# New Covert Channels in HTTP

## Adding Unwitting Web Browsers to Anonymity Sets

Matthias Bauer
Institut für Informatik
Martensstrasse 3
91058 Erlangen, Germany
matthiasb@acm.org

## ABSTRACT

This paper presents new methods enabling anonymous communication on the Internet. We describe a new protocol that allows us to create an anonymous overlay network by exploiting the web browsing activities of regular users. We show that the overlay network provides an anonymity set greater than the set of senders and receivers in a realistic threat model. In particular, the protocol provides unobservability in our threat model.

## Categories and Subject Descriptors

C.2.0 [**Computer-Communication Networks**]: General—*Security and protection*; K.4.1 [**Computers and Society**]: Public Policy Issues—*Privacy*

## General Terms

Security

## Keywords

Covert channel, HTTP, mix network, anonymity

## 1. INTRODUCTION

Privacy on the Internet gains importance as most network activity can be linked to a user's identity. Proposed solutions that use Chaumian mixes show certain traffic patterns if not every user runs a node in the system. We describe a realistic threat model and present a new set of protocols that allow unobservable communication.

In 1981, David Chaum presented the concept of *mixes*, a protocol to provide sender–receiver *unlinkability* under standard cryptographic assumptions. Unlinkability means that an observer does not learn anything to improve her guesses on who communicates with whom (The *a–priori* probability of two entities being related is equal to the *a–posteriori* probability). The notion of the *anonymity set* is essential when measuring anonymity. It is the set of all possible subjects who might cause an action [27]. In the context of classical communication protocols, it consists of the senders and receivers.

Currently employed implementations of mix networks are, for example, the Cypherpunks [34] and Mixmaster [32] remailers and the nascent Mixminion project [13]. Chaum's work motivated other schemes which avoid expensive decryption at each step, to minimize delay, for example, Crowds [36] and Onion Routing [22].

In practice, most users of these systems do not run mix nodes themselves. They cause traffic patterns to and from the set of mix nodes, which a global, passive adversary can use to reduce the anonymity provided by the systems. Possible attacks by such an observer include intersection, timing and packet counting attacks on remailers and other systems derived from Chaumian mixes [11, 3, 35]. Suggested solutions introduce *cover traffic* into the protocols. This is achieved mainly by having the senders inject *dummy messages* [7], which are discarded at some mix.

*Unobservability* is a stronger property than unlinkability, meaning that an observer cannot tell if messages are being sent or received *at all*.

This paper presents techniques to enlarge the anonymity set by including noninvolved subjects who provide cover traffic for the protocol in question. Our approach is to hide communication within transit traffic going through HTTP browsers.

In our model, the adversary cannot distinguish senders or receivers in the hidden protocol from other HTTP users contacting the same set of servers. This enlarges the anonymity set beyond senders and receivers and provides unobservability.

The rest of the paper is organized as follows. In Section 2, we define our adversary model. Section 3 briefly introduces Chaumian mixes and explains why HTTP is a good choice of cover protocol. Related work is examined in Section 4. Section 5 describes a new class of covert channels inside HTTP which allow communication between servers under the cover of user–generated traffic. To show how these channels can be put to use in a Chaumian mix, we present a simple protocol in Section 6. Unsolved problems and areas for future research are discussed in Section 7. We conclude with Section 8.

*WPES'03,* October 30, 2003, Washington, DC, USA.

## 2. THREAT MODEL

To mount the timing and intersection attacks against many employed systems, the observer only needs to inspect the headers in the layers below the application layer of the TCP/IP stack at selected points on the Internet.

This precisely matches the capabilities of current (legal) telecommunication surveillance. To cite the CALEA[1] Implementation Section of the FBI:

> examine[ing] the full packet stream and examine protocol layers higher than layer 3 would place a high load on existing network elements in most architectures. [41].

The specification of "traffic data" in the EU Convention on Cybercrime [12] indicates that the intended mandatory surveillance by internet service providers is restricted to the lower three layers of the TCP/IP stack.

We grant our adversary the additional ability to inspect application layer headers. This adversary model corresponds to an observer who is datamining traffic logs for cliques of communicating people. This is a realistic and impending threat.

## 3. BACKGROUND

In Chaumian mixes, nodes relay messages for each other. Each node has a (*public key*, *private key*) pair. To send a message along a chain of relaying mixes through the mix overlay network, the address of the final recipient is attached to the message. The result is encrypted with the public key of the last node in the chain. The address of the node is attached to the result and the process repeated for each node along the chosen path toward the first. On receipt of a message, a node decrypts it and — if it is not the final recipient itself — forwards it to the node specified in the decrypted text.

Later improvements on Chaum's scheme suggest random delays, various strategies to process and subsequently dispatch messages (*flushing*) [32, 26, 35], re–ordering of messages in the pool, padding the messages to a fixed size after decryption, and other improvements to ensure unlinkability.

Although recently contributed schemes (e.g. MorphMix [37], GNUnet's GAP [4] or Tarzan [19]) require users to transport traffic for other users, many deployed Chaumian mixes and derived systems suffer from the problem that most users do not — or perhaps cannot — run nodes in the systems themselves. They may be hindered by Network Address Translation [40], dynamic — and therefore unstable — IP addresses or restrictive firewalling policies. This greatly weakens the achievable anonymity, as a passive adversary can observe traffic patterns leading to and coming from the mix network.

To thwart traffic analysis, we suggest hiding the protocol inside the well–established HyperText Transfer Protocol (HTTP[25, 18]). According to recent measurements[31], HTTP accounts for the highest percentage of data on the Internet, only slightly less than FastTrack's [15] Peer–to–Peer protocol.

Using HTTP as cover traffic brings another advantage. There is already an extensive body of research, and several implementations, which aim at providing some degree of anonymity for HTTP clients in the presence of various adversaries, see for example [36], [2], [20] and [6]. These techniques can be employed to enhance unlinkability.

HTTP is a client–server protocol. At first, this seems to imply that hidden data can only be forwarded through a chain of alternating clients and servers, all of which have to be participants of the hidden network. We will show, however, that communication between servers is feasable through standard web–clients which need not be part of the community using the covert protocol.

## 4. RELATED WORK

The concept of covert channels was introduced by B. Lampson in 1973 [29]. Covert channels in the network and transport layers of the TCP/IP protocol were examined by Rowland [38] and Fisk et al. [17]. Using HTTP as substrate for other application level protocols is discussed in RFC 3205 [33], where only overt encapsulation of protocols is considered, naturally. There are several tools that tunnel protocols through HTTP, mostly for circumvention of firewalls, for example, Lars Brinkhoff's `httptunnel` [8]. These tools can be used to disguise any protocol as HTTP traffic, but the set of entities in which to hide (the *anonymity set* [27]) consists of just the sender and receiver, whereas the constructions listed in Section 5 use real cover traffic, involving unwitting web surfers as cover. In Infranet [16], covert channels in HTTP are used to circumvent web–censorship. Web servers participating in the Infranet receive hidden requests for censored web pages and return the pages' content steganographically hidden in harmless images. Goldberg and Wagner's TAZ and rewebber network [21] implements anonymous publishing based on HTTP.

In [6], the authors briefly touch on the subject of unobservability, but conclude that real users would inadvertedly destroy this property. Surveys such as Raymond's [35] mention the concept, but do not point to protocols that provide it.

## 5. SERVER–TO–SERVER CHANNEL THROUGH UNWITTING CLIENTS

In this section, we explain how HTTP servers can communicate through clients without the consent or knowledge of the user. This constitutes a new class of covert channel, which transports data indirectly. The main mechanisms inside HTTP/HTML that allow such data transmissions are:

1. Redirects
2. Cookies
3. Referer[2] headers
4. HTML elements
5. "Active Content"

These features can be employed as follows:

### 5.0.1 Redirects

Redirects (RFC 2616 "303" messages [25]) are used to refer the client to another location. The location can be the URL of a CGI script, with optional parameters in the `QUERY_STRING` [9]. This allows CGI scripts to send data in

---

[1] Communications Assistance for Law Enforcement Act

[2] the typo was in the RFC and stuck.

said parameters to other CGI scripts through the browsers of unwitting web surfers. This channel's capacity is restricted to 1024 URL–encoded bytes [5].

### *5.0.2* Cookies

Cookies constitute a mechanism to keep state information on the client side. To advise the client to keep a `(key,value)` pair for further communication, a server sends a `Set-Cookie:` header in the reply to a request. The `value` part is allowed to be up to 4 kilobytes long, and the standard specifies that a client must be able to store up to a maximum of 40 cookies per server. In the server–to–server context, we can use optional features to transport data between the servers. The definition of cookies in RFC 2109 [28] defines a protocol sub–field `domain` which carries information about what group of web servers the cookie is to be sent to. The RFC states that the `domain` must contain at least two dots if it ends in a three–letter Top Level Domain (TLD) and at least three dots if it ends in a two–letter TLD. There are a many free Dynamic DNS services online, most of which provide hostnames in domains with this property, e.g., all hostnames in the zone administered by `dyndns.org` are in the same cookie domain. If a CGI script on server `foo.dyndns.org` sends a cookie of the form

```
KEY = VALUE; domain = .dyndns.org; Path = /;
```

to a browser and the browser connects to server `bar.dyndns.org`, then `bar` will get `foo`'s (key,value) pair. To get the browser to request data objects from `bar.dyndns.org`, the document requested from `foo` could contain one of the tags mentioned below under "HTML elements", or contains active content that requests data from `bar` automatically.

### *5.0.3 Referer*

`Referer` headers contain the location of the web page or script that linked to the presently requested one. Since the naming of contents can be chosen arbitrarily by a server — and forced upon the browser by automatic requests as described below in subsection 5.0.4 — this is another channel between servers through unwitting browsers. The length restriction of redirects applies here, too.

### *5.0.4 HTML Elements*

The HyperText Markup Language (HTML) version 4 contains elements that cause most browsers to automatically request given documents from HTTP servers. The following HTML tags and attributes have this property:

- `frame src=URL` Indicates a part of a `frameset`.
- `iframe src=URL` Defines an embedded frame.
- `img src=URL` Defines an inline image.
- `script src=URL` Indicates that JavaScript (see below) functions for this page should be loaded from `URL`.
- `link href=URL` Indicates out–of–band information for the current page.
- `object src=URL` Defines an embedded multi–media object to load.
- `applet codebase=URL` Indicates that Java (see below) classes for this page should be loaded from `URL`.
- `embed src=URL` Defines an embedded multi–media object to load.
- `layer src=URL` Defines a transparent layer of this page.

If the HTML document is created by a CGI script, the `URL` value in the tags above can be set to contain the address of another script together with parameters.
The `<META HTTP-EQUIV>` tag/attribute allows embedding of HTTP protocol header fields in the body of an HTTP message. This is useful for our purposes, because the header thus embedded in the body escapes the inspection of our adversary defined in Section 2. Interesting applications in our context are:

- Redirects (return code 303 [25]) inside successful replies (return code 500):
  `<META HTTP-EQUIV="Refresh"`
  `CONTENT="3;URL=http://www.some.org/some.html">`
  This line of HTML causes the browser to request `some.html` from `www.some.org` after 3 seconds.
- Setting cookies without a `Set-Cookie` header:
  `<META HTTP-EQUIV="Set-Cookie"`
  `CONTENT="key=value;path=/;domain=.dyndns.org">`
  This line sets a cookie on the browser, which will be transmitted to every server in the `dyndns.org` sub–domain to which the browser subsequently connects.

### *5.0.5 Active Content*

So–called "Active Content" is code that is executed on the client. Currently used languages for active content are SUN's Java [24], Netscape's JavaScript [10], Macromedia's Flash [1] and Microsoft's ActiveX [30], the latter being restricted to a single browser, so it will not be discussed here. In Java's design, considerable effort was made to make the execution of untrusted code on the client secure. Java's security framework inhibits connections to servers differing from the one which supplied the running applet, so it cannot be used to transmit data to different servers. Of the remaining two languages, we chose Javascript, because it is more wide–spread and better documented. Running code on unsuspecting surfer's machines opens a number of channels of varying bandwidth between scripts on servers. To name two examples:

- It is trivial to program redirects to CGI scripts (with parameters) in JavaScript.
- A script may construct an invisible `FORM` [42], fill the fields with data and send all of it to a CGI script in the body of a `POST` request without user interaction. This channel allows almost arbitrarily large payloads.

All the above mechanisms are heavily relied on by authors of HTML documents and CGI scripts.

## 6. THE MUTED POSTHORN — A CHAUMIAN MIX ON BANNER ADVERTS

To demonstrate how a anonymous messaging protocol can use HTTP as cover traffic to achieve unobservability against our adversary, we present a simple Chaumian mix.

## 6.1 The Setup

In our variant of Chaum's protocol, the *Muted Posthorn*, four (not necessarily disjoint) groups of entities are involved:

**The node maintainers** provide CGI scripts on HTTP servers. The scripts work as mix nodes and so every script has a $(publickey, secretkey)$ pair and a pool for messages to be forwarded. A script is called with the message as the parameter of a POST request. The scripts work as in Chaum's mix networks, i.e. on receipt of a message, they decrypt it and look at headers specifying further processing. In our simple protocol, there are three possible actions, forwarding the message to another node, storing the message in a local mailbox with a supplied name (a 128 bit number), and sending the content of a given mailbox back to the requesting HTTP client. The outward visible action of the scripts is to return either an HTML document with JavaScipt code that submits data to another node, or a short, static HTML document.

**The linkers** maintain web pages which all seem to contain the same small icon or banner advert. They do this by including an `iframe` which includes a frameset on one of the nodes. The frameset consists of a frame with the image and a second, invisible frame. This frame is created by a node and either contains the JavaScript code that does the actual transport, or the short HTML document.

**The senders and receivers** use this setup to communicate encrypted messages. Senders construct messages as in recent mix networks, e.g. Mixmaster [32], but the final delivery address of a message is always a mailbox on a node, and special actions must be taken for the first hop in a chain. A message thus constructed is sent to the first of the nodes in the chain by sending a POST request to a script. Receivers must pull their mailboxes. They do this by sending encrypted "send mailbox number N" requests to the nodes where they keep mailboxes.

**Hapless web surfers** just visit the pages maintained by the linkers. Their browsers execute the JavaScript code returned by the node, transfering messages in the process.

## 6.2 A first Version

A simple variant of our protocol uses two kinds of messages:

`To:` messages contain encrypted messages to nodes in the network.

`Get:` messages request mailboxes from nodes.

Messages are always padded to a fixed length with randomness. When preparing a message $m_0$ for a sequence of nodes $n_i$, the sender recursively computes

$$m_{i+1} = \texttt{To}:||n_i||E_{n_i}(m_i).$$

where $E_n(m)$ encrypts message $m$ for $n$'s public key. For the last node, the `To` header is omitted. The sender submits the encrypted message to the last node in a POST request.

A receiving node tries to decrypt the message with its secret key. If decryption succeeds, the resulting text is parsed for headers.

If it is a `Get` message, the node looks up the requested mailbox. If it exists, the node throws a coin. On 0, the content is sent — through the requesting client — as a message to a random node in the mix network. The client can extract the message, for example, from its local browser cache. On 1, a fixed HTML response is sent to the client. If the mailbox does not exist, again a coin is tossed, this time to decide whether to send a randomly chosen message from the pool through the client or the HTML response.

If it is a `To` message, the address is examined. If it is a mailbox number, the message is stored in it. If the addressee is a URL, the message is put in the message pool for further delivery. Again, a coin throw decides whether a randomly chosen message from the pool or the fixed HTML response is returned to the client.

Against a passive observer as the adversary defined in Section 2, this protocol provides unobservability. Senders of messages and requesters of mailboxes send HTTP GET requests as any harmless client. Upon receipt of the JavaScript document, they substitute their own messages for the ones set inside the JavaScript code, and then let the browser execute the code. An observer who is restricted to the IP/TCP/HTTP headers thus cannot distinguish between harmless browsers and senders/receivers. This increases the anonymity set by the noninvolved web surfers.

## 6.3 DoS attack on the first protocol

The simple protocol above is susceptible to a trivial denial of service attack. An adversary can simply request the frameset from a node repeatedly to drain its message pool.

To defend against this attack, we introduce acknowledgements for received messages (ACKs) between the nodes. Each message is kept in the pool and is re–sent until an ACK for the message is received. ACKs are not sent immediatly, but are put in the message pool themselves.

An ACK should be tied to the message it acknowledges and to the node the message was addressed to, to avoid forged ACKs and replays. The standard approach would be to sign ACKs with the node's secret key. But deploying digital signatures at all would imply that the nodes know each other's public keys. Experience with remailers, however, shows that knowledge about such a global state of the mix network is hard to achieve. For this reason we would like to avoid all public key operations at the nodes, except decryption.

Our suggestion is to send the hash of the decrypted text as ACK to the previous node (to make them indistinguishable from other messages, ACKs are padded with randomness to the fixed message size). The original sender knows all intermediate messages on the path, since she constructs them layer by layer. So she can inform every node on the path about what ACK to expect. She does this by including the ACKs as values of additional `Ack` headers. The rule for constructing the next layer is now:

$$m_{i+1} = \texttt{To}:||n_i||\texttt{Ack}:||h(m_i)||E_{n_i}(m_i).$$

A node keeps three tables: the message pool of outgoing messages, a list of outstanding ACKs and a list of mailboxes (see figure 1).

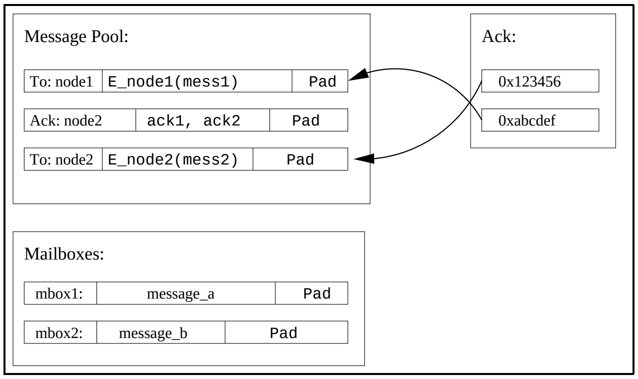

**Figure 1: The internal state of a node: message pool with messages and acknowledgements for received messages, ACK table with outstanding ACKs and references to messages in the pool, and the mailboxes.**

On receipt of a message, a node checks if it is an acknowledgement. This is done by inspecting the first $|h()|$ bits of the message, where $h$ is the cryptographic hash function used for ACKs. The resulting block is checked against the table of outstanding ACKs. If the block matches, the ACK itself and the message corresponding to it are removed from the table and the pool, respectively. Note that the URL of the sending node is transmitted by the client in the `Referer` header.

When processing `To` messages, the node now creates an entry in its ACK table with the value of the `Ack` header. The node computes the hash of the decrypted message and constructs an ACK message for the node that sent the message

### 6.4 Properties of the Protocol

The protocol inherits practical advantages from HTTP. All transactions of senders, receivers and unwitting web surfers can be performed through HTTP anonymizing systems such as Anonymizer [2], Crowds [36] or JAP [6].

The protocol's traffic is typically not blocked or modified at firewalls, and passes though Network Address Translation [40] without problems.

The coin tossing on the nodes makes the auto–submits terminate after two repetitions, in the mean. For a fixed message size of four kilobytes, the resulting traffic for the client is about the same as that for a banner advertisement (typically 16 kb).

## 7. UNSOLVED PROBLEMS AND DIRECTIONS FOR FUTURE RESEARCH

Although the idea of a mix network with an enlarged anonymity set seems promising, a number of open problems and possible enhancements must be discussed.

*Do acknowledgements (or lack thereof) introduce new points of attack?* If a node does not receive an ACK for a message, it will re-send the message at some later time. The repeating pattern marks it as being a message as opposed to an ACK or randomness.

*User behaviour influences the timing of message delivery.* This could lead to a Trickle [39] attack. To reduce this influence, a node could send randomness of appropriate size to a randomly chosen node, if a client connects but the node's batching strategy does not dispatch a message from the pool. This would allow reuse of most of the known pooling algorithms.

*The time a message spends in the mix network before final delivery is dependent on external factors*, namely the whims and inclinations of unknown web surfers, and the willingness of web–site maintainers (linkers) to place links to the nodes on their pages. Should all the linker's pages become unpopular at some point, communication would stop entirely.

One way around this problem would be to combine the mix network with an Internet advertising company. The advertisements (placed in `IFRAME`s) would show ads while at the same time transporting data between the different servers of the advertising company. If cookies are used as the channel of communication, it would not be noticeably different from what Doubleclick Inc. is doing now [14].

*Can we achieve unobservability against a global observer* who inspects complete data payloads, instead of just the headers? Universal re–encryption [23] offers a solution.

In universal re–encryption, a third party (the unwitting clients, in our case) can change the random factor in a probabilistic public key encryption, and the following properties hold:

1. The third party does not need to know the public key with which the message is encrypted.
2. For two given encrypted messages, after re–encryption, an adversary cannot tell which of the outputs corresponds to which original encryption.

In [23], P. Golle et al. show how universal re–encryption can be implemented with El–Gamal and a public (*Group*, *Generator*) pair. They also show how re–encryption can be extended to hybrid encryption schemes, where the public key scheme is used to encrypt a session key and the message itself is encrypted with a symmetric cipher and the session key.

Unfortunately, JavaScript has no built–in functions for arithmetic of large numbers nor symmetric ciphers, and implemented in JavaScript, they would be extremely slow. Java, however, offers the `math.BigInteger` and `SecureRandom` classes necessary for implementing the re–encryption algorithm. Inconsistent with the security requirements of Java, standard browser implementations allow JavaScript to call public methods and variables of Java objects. JavaScript in turn can be used to submit the re–encrypted message to the next node, as in the protocol above.

The global observer would see a random–looking message delivered to the client and another random–looking message from the client to the next node. Because of the properties of El–Gamal (and the symmetric cipher in the case of hybrid encryption), the observer cannot distinguish real messages from randomness. Because of the properties of universal re–encryption, she can only guess whether the outgoing message is a re–encryption of the received one or a completely new message substituted by the client. Inspection of the HTTP body does not help to distinguish senders and receivers from unwitting web surfers.

Universal re–encryption also remedies the problem of repeated messages, mentioned above. The node would re–encrypt the message in the pool before sending, so that observable messages are always different.

## 8. SUMMARY

Privacy is of growing concern for users of the Internet's services. Existing privacy enhancing technologies can assure anonymity only if the anonymity set is sufficiently large. In most current protocols, the size of the anonyity set is bounded by the number of the active users of a protocol. After defining a reasonable adversary model, we showed how the anonymity set of a protocol can be enlarged by having non–participants generate cover traffic. We presented new covert channels in the most wide–spread protocol on the Internet, the HyperText Transfer Protocol, and proceeded to describe a simple Chaumian mix based on CGI scripts, in which the anonymity set consist of senders, receivers and unknowing participants, thereby enhancing anonymity for the senders and receivers. We explained remaining problems of our protocol and suggested areas for future research.

## 9. ACKNOWLEDGEMENTS

We thank Niels Provos, Marius Aamodt Eriksen, Andrei Serjantov and Roger Dingledine for helpful suggestions and comments.

## 10. REFERENCES

[1] Agency, V. M. D. SWF format specification. `http://www.openswf.org/spec.html`.

[2] `http://www.anonymizer.com/`.

[3] Back, A., Möller, U., and Stiglic, A. Traffic analysis attacks and trade-offs in anonymity providing systems. In *Information Hiding (IH 2001)* (2001), I. S. Moskowitz, Ed., Springer-Verlag, LNCS 2137, pp. 245–257. `http://www.cypherspace.org/adam/pubs/traffic.pdf`.

[4] Bennett, K., and Grothoff, C. GAP – practical anonymous networking. In *Proceedings of Privacy Enhancing Technologies workshop (PET 2003 )* (March 2003), R. Dingledine, Ed., Springer-Verlag, LNCS 2760.

[5] Berners-Lee, T., Masinter, L., and McCahill, M. Uniform resource locators (URL). RFC, Internet Engineering Task Force, December 1994. RFC 1738.

[6] Berthold, O., Federrath, H., and Köpsell, S. Web MIXes: A system for anonymous and unobservable internet access. In *Designing Privacy Enhancing Technologies. Proc. Workshop on Design Issues in Anonymity and Unobservability* (2001), H. F. (Ed.), Ed., Springer, pp. 115–129. LNCS 2009.

[7] Berthold, O., and Langos, H. Dummy traffic against long term intersection attacks. In *Privacy Enhancing Technologies (PET 2002)* (2002), R. Dingledine and P. Syverson, Eds., Springer-Verlag, LNCS 2482.

[8] Brinkhoff, L. GNU httptunnel. `http://www.nocrew.org/software/httptunnel.html`.

[9] Coar, K. A. L., and Robinson, D. The WWW Common Gateway Interface, version 1.1. `http://cgi-spec.golux.com/draft-coar-cgi-v11-03.txt`, June 1999.

[10] Corp., N. C. Core JavaScript Guide 1.5. `http://developer.netscape.com/docs/manuals/js/core/jsguide15/contents.html`, 2000.

[11] Cottrell, L. Mixmaster and remailer attacks. `http://www.obscura.com/~loki/remailer/remailer-essay.html`, 1994.

[12] Council of Europe. Convention on cybercrime. Tech. rep., European Union, 2001. available from `http://conventions.coe.int/Treaty/en/Treaties/Html/185.htm`.

[13] Danezis, G., Dingledine, R., and Mathewson, N. Mixminion: Design of a Type III Anonymous Remailer Protocol. In *Proceedings of the 2003 IEEE Symposium on Security and Privacy* (May 2003).

[14] Doubleclick, I. DART. `http://www.doubleclick.com/us/corporate/privacy/privacy/internet-ads/dart.asp`, 2003.

[15] KaZaA BV. `http://www.fasttrack.nu/`.

[16] Feamster, N., Balazinska, M., Harfst, G., Balakrishnan, H., and Karger, D. Infranet: Circumventing Censorship and Surveillance. In *Proceedings of the 11th USENIX Security Symposium* (San Francisco, CA, August 2002).

[17] Fisk, G., Fisk, M., Papadopoulos, C., and Neil, J. Eliminating Steganography in Internet Traffic with Active Wardens. In *Information Hiding 2002* (2002), Springer, pp. 18–35.

[18] Franks, J., Hallam-Baker, P., Hostetler, J., Lawrence, S., Leach, P., Luotonen, A., and Stewart, L. HTTP Authentication: Basic and Digest Access Authentication . RFC, Internet Engeneering Task Force, June 1999. RFC 2617.

[19] Freedman, M. J., and Morris, R. Tarzan: A peer–to–peer anonymizing network layer. In *Proc. of the ACM Conference on Computer and Communications Security (CCS2002)* (November 2002).

[20] Gabber, E., Gibbons, P., Matias, Y., , and Mayer, A. How to make personalized web browsing simple, secure, and anonymous. In *Proceedings of Financial Cryptography 97* (February 1997), Springer. LNCS 1318.

[21] Goldberg, I., and Wagner, D. TAZ servers and the rewebber network: Enabling anonymous publishing on the world wide web. *First Monday 3*, 4 (August 1998).

[22] Goldschlag, D. M., Reed, M. G., and Syverson, P. F. Onion routing for anonymous and private internet connections. *Communications of the ACM 42*, 2 (February 1999).

[23] Golle, P., Jakobsson, M., Juels, A., and Syverson, P. Universal re-encryption for mixnets. preprint at `https://www.rsasecurity.com/rsalabs/staff/bios/mjakobsson/univrenc/univrenc.ps`, 2003.

[24] Gosling, J., Joy, B., Steele, G., and Bracha, G. The Java Language Specification. `java.sun.com/docs/books/jls/`.

[25] Irvine, U., Gettys, J., Mogul, J., Frystyk, H., Masinter, L., Leach, P., and Berners-Lee, T. Hypertext transfer protocol – HTTP/1.1. `http://www.ietf.org/rfc/rfc2616.txt`, June 1999. RFC 2616.

[26] Kesdogan, D., Egner, M., and Büschkes, T. Stop-and-go MIXes providing probabilistic anonymity in an open system. In *Information Hiding (IH 1998)*

(1998), Springer-Verlag, LNCS 1525. `http://www.cl.cam.ac.uk/~fapp2/ihw98/ihw98-sgmix.pdf`.

[27] Köhntopp, M., and Pfitzmann, A. Anonymity, unobservability, and pseudonymity — a proposal for terminology. In *Designing Privacy Enhancing Technologies* (July 2000), Springer.

[28] Kristol, D., and Montulli, L. HTTP state management mechanism. `http://www.ietf.org/rfc/rfc2109.txt`, February 1997. RFC 2109.

[29] Lampson, B. W. A note on the confinement problem. *Communications of the ACM 16*, 10 (October 1973), 613–615.

[30] Microsoft ActiveX (TM) development kit. `http://activex.adsp.or.jp/english/specs/overview.htm`.

[31] Modeling, N., and Project, S. Distributions of traffic stratified by application. Tech. rep., Cooperative Association for Internet Data Analysis (CAIDA), September 2002.

[32] Möller, U., and Cottrell, L. Mixmaster Protocol — Version 2. Unfinished draft, January 2000., 2000. `http://www.eskimo.com/~rowdenw/crypt/Mix/draft-moeller-mixmaster2-protocol-00.txt`.

[33] Moore, K. On the use of HTTP as a substrate. Tech. rep., Internet Engineering Task Force, February 2002. RFC 3205.

[34] Parekh, S. Prospects for remailers. *First Monday 1*, 2 (August 1996). `http://www.firstmonday.dk/issues/issue2/remailers/`.

[35] Raymond, J.-F. Traffic analysis: Protocols, attacks, design issues and open problems. In *Designing Privacy Enhancing Technologies: Proceedings of International Workshop on Design Issues in Anonymity and Unobservability* (2001), H. Federrath, Ed., Springer-Verlag, pp. 10–29. LNCS 2009.

[36] Reiter, M. K., and Rubin, A. D. Crowds: anonymity for Web transactions. *TISSEC 1*, 1 (Nov. 1998), 66–92.

[37] Rennhard, M., and Plattner, B. Introducing MorphMix: Peer-to-Peer based Anonymous Internet Usage with Collusion Detection. In *Proceedings of the Workshop on Privacy in the Electronic Society* (Washington, DC, USA, November 2002).

[38] Rowland, C. H. Covert channels in the TCP/IP protocol suite. *First Monday 2*, 5 (May 1997).

[39] Serjantov, A., Dingledine, R., and Syverson, P. From a trickle to a flood: Active attacks on several mix types. In *Proceedings of Information Hiding Workshop (IH 2002)* (October 2002), F. Petitcolas, Ed., Springer-Verlag, LNCS 2578.

[40] Srisuresh, P., and Holdrege, M. IP Network Address Translator (NAT) Terminology and Considerations . RFC, Internet Engineering Task Force, August 1999. RFC 2663.

[41] Telecommunications Industry Association, C. T. . Report to the federal communications commission on surveillance of packet-mode technologies, September 2000. `http://www.tiaonline.org/policy/filings/JEM_Rpt_Final_092900.pdf`.

[42] W3C, W. W. W. C. HTML 4.01 specification. `http://www.w3.org/TR/html4/`, 1999.