one is to do no verification at all. This is however not desirable from the security point of view.

Another possibility is to only verify trusted proof of identities. By doing so the only attacker could be someone having access to a trusted source of proof of identities.

A third possibility is to relay the request to an other host either by using an anonymity structure such as Tor or by using its own infrastructure. Using Tor would violate the “Zero Trust” principle we are aiming for. Furthermore this measure would only conceal the source of the verification. It would not hide the fact that the message is being processed.

A fourth and most promising technology would be to force the sender of the certificate to include a “proof of non revocation”. This could be a timestamped and signed partial CRL. Such a mandatory proof of non-revocation would allow a node to verify the validity of a certificate without being forced to disclose itself by doing a verification. On the downside has to be mentioned that including a proof of non-revocation involves the requirement to accept a certain amount of caching time to be accepted. This allowed caching time reduces the value of the proof as it may be expired in the mean time. It is recommended to keep the maximum cache time as low as 1d in order to avoid that revoked certificates may be used.

Bugging through DNS traffic: A widely common protocol in the internet is DNS. Almost all network related programs use it without thinking. Normally is the usage of such a protocol not a minor issue since the resolution of a lookup usually done by an ISP. In the case of a small ISP this might however already become a problem.

The bugging in general attack works as follows: We include a unique DNS name to be resolved by a recipient. This can be done most easily by including an external resource such as an image. A recipient will process this resource and might therefore deliver information about the frequency of reading, or the type of client.

It must be taken into account that the transport layer will always do DNS lookups and that we may not avoid this attack completely. We may however minimise the possibilities of this attack.

Bugging through external resources: An easy attack is always to include external resources into a message and wait until they are fetched. In order to avoid this kind of attack plain text or other self contained formats should be used when sending a message. As we may not govern the type of contained message we can make at least recommendations con-

cering its structure

to believe into such a system might be drastically reduced.

5.12.3. Denial of Service Attacks

5.12.3.1. Censorship

Where as traditional censorship is widely regarded as selective information filtering and alteration a very repressive censorship can even include denial of information flows in general. Any anonymity system not offering the possibility to hide in legitimate information flows is therefore not censorship resistant.

5.12.3.2. Credibility Attack

Another type of DoS attack is the credibility attack. While not necessarily a technical attack it is very effective. A system not having a sufficiently big user base is offering thus a bad level of anonymity due to the fact that the anonymity set is too small or the traffic concealing message flow is insufficient.

In a credibility attack a systems reputation is degraded in such a way that the system is no longer used. This may be achieved in serveral ways. This is usually done by reducing the reputation of a system.

This may be achieved in several ways. Examples:

- Disrupt functionality of a system.
This may be done by blocking ports the messaging protocol uses or blocking selectively messages. It may be done by removing publicly known participants from the internet either by law or by threatening.
- Publicly dispute the effectiveness of a system.
This is a very effective way to destroy a system. People are not willing to use a system which is compromised if the main goal of using the system is avoiding being observed.
- Reduce the effectiveness of a system.
A system may be considerably being loaded by an adverser to decrease the positive reception of the system. He may further use the system to send UBE to reduce the overall experience when using the system. Another way of reducing the effectiveness is to misuse the system for bad purposes and making them public.
- Dispute the credibility of the system founders.
Another way of reducing credibility of a system is to undermine its creators. If – for example – people believe that a founders interest was to create a honey pot (e.g. because he is working for a potential state sponsored adverser) for personal secrets they will not be willing to use it.
- Dispute the credibility of the infrastructure.
If an infrastructure is known or suspected to be run by a potential adverser peoples willingness

6. Applied Methodes

Based in the findings of the previous chapter we used the following methodology in order to find a solution:

1. Identify problem hotspots for a new protocol.
2. Design a protocol which addresses the previously identified hotspots.
3. Build a protocol prototype.
4. Analyse the protocol for weaknesses using attack schemes.
 - a) Tagging/Bugging attacks
 - b) Tracing attacks

6.1. Problem Hotspots

Starting off from the previous research we identified several hotspots which have to be taken care off. The following sections list identified problems and the possible countermeasures which have not been broken in the past.



6.1.1. Zero Trust Philosophy

One main disadvantage of almost any system listed in section 5.10 is that a trust (unlimited or limited) has been put into the infrastructure. In example when using Tor you need to trust the directory servers. Control over the directory servers might give an attacker the possibility to redirect a connection to controlled entry and exit nodes which would then break anonymity. In general control of entry and exit nodes makes a system vulnerable.

To avoid this problem we decided to apply a zero trust model. We do not trust any platform except for the sending and receiving computer. We assume that all other devices are compromised and do create detailed logs about what they are doing. We furthermore assume that traffic on the network layer is observed and recorded at any time. This philosophy creates very hard to meet goals. But by assuming so we prevent the system from leaking information through side channels.

RQ1 (Zero Trust): *No infrastructure should be trusted unless it is the senders or the recipients infrastructure.*

6.1.2. Information leakage

Information of messages or their meta data should not be leaked. This means that in a normal message flow any hop should be a valid sender, a valid recipient, or a valid mix this implies some kind of peer-to-peer (P2P) design.

6.1.2.1. P2P design

A main problem of the P2P design is that usually port forwarding or a central infrastructure is required. Technologies such as “hole punching” and “hairpin translation” usually require central infrastructures to support at least the connection and may be depending on the client infrastructure being used fragile or ineffective. To avoid these problems we decided to rely on traditional centralistic transport infrastructures. As the proof of concept we decided to use SMTP.

The approach supports however even mixing transport media. This makes it harder for an attacker to trace a message as the message flow may go through any suitable transport protocol at any time of message transfer.

RQ2 (P2P): *Mixes and peers must be undistinguishable.*

6.1.2.2. Decoy traffic generation

In order to create decoy traffic in an untrusted way we need means to increase and decrease messages in size without knowledge of the routing node. An easy approach would be to create decoy traffic in the initial message. This would however create a pattern of decreasing message size in the net. To avoid this we introduced a set of operations to be applied to the original message. The operations are done in such a way that a mixer is unable to tell whether the message size or decrease results in decoy traffic generation/removal or not.

The main message operations are:

- Split a message in two parts.
- Merge two messages.
- Fork off a block xor'ed (create a new random block of the received message size, then use a bitwise xor of these blocks to create a new block. Send any or all of these blocks further).

6. Applied Methodes

- Join two blocks xor'ed (take two blocks and xor them together)

At this point we could have used homomorphic encryption instead of xor. This would however add a lot of complexity to the algorithm with no obvious gain. The bitwise xor however allows a cheap fast operation and it allows to split and join information at will. Furthermore the implications of this operation are well known and researched.

6.1.2.3. Message tagging or bugging protection

It is important to the protocol that any operation at any point of the protocol handling which is not foreseen should result in the failure of message transport. This makes the protocol very fragile but it prevents mixes from introducing tags which may be followed throughout the system.

In our approach we give a single mix the full control over the message hiding/blending layer. This means that every mix decides for the content there. However – This data is ephemeral and will (or may) be removed in the next node. The data received by a mix may be used to generate a “pseudo reply” on the blending layer to transport any other message (related or unrelated) back to the sending node. So tagging on this layer is worthless.

The reason for not giving control over the behaviour to this layer to the sender of the message is simple. By giving him control over it we would allow him to use the information provided here as the main medium. As an immediate result the system would be suitable to blackmail any user of the world. It furthermore would create unintentional “exit nodes” to the system which might oppose further legal threads for participants.

RQ3 (untagable): *The message should be untagable (neither by a sender, or by an intermediate party such as a mixer).*

RQ4 (unbugable): *The message should be unbugable (neither by a sender, or by an intermediate party such as a mixer).*

6.1.2.4. Message replay protection

Message replay protection is crucial for such a system. With the ability to replay a message an adversary may “highlight” a message flow as it would always generate the same traffic pattern. So there needs to be a replay pattern protecting the protocol from message replay. As we do have MURBs in our protocol this is a problem. A MURB is by design replayable. We therefore need a possibility for the original sender using a MURB to make messages distinguishable which may

not be used by an adversary.

RQ5 (replay): *A message must not be replayable*

It should be able to increase and shrink in size or all messages must have uniform size. Decoy traffic should not be distinguishable from true message traffic.

6.1.2.5. No Dedicated Infrastructure Philosophy

There should be no infrastructure dedicated for the operation of the solution. This avoids single point of failures as well as the possibility for an adversary to shut down this infrastructure to disrupt the operation of the system as a whole. This requirement is already covered implicitly in RQ1 (Zero Trust).

6.1.3. Accounting

The infrastructure must not be misused as UBE sending infrastructure. This implies that sending messages is connected to some kind of “cost”. “Costs” must be connected to some kind of identity to allow accounting. Linking to a global identity would allow to assign traffic to a real world user. Therefore the protocol must allow to create ephemeral local identities not linked to a real identity.

RQ6 (accounting): *The system must be able to do accounting without being linked to a real identity.*

6.1.4. Anonymisation

The system must allow to anonymise message source and message destination at any point. It should not be visible to the infrastructure protocol whether a message has reached its destination or not.

RQ7 (anonymisation): *System must be able to anonymise sender and recipient at any point of the transport layer and at any point of mixing unless it is the sender or the recipient itself.*

6.1.5. Initial Bootstrapping

The system must allow to boot strap from a zero knowledge or near zero knowledge point. Starting off from this point the protocol must be able to extend the network on its own.

RQ8 (bootstrapping): *The system must allow to bootstrap from a zero knowledge or near zero knowledge point and extend the network on its own.*

6.1.6. Cypher selection

In This Protocol a lot of encryption and hashing algorithms have to be used. This Choice should be explained.

First of all we need a subset of encryption algorithms all implementations may rely on. Defining such a subset guarantees interoperability between all nodes regardless of their origins.

Secondly we need to have a spectrum of algorithm in such a manor that it may be (a) enlarged if necessary and (b) there is an alternative if an algorithm is broken (so that algorithms may be withdrawn if required without affecting the function in general).

And third due to the onion like design described in this document asymmetric encryption should be avoided in favour of symmetric encryption to minimize losses due to the key length and the generally higher CPU load opposed by asymmetric keys.

If the algorithm is generally bound to specific key sizes (due to S-Boxes or similar constructs) the key size is incorporated into the definition. If not the key size is handled as parameter.

The key sizes have been chosen in such a manor that the key types form tuples of approximately equal strength. The support of Camellia192 and Aes192 has been defined as optional. But as they are wildly common in implementations they have already been standardized as they build a possibility to step up security in future.

Having these criteria for choice we chose to use the following keys and key sizes:

- Symetric
 - AES (key size: 128, 192, 256)
 - Camellia (key size: 128, 192, 256); optional
- Asymetric
 - RSA (key size: 2048, 4096, 8192)
 - Named Elliptic Curves
 - * secp384r1
 - * sect409k1
 - * secp521r1
- Hashing
 - sha384
 - sha512
 - tiger192; optional

Within the implementation we assigned algorithms to a security strength level:

- LOW
AES128, RSA1024
- MEDIUM
AES192, RSA2048, ECC secp384r1
- HIGH
RSA4096, ECC sect409k1, sha384
- QUANTUM
AES256, RSA8192, ECC secp521r1, sha512

This allows to categorize the used algorithms to a strength. This list however should only serve the purpose of selecting algorithms for people without cryptological know how.

RQ9 (encryption variety): *The system must be able to use multiple symmetric, asymmetric, and hashing algorithms.*



6.1.6.1. Cypher Mode

ECB (Electronic Code Book): This is the most basic operation. Each block is encrypted on its own. This results in a big flaw. blocks containing the same data will always transform to the same byte code. This makes it possible to see some structures of the plain text when looking at the cypher text. This solution allows parallelisation of encryption, decryption, and random access while decrypting.

CBC (Cypher Block Chaining): CBC extends the encryption by xor'ing an initialisation vector into the first block before encrypting. For all subsequent blocks the cyphertext result of the preceding block is taken as xor input. This solution does not allow parallelisation of encryption, but decryption may be paralleled and random access is possible. As another downside CBC requires a shared initialisation vector.

PCBC (Propagation Cypher Block Chaining): CBC extends the encryption by xor'ing an initialisation vector into the first block before encrypting. For all subsequent blocks the cyphertext result of the preceding block xor'ed with its plain text is taken as xor input. This solution does not allow parallel decryption or encryption, nor does it allow random access. As another downside PCBC requires a shared initialisation vector.

EAX: EAX has been broken in 2012[51] and is therefore rejected for our use.

CFB (Cypher Feedback): CFB works exactly as CBC with the difference that the plain text is xor'ed and the initialisation vector respectively the preceding cypher result is encrypted. CFB does not support parallel encryption as the cyphertext input from the preceding operation is required for a round, it does however allow parallel decryption and random access.

OFB: OFB works exactly as CFB except for the fact that not the cyphertext result is taken as feedback but the result of the encryption before xor'ing the plain text. This denies parallel encryption and decryption as well as random access.

OCB (Offset Codebook Mode): This mode is specified in [66]. OCB is specifically designed for AES128, AES192, and AES256. It supports authentication tag lengths of 128, 96, or 64 bits for each specified encryption algorithm. OCB hashes the plaintext of a message with a specialised function $H_{OCB}(M)$



CCM:



CTR: CTR is a mixture between OFB and CBC. A nonce concatenated with a counter which is incremented on every block is encrypted and then xor'ed with the plain text. This allows parallel decryption and encryption as well as random access.

GCM (Galois Counter Mode): GCM is related to CTR but has some major differences. The nonce is not used (just the counter starting with value 1). In order to authenticate the encryption an authentication token *auth* is hashed with H_{GFmult} and then xor'ed with the first cypher block. All subsequent cipher blocks are xor'ed with the previous result and then hashed again with H_{GFmult} . After the last block the output *o* is processed as follows: $H_{GFmult}(o \oplus (len(A) || len(B))) \oplus E^{K^0}(counter_0)$. Encryption and decryption can be paralleled in GCM. Random access is possible. However authentication of a encryption is not parallelizable. The authentication makes it unsuitable for our purposes. Alternatively we could use a fixed authentication string.



6.1.6.2. Padding

A plan text stream may have any length. Since we always encrypt in blocks of a fixed size we need a mechanism to indicate how many bytes of the last encryption

block may be safely discarded. This mechanism is called padding.

Different paddings are used at the end of a cypher stream to indicate how many bytes belong to the decrypted stream.

PKCS1:



PKCS7: This padding is the standard used in symmetric encryption up to 256 bits key length. The free bytes in the last sypher block indicate the number of bytes being used. This makes this padding very compact. It requires only 1 Byte of functional data at the end of the block. All other bytes are defined but not needed.

OAEP with SHA and MGF1 padding: This padding is closely related to PKCS1 padding. The hashsize is however bigger and thus the required space for padding is much higher. OAEP with SHA and MGF1 Padding is used in asymmetric encryption only. Due to its size it is important to note that the payload in the last block shrinks to $keySizeInBits/8 - 2 - MacSize/4$.

In our approach we have chosen to allow these three paddings. The allowed sha sizes match the allowed hash sizes chosen above. It is important to note that padding costs space at the end of a stream. Since we are using always one block for signing we have to take care that the chosen signing mac plus the bytes required for padding do not exceed the key size of the asymmetric encryption. While this is normally not a problem for RSA as there are keys 1024+ Bits required it is a considerable problem for ECC algorithms as there are much shorter keys required to achieve an equivalent strength compared to RSA.

6.1.7. Usability

The system must be usable without cryptographic know-how and with well known tools. This is necessary to accept the system broadly and makes it easy to use for peoples already communicating.

RQ10 (easy handleable): *The system must be usable without cryptographic know-how and with well known tools.*

6.2. Protocol outline

The protocol itself is independently from the transport layer specified. We emphasize in this section to the general building blocks, the cryptographic structure,

and the general protocol attributes. In Section ?? we will then further elaborate the protocols inner structure.

The protocol is built on multiple layers. On the logic side the protocol is split into two parts:

1. Transport Layer
This Layer is provided by normal internet infrastructures. The main goal is to hide or blend our protocol into ordinary traffic within that layer.
2. Blending and subsequent layers
These layers may be provided by any user of the internet. Since these layers may be mixes only or valid endpoints they may or may not be publicly known. In a first implementation we build this system as a normal Java application. The main goal is to compile afterwards either native code and run it on a SoC like infrastructure such as a RaspberryPi or port it to an android device.

We may further split these layers into

- a) Blending layer
This layer takes messages and creates transport layer conformant messages. In an ideal case the messages generated by this layer are undistinguishable from the normal message traffic and the embedded message is only visible for the receiving node.
- b) Routing layer
The routing layer disassembles and reassembles messages. This operation guarantees that messages are generated in such a way that decoy traffic is not differentiable from non decoy traffic.
- c) Accounting layer
The accounting layer has three jobs. First he has to authorise the message processing after decrypting the header block. Secondly he handles all header request blocks and the reply blocks. And third, it keeps track of the accounting in regard to the sent messages.

6.2.1. Protocol Terminology

- **Sender:** The user or process originally composing the message.
- **Recipient:** The user or process destined to receive the message in the end.
- **Mix:** Any node processing the message. Please note all nodes are mixes.
- **Message:** The “real content” to be transferred from the sender to the recipient
- **Payload:** Any data transported between mixes regardless of the meaningfulness or relevance to the message.

- **Decoy traffic:** Any data transported between mixes which has no relevance to the message at the final destination.
- **Identity:** A tuple of a routable address, and a public key.
- **Ephemeral Identity:** An identity created on any node with a limited lifetime anyone possessing the private key (proven by encrypting with it) is accepted as representative of that identity.



6.2.2. Vortex Communication model

In this section we introduce a new consistent, transport independent model for representing the different protocols used by Vortex.



6.2.3. Transport Layer

For our test we used a custom transport layer allowing us to monitor all traffic easily, and build structures in a very flexible way. This can be done with a minimum amount of work for setup and deployment. It furthermore works across multiple hosts in a broadcast domain. The API may be used to support almost any kind of transport layer.

We identified in the previous section the following protocols as suitable for transport:

- SMTP
- XMPP

For a prototype we will implement a SMTP-Transport agent.

6.2.4. Blending Layer

The blending layer is taking care of multiple problems:

- It is translating the message block into a suitable format for transport
This includes jobs such as embedding a block as encoded text, as a binary attachment, or hide it within a message using steganography.
- Extract incoming blocks
Identify incoming messages containing a possible block and extract it from the message.
- Do housekeeping on the storage layer of the transport protocol
It may be required that messages are deleted from time to time in order to stay below sizing quotas of an account.

We define the blending layer to work as follows when receiving messages:

1. Log arrival time (in UTC) on the transport layer.
2. Extract possible blocks.
3. Apply decryption on a suspected header block .
4. Identify header block as valid by querying the accounting.
5. Extract and decrypt subsequent blocks.
6. Pass extracted blocks and information to the routing layer.

We define the blending layer to work as follows for sending messages:

1. Assemble message as passed on by the routing layer.
2. Using the blending method specified in the routing block build an empty message.
3. Create a message decoy content.
4. Send the Message to the appropriate recipient using the transport layer protocol.

There is no specification on the housekeeping part of the blending layer as this part is specific to the requirements of the account owner. We do however recommend to handle messages exactly as if the messages would be handled on a account handled by a human.

6.2.5. Routing Layer

The routing layer receives the message blocks in a decrypted and authorised form from the blending layer. and processes them as follows:

- Build structure representing the block building and the appropriate block IDs.
- Schedule all Routing blocks for processing in an priority queue.
- Authorise all routing blocks ready for processing with the calculated block sizes.
- Process blocks.
- Send prepared building blocks to the Blending layer.

6.2.5.1. Block Structure

The main block structure is defined as a sequence of blocks.

The block sequence starts with a header containing a symmetric key encrypted with public key of the current node and a header block containing the immediate details to decrypt the subsequent blocks (if any).

The header block is followed by a routing block. This block contains information required for subsequent routing. According to this block currently valid data blocks may be assembled and sent to a different location.

The next block is the routing log block. This block protocols the routing information of a message and is somewhat similar to an onionized variant of the received headers in SMTP.

The final sequence of blocks are data blocks. They contain the actual data or decoy traffic.

6.2.5.2. MURBs

The protocol allows to use MURBs. This enables a user to send a limited amount of times a message to an anonymous receiver without having any knowledge about its name or the location or infrastructure he is using.

A MURB in our term is a completely prepared routing instruction built by the recipient of a message. The sender has only the routing blocks and the instructions to assemble the initial message. It has no knowledge about the message path except for the first message hops.

As a MURB is a routing block it generates the same pattern on the network each time it is used. In order to avoid statistical visibility we need to limit the number of uses per MURB. As a maximum number of usages the number 127 has been chosen. This number allows to be used for automated messages. A minute pattern would disappear latest after 2 hours and an hourly pattern after 5 days.


6.3. Protocol design

In this section we emphasize on the protocol blocks. These blocks are extracted from the blending layer and passed to the routing layer. A Vortex message is split into two main parts. The header block and the main block. The header block is divided into the two sub parts "headerKey" and "identity block". Although those blocks are described in IV as ASN.1 encoded structures they are not. In the message they are length prefixed fields.

In reality the structure is as follows:

- headerKey size as 16 bit unsigned int (big endian)
- headerKey bytes
- identityBlock size as 16 bit unsigned int (big endian)
- identityBlock bytes
- mainBlock size as 32 bit unsigned int (big endian)

• mainBlock bytes



The reason for not using ASN.1 encoding is that it might be possible to identify the unencrypted message on the transport layer as vortex message due to the ASN.1 structure.

6.3.1. Header block

The header block contains the identity and should contain all information required to decide whether subsequent blocks of the message should be handled.

The header block contains the following data:

- A symmetric header key (header key)
This key is encrypted with the receiving identities public key. This key guarantees an efficient handling of the header data. As the number of bytes in the header is limited a receiving node may assign all subsequent work to a known identity or discard it.
- An identity block (identityBlock)
This block contains a number of data which reflects the identity of the sender and the use of this (and subsequent blocks).
 - sending ephemeral identity public key (identityKey)
 - serial
 - maximum number of replays for the serial for this identity
 - Minimum number of seconds for replay protection.
 - validity period for this block (in seconds)
 - Symmetric decryption key for subsequent blocks
 - Chain secret for the forwarding block
If specified the specified secret should be named in all subsequent blocks.
 - Protocol requests to this node
 - Identifier and padding for proof of work
- An identity signature (identitySignature)
Contains a signed hash (hash type is specified in identityBlock.hash) with the senders private key.

6.3.1.1. Ephemeral Identity

The identity in this header block is an ephemeral identity. It exists for a limited amount of time (recommended <90d). Creating a new ephemeral identity is done with an identity request. This identity is mapped to all accounting figures.

6.3.1.2. Requests

Requests are always embedded in a header block. All requests are answered with a provided MURB (which is recommended to have a maximum replay value of 1).

There are several header requests defined:

newIdentity request: This request may be answered with either a reject or a puzzle which is required to solve. Solving the puzzle results in the creation of the identity on the node. Identities may be rejected by the node for various reasons:

- The node is not accepting newIdentity requests
- The identity is already taken.
- The identity is not strong enough (should be a longer key).
- The used encryption scheme is not supported by the node.

An identity may be rejected if the wrong types of keys and key sizes are used. However it must accept at least the key types and sizes it uses for its own identity.

If an identity is rejected the request may not be replayed by the same identity again. A sending party must generate a new identity for a new request.

This request should be by far the most expensive request. It must at any time be more expensive to request a new identity compared to raise the quota of an existing one.



queryPeer request: A peer request is a request for publicly known Vortex nodes. This request does offer the possibility of harvesting the Vortex network. To counter this the following limitations should apply:

- The request should be very costly
- Only nodes advertising themselves as public are disclosed.
- Only one or two nodes should be disclosed upon request.
- The number of requests should be limited per identity.
- A node should always pick random nodes out of a 5% pool of known Vortex addresses.

These measures limit the effectivity of harvesting attacks while giving a normal node the possibility of bootstrapping itself.

queryCapability request: This request is the only request answered as a clear text request. To minimize

probing possibilities this request should be only answered if the node owner agrees or generally by public nodes.

messageQuota request: This request raises the number of routing blocks which may be processed for an identity. A node may reject this request depending on the load of the node, personal preferences, or because this identity causes too much traffic.

It is normally answered for all valid identities only. The node may answer it for recently expired identities. It is however not recommended to send a reply to an unknown identity as this behaviour might be used for probing of a node.

transferQuota request: This request raises the number of bytes which may be transferred for an identity. A node may reject this request depending on the load of the node, personal preferences, or because this identity causes too much traffic.

It is normally answered for all valid identities only. The node may answer it for recently expired identities. It is however not recommended to send a reply to an unknown identity as this behaviour might be used for probing of a node.

queryQuota request: This request instructs the node to send information about the given identity.

It is normally answered for all valid identities only. The node may answer it for recently expired identities. It is however not recommended to send a reply to an unknown identity as this behaviour might be used for probing of a node.



6.3.1.3. Replies to Clear Text Requests

It is up to the decision of the node whether it wants to answer a clear text request or not. Recommended for this behaviour is to discard plain text requests.

This should only be a problem when bootstrapping or when adding new identities to the own address book.

6.3.2. Main block

The main two block types are routing blocks and payload blocks.

Routing blocks contain an onionised route chosen by the builder of the routing blocks and may contain instructions for building a message.

Payload blocks contain an encrypted message, parts of it or simply decoy traffic.

6.3.2.1. Routing Blocks

Routing blocks contain the following information:

- The node specification of the next hop (requires a full identity; may be not there if no next hop)
- Purpose of routing block (May be normal/status-OK/statusError)
- The moment of processing as a range in seconds since the time of arrival.
- Retention time in seconds since the time of arrival.
- The identity block for the next hop
- The routing block for the next hop
- Payload ID to be included
- Payload building instructions (optional; only if MURB)
- A signing key for the payload (optional; only if MURB)

6.3.2.2. Payload Building Instructions

Payload is being built right before sending a block (processing a routing block). The building instructions are built as follows:

$$srcIDs \xrightarrow{\text{build operation}} targetIDs$$

Every node maintains a list of received blocks including their IDs and building instructions for them. Any node must keep blocks and building instructions during the whole lifetime of a routing block. It may keep it longer. If a conflicting building instruction arrives all conflicting older rules are removed. Building instructions are always kept on a per identity base. It is not possible to reference building instructions of a foreign identity.

splitMessage: Split a message block into two parts of variable size. The size is expressed in percent of the original block size.

joinMessage: Concatenates two messages of different or equal sizes.

forkMessage: Split a message block into two parts horizontally using an xor operation. Technically the operation works as follows:

- The size of the source block is determined.
- Create a new reproducible random pattern of data with the determined length.

- The original block is xor'ed with the random pattern block generated in the previous step
- Both blocks may be processed further and must be sent to different locations.

With this operation we may create decoy traffic, or split a message into two parts.

unforkMessage: This operation takes two blocks equal in size and uses an xor operation to join them. Blocks with different sizes should not be processed.

encryptMessage: Encrypts a message block with a given symmetric key and algorithm. Please note that this operation changes the size of a message due to the keysize and the padding.

decryptMessage: Decrypts a message block with a given symmetric key and algorithm. Please note that this operation changes the size of a message due to the keysize and the padding.

All the operations specified above have in common that they may be applied on decoy traffic as well as on real message data. The size of incoming and outgoing blocks do not relate as there are messages increasing the size as well as decreasing the size.

6.3.2.3. Reply Block

Reply blocks are embedded in payload blocks. There are very few reply blocks necessary. Unlike normal data blocks these messages are not accounted in quotas on the node generating the reply block.

It is up to the node to decide whether it wants to answer a request or not.

Replies are being built as an ordinary message blocks. To identify a Vortex message it must begin with the string “!vortex!” encoded in ASCII followed by a valid reply block structure. No additional bytes may be appended. Blocks with additional data should be discarded.

replyCapability block: The reply contains the following information:

- Vortex identities (not encoded)
- Supported Vortex transports including blending specification.
- Maximum quotas.
- Minimum identity sizes.
- Supported cyphers and hashes.
- Maximum number of simultaneous valid header serials.

- Maximum number of simultaneous valid building operations.
- Maximum identity lifespan in seconds.



PuzzleRequired

block:

replyStatus block: General answer block signalling a status. The block is limited in length in order to minimize misuse of bandwidth. The Block contains the following data:

- Three digit status number
- Sending node identity
- Status text (optional)
- Affected block ID (optional)

ctxlessNewidentity block: This block may be used to signal the change of identity. As this request is signed with the old known identity no means should exist to hijack such an identity.

This request contains:

- old Identity
- new Identity
- Signature (with old identity)

This message may arrive at any time. Any recipient might decide on its own whether it wants to accept the update or not.

A node should not accept a identity update if the strength has been significantly lowered. A client may make a difference on the fact whether the transport layer address or the key is exchanged.

6.3.2.4. payload Block

The payload block contains the actual message or decoy traffic. Since this block is heavily modified in course of the transport of the block it is built very simple.

It contains:

- A block ID
- The payload data
- A payload signature (optional; required for vortex blocks)

It is important to understand that a block may be exchanged at any time by an evil node. This however does not affect the safety on the message. Any tagging introduced at this point does invalidate the

stream. The output after the next hop is completely unpredictable.

6.3.3. Accounting

Accounting covers several purposes in this system:

- It makes the system costly for nodes sending bulk messages.
- It protects from replaying .
- It offers an ephemeral identity with a limited life-span.

As accounting data may be used to overfill a nodes accounting tables special care has been taken in order to limit the number of information which has to be maintained per identity. We furthermore tried to minimize the risk that someone might occupy accounting memory of a node without costs. Furthermore any node may cancel an illicit behaving identity at any time.

It is important that the accounting described here is for mixes. A node assembling messages needs to keep a lot more information.

6.3.3.1. Accounting Data of an Identity

For an ephemeral identity very little information has to be kept. This identity expires after a certain amount of time. The maximum time may be queried with a capability request. The choice of Encryption type and key size is left to the node requesting the identity. However, a node may reject the request if it considers the identity to be unsafe, it has no more capacity for new identities, or if it would create an identity clash on the current node.

The following data has to be kept per identity:

- **ID** $\langle pubKey, expiry, messagesLeft, bytesLeft \rangle$

6.3.3.2. Accounting Data of a Header Block

All accounting data of a header block is connected to the respective identity. All header blocks do expire latest with their respective identity. The following data has to be kept on a mix:

- **HL** $\langle serial, remainingReplays, expiry \rangle$
This is the long term header list. It lists all headers of an identity, and how many replays are left until the requests are rejected.
- **HS** $\langle serial, arrivalTime, msgHash, duration \rangle$
This is the short term replay protection. It protects a block with the same hash from being replayed.

6.3.3.3. Accounting Data of a Payload Block



6.4. Protocol handling

In the following sections we outline the handling of messages we split the handling into incoming messages and outgoing messages. All handling assumes that we have a blending layer independently picking up messages as advertised in the capabilities messages.

6.4.1. Received Block Processing

A Block picked up in the blending layer is handled as shown in image 6.1.



6.4.2. Transmission Block Processing





Figure 6.1.: flow diagram showing processing of incoming messages

Part II.

Results

To verify the hypothesis made in this paper, and to analyse properties of the protocol in a real world scenario a library was implemented in Java which was capable of handling all message packets and the routing stack as a whole. The following paragraphs describe the protocol developed in general as a generic approach. Appendix IV gives the full ASN.1 representation of the protocol.

It is important to notice that ASN.1 has no mean to express encrypted structures. Due to this fact we defined all encrypted fields as `OCTET STRING`.

The protocol is defined in the ASN.1 to support onionized information in an unencrypted form. This is meant for debugging purposes only. At no point should this possibility be used in a production environment.

The protocol described in the next chapter is independent from routing. We built a blending layer for SMTP. Layers for other protocols such as XMPP may be built similarly. The protocol may be extended by adding blending layers and their addressing schemes.

6.5. Vortex Client

We did not create a Vortex client for sending messages. Instead we used a standard Thunderbird email client pointing to a local SMTP and IMAP Server provided by Vortex. On the SMTP side Vortex does encapsulate where possible mails into a Vortex message and builds automated route to the recipient. The SMTP part of vortex may be used to encapsulate automatically all messages with a known Vortex identity into a vortex message. On the IMAP side it merges a local Vortex message store with the standard Email repository building a combined view.

Using Vortex like this offers us the advantages of a known client with the anonymity Vortex offers.

This has certain downsides. At the moment the vortex client has only a local store this makes it impossible to handle multiple simultaneously connected clients to use Vortex. This is however just a lack of the current implementation and not of the protocol itself as we may safely use an IMAP storage for storing vortex mails centrally.

6.6. Vortex Addresses

A Vortex address is built as follows: *vortexAddress* =< *transport* >:< *address* >!< *publicKey* >

To allow storage of Vortex addresses in standard messaging programs such as Outlook or Thunderbird. We define an alternate representation *encodedVortexAddress* = *base64(vortexAddress)@localhost*.

The suffix “@localhost” makes sure that a message intended for Vortex is not routed by any non-participating server.

The main downside of vortex addresses are that they are no longer readable by a human. The main reason for this is the public key which is required. We may abstract this further by allowing clear text requests on the main email address for the public key. Such requests must then be answered by the vortex account with the valid vortex address.

6.6.1. Vortex Accounts

By definition any transport layer address may represent a Vortex identity. This fact may make people believe that their current email or jabber address is suitable as Vortex address. This is technically perfectly true, but should not be done for the following reasons:

- If an address is identified as a vortex address it may be blocked (directly or indirectly) by an adversary.
- If a vortex node is malfunctioning non-vortex messages should remain unaffected. This is more likely to happen if non-Vortex messages are kept in a separate account.
- If a user wants no longer to maintain its Vortex address (hopefully there will be a better technology in future) he just may give up his Vortex accounts. If he would have been using his normal messaging account for Vortex he would receive mixing messages which he has to filter in future.

6.6.2. Vortex node types

6.6.2.1. Public vortex node

Public nodes are nodes which advertise themselves as mixes. Just as all nodes they may be an endpoint or a mix. Typically they accept all requests exactly as outlined in 7.1. As an immediate result of the publicly available information about such a node the owner may be target of our adversary. Pressure may be opposed to close down such a node. However since we do not need a specific account we may safely close down one transport account and open up a different one (on the same or a different infrastructure).

6.6.2.2. Stealth vortex node

This node does not answer any clear text requests. As an immediate result the node is only usable by other nodes knowing the public key of this node. The node is therefore on a known secret base only reachable.

6.6.2.3. Hidden vortex node

A hidden node is a special form to a stealth node it has a set of preset identities. Only these entities are processed. This behaviour has certain drawbacks. An identity may not be changed. As an immediate result traffic may become a pseudonymity. To counter this effect at least partially we may use the same local identity for multiple senders. As an immediate result the sender is only one of all senders knowing the private key of an identity.

7. MessageVortex - Transport Independent Messaging anonymous to 3rd Parties

This approach is different from all approaches discussed previously. Unlike them we put complete distrust into the infrastructure being used. Furthermore we do not rely on a custom server infrastructure in the internet. Instead we take advantage of the availability of internet connected devices such as internet connected mobile phones, tablets, or even commonly available SoC such as RaspberryPi or similar. It is still very hard to maintain a server in the internet and considering the vastly growing amount of automated attack carried out against internet connected servers it is not advisable or realistic to assume that a future user of this system owns either a server or connects to a service which is offering explicitly anonymizing services. These infrastructures would be susceptible to monitoring or even banning. Instead we take a different approach.

We use common messaging protocols as transport layers and connect to them using the respective client protocols. The actual mixes are operated by the users on their “always connected” devices. It goes without saying that such a system is far less reliable than a traditionally run server as this hardware is typically cheap, and normally connected to the internet using a bandwidth shared media.

The basic idea is that a client generates all traffic (including decoy or dummy traffic) by itself. It defines the routes a message takes through the mixes and decides which targets are receiving dummy traffic at the same time. In such a system even when possessing all the nodes routing the traffic (without the endpoints), an anonymity set of k (whereas the size of k is defined by the sender) is guaranteed.

As decoy traffic is generated with the same operations as the true content is split it is impossible for an adversary running a node to determine whether he is generating noise or actually processing the true message.



7.1. Protocol Implementation



7.2. Block Structure

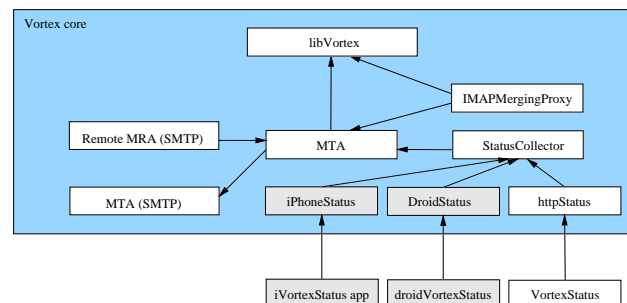


Figure 7.1.: Overview of the Vortex modules
FiXme Fatal: replace image with up to date representation; show implemented and not implemented parts; Maybe make it two column wide

Listing 7.1: Header Block

```
plain [1102] UnencryptedBlocks — should not be used except for internal diagnostic purposes
}
}
— represents the identity of the rights owner
IdentityBlock ::= SEQUENCE {
  headerKey [1000] OCTET STRING OPTIONAL, — contains SymmetricKey encrypted with recipient nodes public key
  identityBlock CHOICE {
    encrypted [1001] OCTET STRING,
    plain [1002] IdentityPayloadBlock
  },
  identitySignature OCTET STRING — contains signature of Identity [as stored in identityBlock; signed identityBlock without Tag]
}
IdentityPayloadBlock ::= SEQUENCE {
  — Public key of the identity representing this transmission
  identityKey AsymmetricKey,
  — serial identifying this block
  serial INTEGER (0..maxSerial),
  — number of times this block may be replayed (Tuple is identityKey, serial while
  maxReplays INTEGER (0..maxNumberOfReplays),
  — subsequent Blocks are not processed before valid time.
  — Host may reject too long retention. Recommended validity support >=1 Mt.
  valid UsagePeriod,
  — represents the chained secret which has to be found in subsequent blocks
  — prevents reassembly attack
  forwardSecret ChainSecret,
  — contains SymmetricKey encrypted with private key of identityKey
  — encryption is done as proof of identity (identity hijack protection)
  decryptionKeyPayload OCTET STRING, — contains DER encoded ASN1BitString with key representation
  decryptionKeyverify OCTET STRING, — contains DER encoded ASN1BitString with key representation
  — contains the MAC-Algorithm used for signing
  hash MacAlgorithm,
  — contains administrative requests such as quota requests
  requests SEQUENCE (SIZE (0..maxNumberOfRequests)) OF HeaderRequest,
}
```

7.3. Message Building



7.4. Accounting

In table 7.1 we show under what circumstances a reply to a header request should be sent. The capitalised words MAY, MUST, SHOULD and SHOULD NOT are used as defined in RFC2119[15].



7.5. Blending layer



7.6. Message Flows



7.7. Considerations for Building Messages

In a worst case scenario we assume that an adversary is controlling most of the network utilized for anonymisation. While this is not necessarily a problem (as pointed out earlier) it allows an adversary to track a message while agents are being used under his control. So for simplicity and as a worst case assumption we always assume that an adversary has perfect knowledge of an associated message flow. This is however a worst case scenario. One missing agent disconnects the whole chain and as messages are not traceable in size.



7.7.1. Ephemeral identities



7.7.2. Timing of messages



7.7.3. Building Diagnostic Paths



7.7.3.1. Implicit Diagnostic



7.7.3.2. Automatic Explicit Diagnostic



7.7.3.3. On-Demand Explicit Diagnostic



7.8. Verification of requirements

In the previous sections we identified the following list of requirements:

RQ1 No infrastructure should be trusted unless it is the senders or the recipients infrastructure.

RQ2 Mixes and peers must be undistinguishable.

RQ3 The message should be untagable (neither by a sender, or by an intermediate party such as a mixer).

RQ4 The message should be unbugable (neither by a sender, or by an intermediate party such as a mixer).

RQ5 A message must not be replayable

RQ6 The system must be able to do accounting without being linked to a real identity.

RQ7 System must be able to anonymise sender and recipient at any point of the transport layer and at any point of mixing unless it is the sender or the recipient itself.

RQ8 The system must allow to boot strap from a zero knowledge or near zero knowledge point and extend the network on its own.

RQ9 The system must be able to use multiple symmetric, asymmetric, and hashing algorithms.

RQ10 The system must be usable without cryptographic know-how and with well known tools.

In the following subsections we will iterate through all requirements and verify to what degree we achieved the goal.



RQ1 (Zero Trust): We have not put any trust into an external infrastructure. While we do assume that all routing nodes act as defined. A misbehaving node may be identified and eliminated without putting any trust on other nodes. Analysis have shown no means for a misbehaving node which might be intentional or unintentional endangering anonymity at any time. We do not rely on any third party technology or infrastructure for our anonymity.

This requirement is therefore fulfilled.

RQ2 (P2P): No node has additional privileges or offers additional services. All are equal and share the

Criteria Request	unknown identity; cleartext	unknown identity; encrypted	expired identity; encrypted	known identity; encrypted
newIdentity queryPeer queryCapability messageQuota transferQuota	SHOULD NOT MUST NOT SHOULD MUST NOT MUST NOT	SHOULD NOT MUST NOT MUST MUST NOT MUST NOT	Invalid (Error) MAY MUST MAY MAY	Invalid (Error) MAY MUST MUST MUST

Table 7.1.: Requests and the applicable criteria for replies

same privileges.

This requirement is therefore fulfilled.



(easy

handleable):

RQ3 (untaggable): Messages may not be tagged. All content is either strictly onionised or defined and linked with unknown hooks. Tampering with a message will cause the message delivery to fail at the next node.

This requirement is therefore fulfilled.

RQ4 (unbugable): There are always means to bug a message. As we put trust in sender and recipient and we know already that a intermediate mixing node is not able to modify the message the protocol is hard to bug. There may be a possibility to bug a message with a routing log entry over DNS. If a recipient is not resolving names or trusts in the content of such a message he is safe.

This requirement is therefore fulfilled.

RQ5 (replay):



RQ6 (accounting):



RQ7 (anonymisation): This point is the hardest to proof. We certainly achieved a high degree of anonymity. No node can tell by observing traffic if a node is a final recipient or just a mix. There are however some weaknesses in the protocol. As the implementation is currently connecting simultaneously to the true named and the Vortex account the user might be identified by that fact. Using a anonymisation proxy could solve the problem but it would violate the Zero trust principle.



(bootstrapping):



(encryption

variety):

7.9. Considerations for Routing Messages

7.9.1. Time of sending

Messages should always be sent timewise nearby other messages. This means that the best moment for sending a message in a ready queue is at a time when sending of other messages is due. However no optimisation should be done to send as many messages as possible at the same time. This would lead to a foreseeable behaviour of the routing layer and thus to misusable behaviour.

7.10. Real World Considerations

This approach is heavily dependent of the transport protocol and builds on top a new obfuscating/routing layer. For this system to become a real peer-to-peer approach some additional quirks are required. A message-Vortex-Account needs always an active routing handler. This routing handler may be introduced by new server capabilities or by having a device handling the routing from the client side. For this reason we built a RaspberryPi appliance capable of connecting to one (or more) accounts fetching incoming mails, analysing them and reroute them if necessary. Although the system is designed to be run on a RaspberryPi the software might be installed to any Java capable client. The RaspberryPi is just one affordable lightweight device which offers all required capabilities.

7.10.1. No Routing Log

There was up until very late a routing log functionality in the protocol. This functionality did however have the disadvantage that it allowed bugging and disclosed intermediate mixes to a recipient which did not comply with the policy the mixes might have chosen. Therefore this feature was dropped and replaced with the fetch block behaviour.

7.10.2. Message Content



8. Security Analysis

In the following sections we emphasize on attacks targeting either sender recipient tuples or on identification of participants.

Based on the protocol we may safely assume the following key points:

- An adversary knows and controls a significant number of nodes (for our analysis we assume less than 80%).
- An adversary may observe the traffic at any point without getting any information about the message content
- An adversary is not capable of matching multiple messages on different nodes to one message.

We always assume an adversary to have more knowledge than we think he may extract from the messages.

- We assume that an adversary knows all messages of a transaction running over his nodes and matches them correctly to the same message.
-

We assume that the adversary is targeting the following informations:

- Sender identity
- Recipient identity
- Message content
- Message size

8.0.1. Attack on Users Identity



8.0.1.1. Frequency and Bandwidth Analysis



8.0.2. Attack on Message content



8.0.2.1. Attacking Routing Blocks



8.0.3. Attack on Message size



9. Additional Considerations

9.1. Man in the Middle Attacks to Conversations



9.2. Identification of participating account



9.2.1. Identification by content

It is possible to identify a message by content. Assuming that an adversary knows the applied blending methode he may identify an ASN.1 structure of



9.2.2. Identification by Query



9.2.3. Identification by Traffic Type



9.2.4. Identification by Bandwidth



9.2.5. Identification by Behavioural analysis



9.3. Storage of Messages and queues

The storage of messages sent though MessageVortex should be handled with great care. It seems on the first sight a good idea to merge all messages in a globally available storage such as the mail account of the receiving entity. However – In doing so we would

discover the message content to the providing party of a mail account. Since we handled the message with great care and tremendous costs up until this point it would be careless doing so.

Storing them in a localized and receiving entity controlled storage is definitely a good idea but leaves security considerations like a backup possibly to an end user. This might be better but in effect a questionable decision. There is however a third option. By leaving the message unhandled on the last entity of the MessageVortex chain we may safely backup the data without disclosing the message content. Merging the content then dynamically through a specialized proxy would allow the user to have a unified view on his without compromising the security.



9.4. Economy of transfer



Part III.

Discussion



10. Recommendations on using the Vortex Protocol

10.1. Message content

Although it is possible to embed any type of content into a Vortex message great care should be taken as content may allow to disclose a readers identity or location. For this reason only self contained messages should be used (such as plain text messages).



11. Anonymity



11.1. Effects of anonymous communication on behaviour



Part IV.

Appendix

ASN.1 representation of the protocol

Listing 1: ASN.1 representation of the protocol

```
1  -- FIXME ADAPT NeoScript
2
3  -- encryption: as specified in the key. If not specified default mode is ECB and default padding is PKCS1Padding
4
5  -- States: Tuple()=Value() [validity; allowed operations] {Store}
6  -- - Tuple(identity)=Value(messageQuota,transferQuota,sequence of Routingblocks for Error Message Routing) [validity; Requested at creation; may be extended ✓
7  -- upon request] {identityStore}
8  -- - Tuple(identity,Serial)=maxReplays ['valid' from Identity Block; from First Identity Block; may only be reduced] {IdentityReplayStore}
9
10 Message--Blocks DEFINITIONS EXPLICIT TAGS ::=
11 BEGIN
12
13 -- define constants
14 maxSerial          INTEGER ::= 4294967295 -- maximum serial number
15 maxChunkSize       INTEGER ::= 4294967295 -- maximum size of a message chunk
16 maxNumberOfReplays INTEGER ::= 127        -- maximum number a block may be replayed
17 maxNumberOfRequests INTEGER ::= 8         -- maximum number of administrative requests
18 maxDurationOfProcessing INTEGER ::= 86400 -- maximum number of seconds which the message might be delayed in the local queue (starting from ✓
19 startOffset)
20 maxID              INTEGER ::= 32767      -- maximum id of an operation
21 maxPayloadBlocks   INTEGER ::= 127        -- maximum number of payload blocks in a message
22 maxTimeCachedProof INTEGER ::= 86400      -- maximum number of seconds a proof of non revocation may be old
23
24 puzzleIdentifier ::= OCTET STRING (size(16))
25
26 Message ::= SEQUENCE {
27   header IdentityBlock,
28   blocks CHOICE {
29     encrypted [1101] OCTET STRING, -- contains encrypted UnencryptedBlocks structure; Decryption key is in identity block [decryptionKey]
30     -- it is not allowed to use plain in production environments; This is for testing and analysis only
31     plain [1102] UnencryptedBlocks -- should not be used except for internal diagnostic purposes
32   }
33 }
34
35 -- represents the identity of the rights owner
36 IdentityBlock ::= SEQUENCE {
37   headerKey [1000] OCTET STRING OPTIONAL, -- contains SymmetricKey encrypted with recipient nodes public key
38   identityBlock CHOICE {
39     encrypted [1001] OCTET STRING,
40     plain [1002] IdentityPayloadBlock
41   },
42   identitySignature OCTET STRING -- contains signature of Identity [as stored in identityBlock; signed identityBlock without Tag]
43 }
44
45 IdentityPayloadBlock ::= SEQUENCE {
46   -- Public key of the identity representing this transmission
47   identityKey AsymmetricKey,
48
49   -- serial identifying this block
50   serial INTEGER (0..maxSerial),
51
52   -- number of times this block may be replayed (Tuple is identityKey, serial while
53   maxReplays INTEGER (0..maxNumberOfReplays),
54
55   -- subsequent Blocks are not processed before valid time.
56   -- Host may reject too long retention. Recommended validity support >=1Mt.
57   valid UsagePeriod,
58
59   -- represents the chained secret which has to be found in subsequent blocks
60   -- prevents reassembly attack
61   forwardSecret ChainSecret,
62
63   -- contains SymmetricKey encrypted with private key of identityKey
64   -- encryption is done as proof of identity (identity hijack protection)
65   decryptionKeyPayload OCTET STRING, -- contains DER encoded ASN1BitString with key representation
66   decryptionKeyverity OCTET STRING, -- contains DER encoded ASN1BitString with key representation
67
68   -- contains the MAC-Algorithm used for signing
69   hash MacAlgorithm,
70
71   -- contains administrative requests such as quota requests
72   requests SEQUENCE (SIZE (0..maxNumberOfRequests)) OF HeaderRequest,
73
74   -- padding and identifier required to solve the cryptopuzzle
75   identifier [2001] puzzleIdentifier OPTIONAL,
76   proofOfWork [2002] OCTET STRING OPTIONAL -- This is for solving crypto puzzles
77 }
78
79 UnencryptedBlocks ::= SEQUENCE {
80   -- contains routing information (next hop) for the payloads
81   routing [3000] RoutingBlock OPTIONAL,
82
83   -- contains the actual payload
84   payload [3100] SEQUENCE (SIZE (0..maxPayloadBlocks)) OF PayloadChunk
85 }
86
87 -- represents the building and sending process for the next hop
88 -- FIXME rework this part intently (Missing features reply block for header requests; Insufficient handling of operation stack)
89 RoutingBlock ::= SEQUENCE {
90   -- contains the next recipient in sequence
91   recipient NodeSpec,
92
93   -- contains the period when the payload should be processed
94   -- Router might refuse to long queue retention
95   -- Recommended support for retention >=1h
96   minProcessTime INTEGER (0..maxDurationOfProcessing),
97   maxProcessTime INTEGER (0..maxDurationOfProcessing),
98
99   -- routing blocks for the next operation
100  nextHop SEQUENCE (SIZE (0..128)) OF NextHopBlock OPTIONAL,
```

ASN.1 representation of the protocol

```

101  -- contains the secret of the identity block
102  forwardSecret  ChainSecret,
103
104  -- contains a routing block which may be used when sending error messages back to the quota owner
105  -- this routing block may be cached for future use
106  replyBlock [131]  RoutingBlock OPTIONAL,
107
108  -- contains information for building replies (when used as MURB ID 1 denotes original message)
109  cascade [300] SEQUENCE (SIZE (0..255)) OF PayloadOperation,
110  replyCascade [301] SEQUENCE (SIZE (0..255)) OF PayloadOperation
111 }
112
113
114 NextHopBlock ::= SEQUENCE {
115   nextIdentityBlock [13100] OCTET STRING,
116   nextRoutingBlock [13200] OCTET STRING,
117   nextReplyBlock [13300] OCTET STRING OPTIONAL,
118   nextErrorReplyBlock [13400] OCTET STRING OPTIONAL,
119   nextPayloadIdBlock [13500] SEQUENCE (SIZE (0..maxPayloadBlocks)) OF INTEGER (1..maxID)
120 }
121
122 PayloadOperation ::= CHOICE {
123   splitPayload [150] SplitPayloadOperation,
124   mergePayload [200] MergePayloadOperation,
125   xorMergePayload [250] XorMergePayloadOperation,
126   encryptPayload [300] EncryptPayloadOperation,
127   decryptPayload [350] DecryptPayloadOperation,
128   ...
129 }
130
131 PercentSizeType ::= SEQUENCE {
132   fromPercent REAL (0..100),
133   toPercent REAL (0..100)
134 }
135
136 AbsoluteSizeType ::= SEQUENCE {
137   fromAbsolute INTEGER (0..maxChunkSize),
138   toAbsolute INTEGER (0..maxChunkSize)
139 }
140
141 SizeType ::= SEQUENCE {
142   size CHOICE {
143     percent [15001] PercentSizeType,
144     absolute [15101] AbsoluteSizeType
145   }
146 }
147
148 SplitPayloadOperation ::= SEQUENCE {
149   originalId INTEGER (0..maxID),
150   firstSize SizeType,
151   newFirstId INTEGER (1..maxID),
152   newSecondId INTEGER (1..maxID)
153 }
154
155 MergePayloadOperation ::= SEQUENCE {
156   originalFirstId INTEGER (0..maxID),
157   originalSecondId INTEGER (0..maxID),
158   newId INTEGER (1..maxID)
159 }
160
161 XorMergePayloadOperation ::= SEQUENCE {
162   originalFirstId INTEGER (0..maxID),
163   originalSecondId INTEGER (-1..maxID),
164   originalFirstSize SizeType,
165   newId INTEGER (1..maxID)
166 }
167
168 EncryptPayloadOperation ::= SEQUENCE {
169   originalId INTEGER (0..maxID),
170   key SymmetricKey,
171   newId INTEGER (1..maxID)
172 }
173
174 DecryptPayloadOperation ::= SEQUENCE {
175   originalId INTEGER (0..maxID),
176   key SymmetricKey,
177   newId INTEGER (1..maxID)
178 }
179
180 EncryptedRoutingLogBlock ::= OCTET STRING -- contains symmetrically encrypted RoutingLogBlock
181 RoutingLogBlock ::= SEQUENCE {
182   routingLog SEQUENCE (SIZE (0..16)) OF RoutingLog,
183   nestedRoutingInformationBlock EncryptedRoutingLogBlock
184 }
185
186 RoutingLog ::= SEQUENCE {
187   nodeIdIdentifier IA5String,
188   time GeneralizedTime,
189   code ErrorCode,
190   information IA5String
191 }
192
193 IdentityReplayStore ::= SEQUENCE {
194   replays SEQUENCE (SIZE (0..4294967295)) OF IdentityReplayBlock
195 }
196
197 IdentityReplayBlock ::= SEQUENCE {
198   identity AsymmetricKey,
199   valid UsagePeriod,
200   replaysRemaining INTEGER (0..4294967295)
201 }
202
203 IdentityStore ::= SEQUENCE {
204   identities SEQUENCE (SIZE (0..4294967295)) OF IdentityStoreBlock
205 }
206
207 IdentityStoreBlock ::= SEQUENCE {
208   valid UsagePeriod,
209   messageQuota INTEGER (0..4294967295),
210   transferQuota INTEGER (0..4294967295),
211   identity [1001] AsymmetricKey OPTIONAL, -- if omitted this is a node identity
212   nodeAddress [1002] NodeSpec OPTIONAL, -- if omitted own identity key
213   nodeKey [1003] SEQUENCE OF AsymmetricKey OPTIONAL, -- Contains the identity of the owning node; May be omitted if local node
214   routingBlocks [1004] SEQUENCE OF RoutingBlock OPTIONAL,
215   ...
216 }
217
218 -- contains a node spec of a routing point
219 -- At the moment either smip:<email> or xmpp:<jabber>
220 NodeSpec ::= IA5String
221

```

```

222 ChainSecret ::= INTEGER (0..4294967295)
223
224 -- FIXME define requests
225 HeaderRequest ::= CHOICE {
226   identity      [0] HeaderRequestIdentity ,
227   capabilities   [1] HeaderRequestCapability ,
228   messageQuota   [2] HeaderRequestIncreaseMessageQuota ,
229   transferQuota  [3] RequestIncreaseTransferQuota ,
230   quotaQuery     [4] HeaderRequestQueryQuota ,
231   ...
232 }
233
234 ReplyBlock ::= CHOICE {
235   identity      [0] ReplyIdentity ,
236   capabilities   [1] ReplyCapability ,
237   ...
238 }
239
240 HeaderRequestIdentity ::= SEQUENCE {
241   identity AsymmetricKey ,
242   period UsagePeriod ,
243   ...
244 }
245
246 replyPuzzleRequired ::= SEQUENCE {
247   challenge      BIT STRING, -- bit sequence at beginning of hash from encrypted identity block
248   hash           MacAlgorithmIdentifier ,
249   valid          UsagePeriod ,
250   identifier     INTEGER (0..4294967295) ,
251   ...
252 }
253
254 HeaderRequestQueryQuota ::= SEQUENCE {
255   identity AsymmetricKey ,
256   ...
257 }
258
259 HeaderRequestIncreaseMessageQuota ::= SEQUENCE {
260   identity AsymmetricKey ,
261   messages INTEGER (0..4294967295) ,
262   ...
263 }
264
265 RequestIncreaseTransferQuota ::= SEQUENCE {
266   identity AsymmetricKey ,
267   size     INTEGER (0..4294967295) ,
268   ...
269 }
270
271 HeaderRequestCapability ::= SEQUENCE {
272   period UsagePeriod ,
273   ...
274 }
275
276 ReplyCapability ::= SEQUENCE {
277   cypher           SEQUENCE (SIZE (2..256)) OF CypherSpec ,
278   maxTransferQuota INTEGER (0..4294967295) ,
279   maxMessageQuota  INTEGER (0..4294967295) ,
280   supportedProtocol SEQUENCE OF Protocol ,
281   ...
282 }
283
284 CypherSpec ::= SEQUENCE {
285   asymmetric AsymmetricAlgorithmIdentifier ,
286   symmetric   SymmetricAlgorithmIdentifier ,
287   mac         MacAlgorithmIdentifier
288 }
289
290 Protocol ::= ENUMERATED {
291   smtp (100) ,
292   xmmp (110) ,
293   ...
294 }
295
296 ErrorCode ::= ENUMERATED {
297   -- System messages
298   ok (2001) ,
299   transferQuotaStatus (2101) ,
300   messageQuotaStatus (2102) ,
301   -- protocol usage failures
302   transferQuotaExceeded (3001) ,
303   messageQuotaExceeded (3002) ,
304   identityUnknown (3101) ,
305   messageChunkMissing (3201) ,
306   messageLifeExpired (3202) ,
307   -- Mayor host specific errors
308   hostError (5001) ,
309   ...
310 }
311
312 PayloadChunk ::= SEQUENCE {
313   id                INTEGER (0..maxId) ,
314   routingBlockForwardSecret INTEGER (0..maxSerial) ,
315   payload           [100] OCTET STRING
316 }
317
318 -- Compatible to PrivateKeyUsagePeriod taken from RFC3280
319 UsagePeriod ::= SEQUENCE {
320   notBefore [0] GeneralizedTime OPTIONAL ,
321   notAfter  [1] GeneralizedTime OPTIONAL
322 }
323
324 -- adapted from RFC3280
325 SymmetricAlgorithmIdentifier ::= SEQUENCE {
326   algorithm SymmetricAlgorithm ,
327   padding    CypherPadding ,
328   mode       CypherMode ,
329   parameter  AlgorithmParameters OPTIONAL
330 }
331
332 AsymmetricAlgorithmIdentifier ::= SEQUENCE {
333   algorithm AsymmetricAlgorithm ,
334   parameter AlgorithmParameters OPTIONAL
335 }
336
337 MacAlgorithmIdentifier ::= SEQUENCE {
338   algorithm MacAlgorithm ,
339   parameter AlgorithmParameters
340 }

```

```

343 }
344
345 SymmetricAlgorithm ::= ENUMERATED {
346     aes128      (1000),
347     aes192      (1001),  -- optional support
348     aes256      (1002),
349     camellia128 (1100),
350     camellia192 (1101),  -- optional support
351     camellia256 (1102)
352 }
353
354 CypherMode ::= ENUMERATED {
355     ECB      (1000),
356     CBC      (1001)
357 }
358
359 CypherPadding ::= ENUMERATED {
360     PKCS7      (1000),
361     PKCS1      (1001)
362 }
363
364 AsymmetricAlgorithm ::= ENUMERATED {
365     rsa      (2000),
366     dsa      (2100),
367     secp384r1 (2500),
368     sect409k1 (2501),
369     secp521r1 (2502)
370 }
371
372 MacAlgorithm ::= ENUMERATED {
373     sha384      (3000),
374     sha512      (3001),
375     -- FIXME check AEAD
376     tiger192    (3100)
377 }
378
379 ECCurveType ::= ENUMERATED{
380     secp192r1 ,
381     sect163k1 ,
382     sect163r2 ,
383     secp224r1 ,
384     sect233k1 ,
385     sect233r1 ,
386     secp256r1 ,
387     sect283k1 ,
388     sect283r1 ,
389     secp384r1 ,
390     sect409k1 ,
391     sect409r1 ,
392     secp521r1 ,
393     sect571k1 ,
394     sect571r1 ,
395     ...
396 }
397
398 AlgorithmParameters ::= SEQUENCE {
399     keySize  [10000] INTEGER (0..65535) OPTIONAL,
400     curveType [10001] ECCurveType OPTIONAL,
401     ...
402 }
403
404 -- Symmetric key
405 SymmetricKey ::= SEQUENCE {
406     keyType SymmetricAlgorithmIdentifier ,
407     key      OCTET STRING (size(1..512))
408 }
409
410 -- Asymmetric Key
411 AsymmetricKey ::= SEQUENCE {
412     keyType      AsymmetricAlgorithmIdentifier ,
413     publicKey    [1] OCTET STRING,
414     privateKey    [2] OCTET STRING OPTIONAL
415 }
416
417 pkcs-1 OBJECT IDENTIFIER ::= { iso(1) member-body(2) us(840) rsadsi(113549) pkcs(1) 1 }
418
419 END

```

Glossary

adverser FIXME

Agent FIXME

EWS FIXME

IMAP IMAP (currently IMAPv4) is a typical protocol to be used between a Client MRA and a Remote MDA. It has been specified in its current version in [21]. The protocol is capable of fully maintaining a server based message store. This includes the capability of adding, modifying and deleting messages and folders of a mailstore. It does not include however sending mails to other destinations outside the server based store.

Item of Interest (Iol) FIXME

LMTP FIXME

Local Mail Store A Local Mail Store offers a persistent store on a local non volatile memory in which messages are being stored. A store may be flat or structured (eg. supports folders). A Local Mail Store may be an authoritative store for mails or a "Cache Only" copy. It is typically not a queue.

mail server admin FIXME

MDA An MDA provides an uniform access to a Local Mail Store.

Remote MDA A Remote MDA is typically supporting a specific access protocol to access the data stored within a Local Mail Store .

Local MDA A Local MDA is typically giving local applications access to a server store. This may be done thru an API, a named socket or similar mechanisms.

MRA A Mail receiving Agent. This agent receives mails from a agent. Depending on the used protocol two subtypes of MRAs are available.

Client MRA A client MRA picks up mails in the server mail storage from a remote MDA. Client MRAs usually connect thru a standard protocol which was designed for client access. Examples for such protocols are POP or IMAP

Server MRA Unlike a Client MRA a server MRA listens passively for incoming connections and forwards received Messages to a MTA for delivery and routing. A typical protocol supported by an Server MRA is SMTP

MS-OXMAPIHTTP FIXME

MSA A Mail Sending Agent. This agent sends mails to a Server MRA.

MTA A Mail Transfer Agent. This transfer agent routes mails between other components. Typically an MTA receives mails from an MRA and forwards them to a MDA or MSA. The main task of a MTA is to provide

reliable queues and solid track of all mails as long as they are not forwarded to another MTA or local storage.

MTS A Mail Transfer Service. This is a set of agents which provide the functionality to send and receive Messages and forward them to a local or remote store.

MSS A Mail Storage Service. This is a set of agents providing a reliable store for local mail accounts. It also provides Interfacing which enables clients to access the users mail.

MUA A Mail User Agent. This user agent reads mails from a local storage and allows a user to read existing mails, create and modify mails.

Privacy From the Oxford English Dictionary: "

1. The state or condition of being withdrawn from the society of others, or from the public interest; seclusion. The state or condition of being alone, undisturbed, or free from public attention, as a matter of choice or right; freedom from interference or intrusion.
2. Private or retired place; private apartments; places of retreat.
3. Absence or avoidance of publicity or display; a condition approaching to secrecy or concealment. Keeping of a secret.
4. A private matter, a secret; private or personal matters or relations; The private parts.
5. Intimacy, confidential relations.
6. The state of being privy to some act.

"[72, FIXME]

In this work privacy is related to definition two. Mails should be able to be handled as a virtual private place where no one knows who is talking to whom and about what or how frequent (except for directly involved people).

POP POP (currently in version 3) is a typical protocol to be used between a Client MRA and a Remote MDA. Unlike IMAP it is not able to maintain a mail store. Its sole purpose is to fetch and delete mails in a server based store. Modifying Mails or even handling a complex folder structure is not doable with POP

Service FIXME

SMTP SMTP is the most commonly used protocol for sending mails across the internet. In its current version it has been specified in [44].

Storage A store to keep data. It is assumed to be

Glossary

temporary or persistent in its nature.

user FIXME

UBE FIXME

Bibliography

- [1] Martin Abadi, Mike Burrows, Mark Manasse, and Ted Wobber. "Moderately hard, memory-bound functions". In: *ACM Transactions on Internet Technology (TOIT)* 5.2 (2005), pp. 299–327. URL: <http://www.isoc.org/isoc/conferences/ndss/03/proceedings/papers/2.pdf> (cit. on p. 30).
- [2] Luis von Ahn, Andrew Bortz, and Nicholas J. Hopper. "k-Anonymous Message Transmission". In: *Proceedings of the 10th ACM Conference on Computer and Communications Security (CCS 2003)*. Ed. by Vijay Atluri and Peng Liu. ACM Press, Oct. 2003, pp. 122–130. DOI: 10.1145/948109.948128. URL: <http://www.abortz.com/papers/k-anon.pdf> (cit. on p. 19).
- [3] IS Amiri and MRK Soltanian. *Theoretical and Experimental Methods for Defending Against DDoS Attacks*. Syngress, 2015. URL: https://books.google.ch/books?hl=de&lr=&id=75-4CgAAQBAJ&oi=fnd&pg=PP1&dq=Theoretical+and+experimental+methods+for+defending+against+ddos+attacks&ots=U_12I0fVIP&sig=Zx6g2jDjUPRBur-Y3k0kJm0Hlvk#v=onepage&q=Theoretical%20and%20experimental%20methods%20for%20defending%20against%20ddos%20attacks&f=false (cit. on p. 29).
- [4] *AMQP v1.0*. AMQP.org, Oct. 2011. URL: <http://www.amqp.org/confluence/display/AMQP/AMQP+Specification> (cit. on p. 16).
- [5] Banks Andrew and Gupta Rahul. *MQTT*. en. OASIS, Apr. 2014. URL: <http://docs.oasis-open.org/mqtt/mqtt/v3.1.1/mqtt-v3.1.1.pdf> (cit. on p. 16).
- [6] Elias Athanasopoulos, Mema Roussopoulos, Kostas G. Anagnostakis, and Evangelos P. Markatos. "GAS: Overloading a File Sharing Network as an Anonymizing System". In: *Proceedings of Second International Workshop on Security, (IWSEC 2007)*. Nara, Japan, 2007. URL: <http://dcs.ics.forth.gr/Activities/papers/gas%20iwsec07.pdf> (cit. on p. 26).
- [7] Tuomas Aura, Pekka Nikander, and Jussipekka Leiwo. "DOS-resistant authentication with client puzzles". In: *International workshop on security protocols*. Springer, 2000, pp. 170–177. URL: <http://proceedings.aura2000resistant,title={DOS-resistantauthenticationwithclientpuzzles},author={Aura,TuomasandNikander,PekkaandLeiwo,Jussipekka},booktitle={Internationalworkshoponsecurityprotocols},pages={170--177},year={2000},organization={Springer}}> (cit. on pp. 29, 30).
- [8] Marco Valerio Barbera, Vasileios P. Kemerlis, Vasilis Pappas, and Angelos Keromytis. "CellFlood: Attacking Tor Onion Routers on the Cheap". In: *Proceedings of ESORICS 2013*. Sept. 2013. URL: <http://www.cs.columbia.edu/~vvp/papers/cellflood.esorics13.pdf> (cit. on p. 25).
- [9] Kevin Bauer, Damon McCoy, Dirk Grunwald, Tadayoshi Kohno, and Douglas Sicker. "Low-Resource Routing Attacks Against Tor". In: *Proceedings of the Workshop on Privacy in the Electronic Society (WPES 2007)*. Washington, DC, USA, Oct. 2007. DOI: 10.1145/1314333.1314336. URL: <http://systems.cs.colorado.edu/~bauer/papers/wpes25-bauer.pdf> (cit. on p. 25).
- [10] Mike Belshe, Roberto Peon, and Martin Thomson. *Hypertext Transfer Protocol Version 2 (HTTP/2)*. RFC 7540. May 2015. DOI: 10.17487/rfc7540. URL: <https://rfc-editor.org/rfc/rfc7540.txt> (cit. on p. 15).
- [11] Alex Biryukov, Daniel Dinu, and Dmitry Khovratovich. "Argon2: new generation of memory-hard functions for password hashing and other applications". In: *2016 IEEE European Symposium on Security and Privacy (EuroS&P)*. IEEE, 2016, pp. 292–302. URL: <https://www.cryptolux.org/images/0/06/Argon2-euro.pdf> (cit. on p. 30).
- [12] Alex Biryukov, Ivan Pustogarov, and Ralf Philipp Weinmann. "TorScan: Tracing Long-lived Connections and Differential Scanning Attacks". In: *Proceedings of the European Symposium Research Computer Security - ESORICS'12*. Springer, Sept. 2012. URL: <http://freehaven.net/anonbib/papers/torscan-esorics2012.pdf> (cit. on p. 25).
- [13] Alex Biryukov, Ivan Pustogarov, and Ralf-Philipp Weinmann. "Trawling for Tor Hidden Services: Detection, Measurement, Deanonimization". In: *Proceedings of the 2013 IEEE Symposium on Security and Privacy*. May 2013. URL: <http://www.ieee-security.org/TC/SP2013/papers/4977a080.pdf> (cit. on p. 25).
- [14] Carsten Bormann, Klaus Hartke, and Zach Shelby. *RFC7252: The Constrained Application Protocol (CoAP)*. RFC 7252. June 2014. DOI: 10.17487/rfc7252. URL: <https://rfc-editor.org/rfc/rfc7252.txt> (cit. on p. 16).
- [15] S. Bradner. *RFC2119 Key words for use in RFCs to Indicate Requirement Levels*. IETF, 1997. URL: <http://tools.ietf.org/pdf/rfc2119.pdf> (cit. on p. 52).
- [16] *Campaign Monitor*. 2012. URL: <http://www.campaignmonitor.com/resources/will-it-work/email-clients/> (cit. on p. 28).
- [17] David Chaum. "Untraceable Electronic Mail, Return, Addresses, and Digital Pseudonyms". In: *Communications of the ACM* (1981). URL: <http://www.cs.utexas.edu/~shmat/courses/cs395t-fall104/chaum81.pdf> (cit. on pp. 20, 23, 24).

- [18] David Chaum. "The Dining Cryptographers Problem: Unconditional Sender and Recipient Untraceability". In: *Journal of Cryptology* 1 (1988), pp. 65–75. URL: <http://www.cs.ucsb.edu/~ravenben/classes/595n-s07/papers/dcnet-jcrypt88.pdf> (cit. on p. 24).
- [19] Ian Clarke, Oskar Sandberg, Brandon Wiley, and Theodore W. Hong. "Freenet: A Distributed Anonymous Information Storage and Retrieval System". In: *Proceedings of Designing Privacy Enhancing Technologies: Workshop on Design Issues in Anonymity and Unobservability*. July 2000, pp. 46–66. URL: <http://citeseer.nj.nec.com/clarke00freenet.html> (cit. on p. 26).
- [20] Henry Corrigan-Gibbs and Bryan Ford. "Dissent: Accountable Anonymous Group Messaging". In: *Proceedings of the 17th ACM Conference on Computer and Communications Security*. CCS '10. Chicago, Illinois, USA: ACM, 2010, pp. 340–350. ISBN: 978-1-4503-0245-6. DOI: 10.1145/1866307.1866346. URL: <http://doi.acm.org/10.1145/1866307.1866346> (cit. on p. 26).
- [21] M. Crispin. *RFC3501 INTERNET MESSAGE ACCESS PROTOCOL - VERSION 4rev1*. IETF, 2003. URL: <http://tools.ietf.org/pdf/rfc3501.pdf> (cit. on p. A7).
- [22] Norman Danner, Sam DeFabbia-Kane, Danny Krizanc, and Marc Liberatore. "Effectiveness and detection of denial of service attacks in Tor". In: *Transactions on Information and System Security* 15.3 (2012), 11:1–11:25. DOI: 10.1145/2382448.2382449. URL: <http://arxiv.org/pdf/1110.5395v3.pdf> (cit. on p. 25).
- [23] Roger Dingledine and Nick Mathewson. *Tor Protocol Specification*. URL: <https://gitweb.torproject.org/torspec.git/tree/tor-spec.txt> (cit. on p. 25).
- [24] Sujata Doshi, Fabian Monrose, and Aviel D Rubin. "Efficient memory bound puzzles using pattern databases". In: *International Conference on Applied Cryptography and Network Security*. Springer, 2006, pp. 98–113. URL: <https://pdfs.semanticscholar.org/7f4c/79649a55eecbfc8c2fbf4f8b0c5e68e2376a.pdf> (cit. on p. 30).
- [25] M. Elkins. *RFC2015 MIME Security with Pretty Good Privacy (PGP)*. IETF, 1996. URL: <http://tools.ietf.org/pdf/rfc2015.pdf> (cit. on p. 1).
- [26] *Email Client Market Share*. 2014. URL: <http://emailclientmarketshare.com/> (cit. on p. 28).
- [27] Nathan Evans, Roger Dingledine, and Christian Grothoff. "A Practical Congestion Attack on Tor Using Long Paths". In: *Proceedings of the 18th USENIX Security Symposium*. Aug. 2009. URL: <http://freehaven.net/anonbib/papers/congestion-longpaths.pdf> (cit. on p. 25).
- [28] *Fact Sheet Suite B Cryptography*. 2008. URL: http://www.nsa.gov/ia/industry/crypto-suite_b.cfm (cit. on p. 22).
- [29] W. Feng, E. Kaiser, and A. Luu. "Design and implementation of network puzzles". In: *Proceedings IEEE 24th Annual Joint Conference of the IEEE Computer and Communications Societies*. Vol. 4. Mar. 2005, 2372–2382 vol. 4. DOI: 10.1109/INFCOM.2005.1498523. URL: <http://ieeexplore.ieee.org/document/1498523/> (cit. on p. 30).
- [30] W. c. Feng and E. Kaiser. "The Case for Public Work". In: *2007 IEEE Global Internet Symposium*. May 2007, pp. 43–48. DOI: 10.1109/GI.2007.4301429 (cit. on p. 30).
- [31] Christian Forler, Stefan Lucks, and Jakob Wenzel. "Memory-demanding password scrambling". In: *International Conference on the Theory and Application of Cryptology and Information Security*. Springer, 2014, pp. 289–305 (cit. on p. 31).
- [32] N. Freed and N. Borenstein. *RFC2045 Multipurpose Internet Mail Extensions; (MIME) Part One: Format of Internet Message Bodies*. IETF, 1996. URL: <http://tools.ietf.org/pdf/rfc2045.pdf> (cit. on pp. 1, 17).
- [33] N. Freed and N. Borenstein. *RFC2046 Multipurpose Internet Mail Extensions; (MIME) Part Two: Media Types*. IETF, 1996. URL: <http://tools.ietf.org/pdf/rfc2046.pdf> (cit. on p. 17).
- [34] R. Gellens and J. Klensin. *RFC4409 Message Submission for Mail*. IETF, 2006. URL: <http://tools.ietf.org/pdf/rfc4409.pdf> (cit. on p. 28).
- [35] Sharad Goel, Mark Robson, Milo Polte, and Emin Gun Sirer. *Herbivore: A Scalable and Efficient Protocol for Anonymous Communication*. Tech. rep. 2003-1890. Ithaca, NY: Cornell University, Feb. 2003. URL: <http://www.cs.cornell.edu/People/egs/papers/herbivore-tr.pdf> (cit. on p. 26).
- [36] Philippe Golle and Ari Juels. "Dining Cryptographers Revisited". In: *Proceedings of Eurocrypt 2004*. May 2004. URL: <http://crypto.stanford.edu/~pgolle/papers/nim.pdf> (cit. on p. 24).
- [37] Bogdan Groza and Dorina Petrica. "On Chained Cryptographic Puzzles". In: URL: https://www.researchgate.net/profile/Dorina_Petrica/publication/228973617_On_chained_cryptographic_puzzles/links/004635310530eb4340000000.pdf (cit. on p. 30).
- [38] Ceki Gülcü and Gene Tsudik. "Mixing E-mail With Babel". In: *Proceedings of the Network and Distributed Security Symposium - NDSS '96*. IEEE, Feb. 1996, pp. 2–16. URL: <http://citeseer.nj.nec.com/2254.html> (cit. on p. 24).
- [39] Amir Houmansadr, Chad Brubaker, and Vitaly Shmatikov. "The Parrot is Dead: Observing Unobservable Network Communications". In: *Proceedings of the 2013 IEEE Symposium on Security and Privacy*. May 2013. URL: <http://www.cs.utexas.edu/~amir/papers/parrot.pdf> (cit. on p. 21).
- [40] Jan Iwanik, Marek Klonowski, and Mirosław Kutylowski. "DUO-Onions and Hydra-Onions: Failure and adversary resistant onion protocols". In: *Communications and Multimedia Security*. Springer, 2005, pp. 1–15. URL: <http://dl.ifip.org/db/conf/cms/cms2004/IwanikKK04.pdf> (cit. on p. 26).

- [41] AJP Jeckmans. "Practical client puzzle from repeated squaring". In: (2009). URL: http://essay.utwente.nl/59133/1/scriptie_A_Jeckmans.pdf (cit. on p. 30).
- [42] Aaron Johnson, Chris Wacek, Rob Jansen, Micah Sherr, and Paul Syverson. "Users Get Routed: Traffic Correlation on Tor by Realistic Adversaries". In: *Proceedings of the 20th ACM conference on Computer and Communications Security (CCS 2013)*. Nov. 2013. URL: <http://www.ohmygodel.com/publications/usersrouted-ccs13.pdf> (cit. on p. 25).
- [43] Ari Juels and John G Brainard. "Client Puzzles: A Cryptographic Countermeasure Against Connection Depletion Attacks." In: *NDSS*. Vol. 99. 1999, pp. 151–165. URL: <http://www.isoc.org/isoc/conferences/ndss/99/proceedings/papers/juels.pdf> (cit. on pp. 29, 30).
- [44] J. Klensin. *RFC5321 Simple Mail Transfer Protocol*. IETF, 2008. URL: <http://tools.ietf.org/pdf/rfc5321.pdf> (cit. on pp. 17, 26, A7).
- [45] Neal Koblitz, Alfred Menezes, and Scott Vanstone. *Guide to Elliptic Curve Cryptography*. 2004. URL: <http://www.ams.org/journals/mcom/1987-48-177/S0025-5718-1987-0866109-5/S0025-5718-1987-0866109-5.pdf> (cit. on p. 22).
- [46] Butler W. Lampson. *A Note on the Confinement Problem*. 1973. URL: <http://faculty.kfupm.edu.sa/COE/mimam/Papers/73%20A%20Note%20on%20the%20Confinement%20Problem.pdf> (cit. on p. 21).
- [47] Arjen K. Lenstra. *Key Length. Contribution to The Handbook of Information Security*. 2004. URL: <https://infoscience.epfl.ch/record/164539/files/NPDF-32.pdf> (cit. on p. 22).
- [48] Brian Neil Levine and Clay Shields. "Hordes — A Multicast Based Protocol for Anonymity". In: *Journal of Computer Security* 10.3 (2002), pp. 213–240. URL: <http://prisms.cs.umass.edu/brian/pubs/brian.hordes.jcs01.pdf> (cit. on p. 26).
- [49] Ashwin Machanavajjhala, Daniel Kifer, Johannes Gehrke, and Muthuramakrishnan Venkatasubramanian. "l-diversity: Privacy beyond k-anonymity". In: *ACM Transactions on Knowledge Discovery from Data (TKDD)* 1.1 (2007), p. 3. URL: <http://www.cs.cornell.edu/~vmuthu/research/ldiversity.pdf> (cit. on p. 19).
- [50] Victor S. Miller. "Use of Elliptic Curves in Cryptography". In: *Advances in Cryptology — CRYPTO '85 Proceedings*. Ed. by Hugh C. Williams. Berlin, Heidelberg: Springer Berlin Heidelberg, 1986, pp. 417–426. ISBN: 978-3-540-39799-1. DOI: 10.1007/3-540-39799-1_X_31. URL: http://dx.doi.org/10.1007/3-540-39799-1_X_31 (cit. on p. 22).
- [51] Kazuhiko Minematsu, Stefan Lucks, Hiraku Morita, and Tetsu Iwata. "Attacks and security proofs of EAX-prime". In: *International Workshop on Fast Software Encryption*. Springer. 2013, pp. 327–347. URL: <http://eprint.iacr.org/2012/018.pdf> (cit. on p. 37).
- [52] Alan Mislove, Gaurav Oberoi, Ansley Post, Charles Reis, Peter Druschel, and Dan S Wallach. "AP3: Cooperative, decentralized anonymous communication". In: *Proceedings of the 11th workshop on ACM SIGOPS European workshop*. ACM. 2004, p. 30. URL: <http://www-dev.ccs.neu.edu/home/amislove/publications/AP3-SIGOPSEW.pdf> (cit. on p. 26).
- [53] Prateek Mittal and Nikita Borisov. "Information Leaks in Structured Peer-to-peer Anonymous Communication Systems". In: *Proceedings of the 15th ACM Conference on Computer and Communications Security (CCS 2008)*. Ed. by Paul Syverson, Somesh Jha, and Xiaolan Zhang. Alexandria, Virginia, USA: ACM Press, Oct. 2008, pp. 267–278. URL: <http://www.hatswitch.org/~nikita/papers/information-leak.pdf> (cit. on p. 26).
- [54] Jeffrey Mogul, Larry M Masinter, Roy T. Fielding, Jim Gettys, Paul J. Leach, and Tim Berners-Lee. *Hyper-text Transfer Protocol — HTTP/1.1*. RFC 2616. June 1999. DOI: 10.17487/rfc2616. URL: <https://rfc-editor.org/rfc/rfc2616.txt> (cit. on p. 15).
- [55] Arjun Nambiar and Matthew Wright. "Salsa: A Structured Approach to Large-Scale Anonymity". In: *Proceedings of CCS 2006*. Nov. 2006. URL: <http://ranger.uta.edu/~mwright/papers/salsa-ccs06.pdf> (cit. on p. 26).
- [56] Suresh Venkatasubramanian Ninghui Li Tiancheng Li. "t-Closeness: Privacy Beyond k-Anonymity and". In: (). URL: http://www.cs.purdue.edu/homes/li83/papers/icde_closeness.pdf (cit. on p. 19).
- [57] Lasse Øverlier and Paul Syverson. "Locating Hidden Servers". In: *Proceedings of the 2006 IEEE Symposium on Security and Privacy*. IEEE CS, May 2006. URL: <http://tor-svn.freehaven.net/anonbib/cache/hs-attack06.pdf> (cit. on p. 25).
- [58] Andreas Pfitzmann and Marit Hansen. *A terminology for talking about privacy by data minimization: Anonymity, Unlinkability, Undetectability, Unobservability, Pseudonymity, and Identity Management*. http://dud.inf.tu-dresden.de/literatur/Anon_Terminology_v0.34.pdf. v0.34. Aug. 2010. URL: http://dud.inf.tu-dresden.de/literatur/Anon_Terminology_v0.34.pdf (cit. on pp. 19, 20).
- [59] Jon Postel and Joyce Reynolds. *RFC 959: File transfer protocol*. 1985. URL: <https://tools.ietf.org/pdf/rfc959.pdf> (cit. on p. 15).
- [60] B. Ramsdell. *RFC2440 Secure/Multipurpose Internet Mail Extensions (S/MIME) Version 3.1 Message Specification*. IETF, 2004. URL: <http://tools.ietf.org/pdf/rfc2440.pdf> (cit. on p. 29).
- [61] B. Ramsdell. *RFC3851 Secure/Multipurpose Internet Mail Extensions (S/MIME) Version 3.1 Message Specification*. IETF, 2004. URL: <http://tools.ietf.org/pdf/rfc3851.pdf> (cit. on p. 28).

- [62] Marc Rennhard and Bernhard Plattner. "Practical Anonymity for the Masses with Mix-Networks". In: *Proceedings of the IEEE 8th Intl. Workshop on Enterprise Security (WET ICE 2003)*. Linz, Austria, June 2003. URL: <https://gnunet.org/sites/default/files/RP03-1.pdf> (cit. on p. 23).
- [63] P. Resnick. *RFC5322 Internet Message Format*. IETF, 2008. URL: <http://tools.ietf.org/pdf/rfc5322.pdf> (cit. on p. 17).
- [64] R. L. Rivest, A. Shamir, and L. Adleman. "A Method for Obtaining Digital Signatures and Public-key Cryptosystems". In: *Commun. ACM* 21.2 (Feb. 1978), pp. 120–126. ISSN: 0001-0782. DOI: 10.1145/359340.359342. URL: <http://doi.acm.org/10.1145/359340.359342> (cit. on p. 22).
- [65] Ronald L Rivest, Adi Shamir, and David A Wagner. "Time-lock puzzles and timed-release crypto". In: (1996). URL: <http://bitsavers.trailing-edge.com/pdf/mit/lcs/tr/MIT-LCS-TR-684.pdf> (cit. on p. 30).
- [66] Phillip Rogaway and Ted Krovetz. *The OCB Authenticated-Encryption Algorithm*. Internet-Draft draft-krovetz-ocb-04. Work in Progress. Internet Engineering Task Force, July 2012. 17 pp. URL: <https://tools.ietf.org/html/draft-krovetz-ocb-04> (cit. on p. 38).
- [67] J. P. Sain-Andre. *RFC3923: End-to-End Signing and Object Encryption for the Extensible Messaging and Presence Protocol (XMPP)*. IETF, 2004. URL: <http://tools.ietf.org/pdf/rfc3923.pdf> (cit. on p. 17).
- [68] P. Saint-Andre. *RFC3922: Mapping the Extensible Messaging and Presence Protocol (XMPP) to Common Presence and Instant Messaging (CPIM)*. IETF, 2004. URL: <http://tools.ietf.org/pdf/rfc3922.pdf> (cit. on p. 17).
- [69] P. Saint-Andre. *RFC6120: Extensible Messaging and Presence Protocol (XMPP): Core*. IETF, 2011. URL: <http://tools.ietf.org/pdf/rfc6120.pdf> (cit. on p. 17).
- [70] Rob Sherwood, Bobby Bhattacharjee, and Aravind Srinivasan. "P5: A Protocol for Scalable Anonymous Communication". In: *Proceedings of the 2002 IEEE Symposium on Security and Privacy*. May 2002. URL: <http://www.cs.umd.edu/projects/p5/p5.pdf> (cit. on p. 26).
- [71] Peter W. Shor. "Polynomial-Time Algorithms For Prime Factorization And Discrete Logarithms On A Quantum Computer". In: *SIAM Journal on Computing* 26 (1997), pp. 1484–1509. URL: <https://arxiv.org/pdf/quant-ph/9508027v2> (cit. on p. 22).
- [72] A. Stevenson. *Oxford Dictionary of English*. Oxford reference online premium. OUP Oxford, 2010. ISBN: 9780199571123. URL: <http://www.oed.com> (cit. on p. A7).
- [73] Almon Brown Strowger. "Automatic Telephone-Exchange". en. Pat. 447918. Mar. 1891 (cit. on p. 1).
- [74] Muldowney Thomas, Miller Mathew, Eatmon Ryan, and Saint-Andre Peter. *XEP-0096: SI File Transfer*. XMPP Standards Foundation, 2004. URL: <http://xmpp.org/extensions/xep-0096.html> (cit. on p. 17).
- [75] Suratose Tritilanunt, Colin Boyd, Ernest Foo, and Juan Manuel González Nieto. "Toward non-parallelizable client puzzles". In: *International Conference on Cryptology and Network Security*. Springer, 2007, pp. 247–264. DOI: 10.1007/978-3-540-76969-9_16. URL: http://link.springer.com/chapter/10.1007/978-3-540-76969-9_16 (cit. on p. 30).
- [76] UNHR. *International Covenant on Civil and Political Rights*. 1966. URL: <http://www.ohchr.org/en/professionalinterest/pages/ccpr.aspx> (cit. on p. 11).
- [77] Michael Waidner and Birgit Pfitzmann. "The dining cryptographers in the disco: Unconditional Sender and Recipient Untraceability". In: *Proceedings of EUROCRYPT 1989*. Springer-Verlag, LNCS 434, 1990. URL: http://www.semper.org/sirene/publ/WaPfl_89DiscoEngl.ps.gz (cit. on p. 24).
- [78] Brent Waters, Ari Juels, J Alex Halderman, and Edward W Felten. "New client puzzle outsourcing techniques for DoS resistance". In: *Proceedings of the 11th ACM conference on Computer and communications security*. ACM, 2004, pp. 246–256. URL: http://www.cs.utexas.edu/~bwaters/publications/papers/outsource_paper.pdf (cit. on p. 30).
- [79] Li Zhuang, Feng Zhou, Ben Y Zhao, and Antony Rowstron. "Cashmere: Resilient anonymous routing". In: *Proceedings of the 2nd conference on Symposium on Networked Systems Design & Implementation-Volume 2*. USENIX Association, 2005, pp. 301–314. URL: https://www.usenix.org/legacy/publications/library/proceedings/nsdi05/tech/full_papers/zhuang/zhuang.pdf (cit. on p. 26).