The increasing amount of personal information disseminated over the Internet raises serious privacy concerns. Data may linger forever, and users often lose its control and ownership. This motivates the desire of binding availability of contents to expiration times set by the data owner. To this end, we discuss and formalize the notion of Ephemeral Data Systems (EDSs): EDSs protect privacy of past data and prevent malicious parties from accessing expired contents.

We present EphCom, a practical EDS using only a primary Internet service — the Domain Name Service (DNS) and its caching mechanism. EphCom does not rely on Trusted Platform Modules (TPM), centralized servers, peer-to-peer networks, or proactive actions of the users. It is transparent to existing applications and services, and allows users to tightly control data lifetime. We analyze its security and show that EphCom instantiates a secure and practical EDS, with a negligible overhead on the DNS infrastructure.

In the process of testing EphCom’s reliability, we performed extensive measurements on the caching behavior of Open DNS servers, which might be of independent interest. This is to our knowledge the first such measurement. We found that 10% of the DNS servers follow IETF’s recommended caching behavior. Finally, we present a proof-of-concept Firefox extension that provides ephemeral email capabilities and a command line tool for ephemeral files.

1. INTRODUCTION

As the amount of private information disseminated over the Internet increases, so do related privacy threats. Private contents are often cached, stored, or archived in the cloud, and users may lose their control forever. In a number of circumstances, users are unable to successfully delete their personal data. For instance, email providers are required by law to maintain copies of users’ emails [22]; social network providers maintain data backups on tapes and do not physically erase “deleted” contents from all backups [14], ascribing to the expensiveness of this operation. As a result, this everlasting information becomes an easy target of subpoena, government surveillance, or data theft. Legal issues and data thefts are only a part of the related privacy concerns. Consider the following examples: a college student publishing pictures from previous night’s party, where she and her friends may be evidently drunk, or a social network user (or a blogger) posting controversial messages. After some time, even years, those pictures may regretfully “appear” during a job interview, or the controversial posts may compromise an election campaign. Thus, if private contents are perpetually available, then the threat for user privacy also becomes perpetual.

We aim at ensuring that private information becomes automatically inaccessible after a given “expiration” time. A well-known attempt in this direction is Vanish [17]. The idea is to store and transmit only encrypted data, whereas, cleartext is assumed to be securely erased as soon as it is consumed (i.e., read or processed). Each piece of data is encrypted using a “vanishing” key, i.e., a key that, with high probability, disappears after some time. Hence, users can decrypt and access data only as long as the corresponding keys are available. Keys are assumed to “vanish” as they are stored on a Distributed Hash Table (DHT): since peers store data only for a limited period of time (so-called churn, typically around 8 hours), key shares are eventually erased. Unsurprisingly, as DHTs are vulnerable to Sybil attacks [11], Vanish can be attacked: [30] shows that, at a reasonable cost, an attacker can collect the keys distributed over the DHT before they expire. Then, she can reconstruct any vanishing key, even after its expiration time. Although authors of Vanish have proposed some countermeasures to the specific attack [16], these defenses only raise the bar, due to the intrinsic vulnerability of DHTs to Sybil attack. Also, we observe that Vanish cannot prevent a malicious user (accessing data before expiration) from copying and/or distributing it over the Internet: thus, contents do not physically vanish or self-destruct.

1.1 Roadmap

In this paper, we explore and formalize the concept of Ephemeral Data Systems (EDSs) – interactive systems geared to guarantee retroactive privacy. Retroactive privacy allows users to set an expiration time on their private information and prevents an adversary from retrieving messages after expiration. The concept of retroactive privacy applies to a number of applications, besides the ones dis-
discussed in Section 1 for instance, [15] discusses the benefit of Ephemeral Data Systems in the context of Location Sharing Services (LSS), that enable “friends” to share their locations with each other.

Next, we propose EphCom, a novel EDS that achieves high degrees of security, robustness, and efficiency. EphCom leverages a fully-distributed and ubiquitous Internet service – the Domain Name System (DNS). We exploit its caching mechanism: DNS servers cache the response to a recursive DNS query for potential further requests. These cache entries are kept for a fixed period of time – the record’s TTL (Time To Live). Once the TTL has expired, the server erases the record from its cache. We implement encryption keys as ephemeral keys\(^1\). Each ephemeral key is composed of ephemeral bits, i.e., it is divided into single bits that independently become inaccessible after a period of time.

To set an ephemeral bit to 1, a recursive DNS query of an existing domain name is performed to an open DNS resolver. This resolver caches the response for a period of time corresponding to domain’s TTL. Whereas, to set an ephemeral bit to 0, no DNS request is performed. An ephemeral bit is thereafter coded by the domain name and the resolver address. Before TTL expires, one can retrieve the ephemeral bit with a non-recursive DNS query: if the resolver answers the query (i.e., an entry in its cache exists) then bit 1 is read, otherwise – a bit 0. We use domain names generated at random, so that they have a negligible probability to be queried by entities external to the system. To deal with events that may generate faulty bits (DNS servers churn, connectivity problems, caching implementations, policies issues, servers failures, etc.), we use an error correction code.

Observe that our approach is, to some extent, steganographic: we hide ephemeral keys spread across different DNS servers. No one, apart from the sender and the intended recipient, can tell whether one is performing DNS queries or storing/receiving ephemeral bits. This contrasts with the approach of Vanish, where keys are explicitly stored on the DHT. Thus, an adversary attacking retroactive privacy may decide to monitor the DHT and retrieve the keys (with an acceptable cost, through Sybil attacks). Whereas, such an adversarial strategy is unfeasible in EphCom, as monitoring the entire set of DNS servers is realistically impossible (as we discuss in Sec. 4).

### 1.2 Contribution & Organization

This paper makes several contributions. First, we formalize the concept of Ephemeral Data Systems. We define the related system requirements, adversarial capabilities, and privacy goals, focusing on retroactive privacy. Then, we propose a secure and practical Ephemeral Data System, EphCom, that only uses for a primary Internet service—the DNS—and achieves solid privacy guarantees.

We show that:

1. EphCom allows users to set data expiration time with a fine granularity (whereas, in Vanish expiration time is related to DHT implementation specific timeouts).
2. It is easily deployable and does not require any additional infrastructure (such as DHTs or trusted servers).
3. It is, by design, immune to the attacks targeting DHTs, such as the Sybil attack [11].
4. It improves usability and does not require users to install and execute any additional software (e.g., a P2P client), and can therefore be deployed to any Internet-enabled device (including mobile phones).
5. We analyze the behavior of Open DNS cache servers and show that, from a dataset of 900,000 servers, 10% behave as recommended by the IETF. We further classify the non standard behaviors in 5 groups.

Finally, we present two proof-of-concept prototype implementations\(^2\): (1) a command-line tool that creates ephemeral files (i.e., files that can be decrypted only before expiration time), and (2) a (stand-alone) Firefox extension that makes any web text ephemeral (e.g., emails, Facebook posts, etc.).

**Paper Organization.** The rest of the paper is organized as follows. In Sec. 2 we formally define the problem model and system assumptions. Then, we describe our Ephemeral Data System in Sec. 3. We analyze its security in Sec. 4, while Sec. 5 discusses additional EphCom possible extensions. Sec. 6 describes our experimental methodology and results. In Sec. 7 we present the details of our prototype implementation. Finally, Sec. 8 overviews relevant related work, and Sec. 9 concludes the paper.

### 2. EPHEMERAL DATA SYSTEMS

In this section, we formalize the concept of Ephemeral Data Systems. We discuss system model and the assumptions, and system requirements that a practical Ephemeral Data System should meet. Finally, we present the adversarial models and the definition of retroactive privacy.

#### 2.1 System Model

An Ephemeral Data System (EDS) involves a sender, \(S\), and a receiver, \(R\). \(S\) sends ephemeral, i.e., time-bounded, messages \(M\)'s to \(R\). A message \(M\) is time-bounded if it can only be read for a given period of time specified by \(S\), that we denote with \(T_v\), and expires afterwards. Also, we denote with \(t\) the time at which the validity of the message starts, e.g., when the sender posts the message. Thus, the “life cycle” of \(M\) starts at \(t\) and ends at \(t_v = t + T_v\).

An EDS involves an encoding function \(Encode(\cdot)\). \(Encode(M, t_v)\) denotes the encoding of time-bounded message \(M\) as a function of \(M\) itself and the expiration time \(t_v\). This is the information that is actually exchanged between \(S\)

\(^1\)This is not to be confused with the concept of ephemeral keys in Cryptography, used to denote a key (re)generated for each execution of a key establishment process (as opposed to static keys).

\(^2\)The source code of our implementations is available upon request.
and $R$. The function $\text{Decode}(\cdot)$ denotes the inverse operation, i.e., $\text{Decode}(\text{Encode}(M, t_v)) = M$.

Note that sender $S$ and receiver $R$ can be the same or different entities. Consider, for instance, the use of an EDS by a user $S$ to store her data on a local or remote storage device. Such system guarantees that content will become unrecoverable after a given period of time. In this scenario, $S$ and $R$ are the same entity, i.e., she stores the content on a storage device at a given time $t$ and then can freely retrieve it at any time before it expires. Alternatively, as discussed above, an EDS can be used by a user $S$ to send time-bounded messages to another user $R$. These messages can be sent directly, or stored on an intermediate server and then fetched—before they expire—by the receiver $R$. Finally, the EDS can also broadcast messages, e.g., to publish contents on online social networks (such as Facebook).

In the rest of the paper, we focus on the email scenario for ease of presentation. However, as previously described, an Ephemeral Data System is not limited to this application.

### 2.2 System Requirements

We define a practical Ephemeral Data System (EDS) to meet the following minimum requirements. It should:

1. Provide retroactive-privacy. Sec. 2.3 provides a formal definition of retroactive-privacy under two different adversarial models.
2. Work for synchronous and asynchronous communications. The sender and receiver could have intermittent Internet connectivity and do not need to be connected at the same time. In particular, the sender and receiver could be turned off at anytime in $[t; t_v]$.
3. Rely only on existing primary Internet services, and not on yet-to-be deployed, services or infrastructure. In addition, in order to avoid single points of failure and trust, it should not depend on centralized services or require the existence of specific hardware or devices, such as a TPM (Trusted Platform Module). It should also be transparent to existing applications and services. For instance, it should not require Internet service providers or email providers to modify their systems.
4. Be flexible and allow the sender to set and control the lifetime of data with appropriate granularity.

On the other hand, we make the following assumptions. First, $S$ and $R$ securely erase the plaintext message $M$ on their local storage, as well as any additional information that could lead to the recovery of $M$ (such as the decryption keys), as soon as possible, and not later than time $t_v = t + T_v$. Messages are only stored in their encrypted form. Finally, $S$ and $R$ know the expiration time $t_v$.

### 2.3 Retroactive Privacy

Retroactive-privacy guarantees that an adversary, that did not have access to a transmitted message $M$ before its defined expiration time, is not able to retrieve it after its expiration. We distinguish between two types of adversaries, then we formally describe the following privacy games.

#### 2.3.1 Adversarial Models

**Weak Adversary:** Informally, a weak adversary (W-ADV) has access to the same primitives and services as any user $S$ and $R$, throughout the protocol execution. W-ADV can inject, alter, and replay any message between $S$ and $R$. Besides, after message expiration time, W-ADV may have full access to $S$ and $R$’s internal memory. However, we assume that W-ADV does not have access to $\text{Encode}(M, t_v)$ before expiration time $t_v$, i.e., she does not access the information exchanged between $S$ and $R$.

An example of such adversarial setting is an investigation authority wishing to retrieve all emails previously sent or received by a user, Alice. The authority may obtain a court order to seize Alice’s PC, as well as to obtain emails stored by Alice’s email provider. Thus, even in the case email messages were encrypted, the authority may obtain the related keys. However, in this scenario the authority is assumed not to constantly monitor the communication channel used to exchange emails.

**Strong Adversary:** Informally, a strong adversary (S-ADV) has the same capabilities as a weak adversary. Additionally, S-ADV may have access to $\text{Encode}(M, t_v)$ at any time. In other words, she may eavesdrop all information exchanged between $S$ and $R$.

An example of this additional adversarial setting is a company concerned with behavior of one of its employees, Bob. The company obtains his emails from the internal mail server and it seizes Bob’s PC and may even log all traffic in the network.

#### 2.3.2 Retroactive Privacy Definitions

**Weak ADV:** We say that an Ephemeral Data System $EDS$ is retroactive-private against a weak adversary if any efficient weak adversary ADV can win the following game with probability non-negligibly over $1/2$. The game is between ADV and a two-sided challenger $Ch = (Ch_S, Ch_R)$:

1. ADV announces two equal-length messages $M_0, M_1$, validity starting time $t_e$ and expiration time $t_v = t + T_v$.
2. At time $t$, $Ch$ randomly selects a bit $b \in \{0, 1\}$, computes $\text{Encode}(M_{b}, t_v)$, and transfers it from $Ch_S$ to $Ch_R$ according to the Ephemeral Data System $EDS$.
3. ADV may inject, replay, and modify messages in the communication between $Ch_S, Ch_R$.
4. After time $t_v$, ADV accesses $\text{Encode}(M_{b}, t_v)$.
5. ADV outputs $b’$ (and wins if $b’ = b$).

**Strong ADV:** We say that an Ephemeral Data System $EDS$ is retroactive-private against a strong adversary if any efficient strong adversary ADV can win the following game...
with probability non-negligibly over 1/2. The game is between ADV and a two-sided challenger \( Ch = (Ch_S, Ch_R) \):

1. Same as above.
2. ADV may eavesdrop, inject, replay, and modify messages in the communication between \( Ch_S, Ch_R \).
3. At any time, ADV accesses \( Encode(M_b, t_v) \).
4. Same as above.

3. THE EPHECOM PROTOCOL

The EphCom protocol relies on the DNS caching mechanism to implement an Ephemeral Data System (EDS). We describe our EDS design as follows. A user \( S \) wants to send a message to user \( R \) with validity period \( T_v \): \( S \) encrypts the message using a key \( k \), so that the key is accessible only within the validity period. In EphCom, each bit of the key is distributed on separate DNS cache servers. Since entries in the DNS caches expire according to their TTL, the encryption key cannot be recovered after a certain period of time.

This section describes how a key is distributed using the EphCom protocol. We first discuss how to implement the concept of ephemeral bits using DNS. The, we extend this mechanism to several bits, i.e., to a key.

3.1 Domain Name System (DNS)

The DNS is a crucial service of the Internet [13]. It allows to resolve domain names for resources (e.g., websites) to IP addresses. The domain name space is divided into zones, and each has one authoritative DNS server.

DNS Resolution. To resolve a domain name to an IP address the client sends a query to a local DNS agent, the “resolver”, which performs the resolution. There are two types of queries.

Recursive Query: When the resolver sends a recursive query to a recursive name server, the full name resolution is returned by this name server.3 The recursive server performs the resolution by walking the DNS servers hierarchy, starting from the root servers. The final record is returned to the resolver (Fig. 1).

Non-Recursive Query (or Iterative): When asked to resolve a domain name, the server only return the best information it currently has locally, in the worst case it returns the list of root servers.

DNS Caching. Caching allows to reduce the load on individual DNS servers [23]. After a successful resolution, the resolver keeps the record in cache for the time specified in the record’s TTL value (in seconds). This caching speeds-up responses to subsequent queries as those will be answered directly from the cache without any other query. The TTL is defined by the domain administrator for each authoritative DNS record. Typical values of the TTL are from 1 to 5 days, but this period may vary from seconds to weeks [5]. We will present the results of our own measurements in Sec. 6.

\[ \text{Figure 1: DNS Recursive Query.} \]

Open DNS Servers. The Internet features a large number of open DNS servers. Open DNS servers are devices that respond to DNS queries on port 53. EphCom uses DNS servers that allow recursive queries and perform caching. In the rest of the paper, we refer to them as DNS cache servers. During our experiments, we collected 900,000 DNS servers’ IP addresses by scanning arbitrary address ranges. Our study (presented in Sec. 6) reveals that more than 10% of the identified open DNS servers perform caching properly. Dagon et al. in [8] estimated the number of open recursive DNS servers to 17 million. We can therefore estimate the number of open DNS cache servers to 1.7 million. For additional measurement and probing studies on DNS, we also refer the reader to [20, 29].

3.2 Ephemeral Bits

In the following, we describe how the EphCom process encodes ephemeral bits. The main idea is that the existence (resp., absence) of a record in a particular DNS server’s cache is associated to the bit 1 (resp., 0). To store an ephemeral bit 1, \( S \) performs a recursive DNS request of an existing domain name, \( dname \), to an open DNS cache server, \( serv \). The server replies with the domain’s record and caches the response for a period of time corresponding to domain’s TTL.4 Hence, the existence of an entry in the cache for a given domain name is interpreted as a bit 1. Whereas, a non-existing entry is considered as a bit 0.

At time \( t \), \( S \) can transfer the bit 1 to \( R \) by sending the triplet \( \{dname, serv, t_v\} \). To store an ephemeral bit 0, \( S \) sends the same triplet to \( R \) without performing any recursive DNS request. To read the bit \( R \) performs a non-recursive DNS request of the domain name \( dname \) to \( serv \). If \( dname \) is in the cache, \( serv \) replies with the corresponding entry and the bit is read as 1. If the entry is not in the cache the bit reads

\[ \text{An error is returned if the server does not allow recursive queries.} \]

\[ \text{To ease exposition, in the following we assume that TTL is equal to the desired } T_v. \]

4An error is returned if the server does not allow recursive queries.
If a DNS request is performed once \( t_v \) has passed, \( serv_i \) will reply with an empty record, i.e., the bit will read as 0 independently of its original value.

### 3.3 Protocol Description

In EphCom, a user can encrypt a message at time \( t \) with a key that disappears after a period of time, \( T_v \), i.e., at time \( t_v = t + T_v \). In the following, we extend our DNS-based approach to implement ephemeral bits to distribute (resp., retrieve) an entire encryption (resp., decryption) key.

#### Message Encryption

First, the sender generates a random key \( k \), of \( n \) bits, where \( k_i \) denotes the \( i \)-th bit. Using a secure encryption scheme, the sender uses \( k \) to encrypt a message \( M \), and produces a ciphertext \( CT \). The goal is to make message \( M \) disappear after a period of time \( T_v \).

#### Key Distribution

The distribution of ephemeral key bits over DNS cache servers is illustrated in Fig. 2(a) and proceeds as follows. This instantiates the \( Encode() \) function introduced in Sec. 2.1. The sender \( S \) generates \( Sv = \{ serv_1, \ldots, serv_n \} \), a list of \( n \) random (different) open DNS cache servers, and \( Dn = \{ dname_1, \ldots, dname_n \} \), a list of \( n \) random valid domain names that have a TTL significantly close to \( T_v \). Each domain \( dname_i \) is selected as follows: \( S \) first picks a candidate \( dname_i \) at random from a (precomputed) list of domains with the related TTL; next, it verifies whether \( dname_i \) is already in the cache of \( serv_i \), through a non-recursive DNS request of \( dname_i \). If \( serv_i \) replies with a valid record, \( dname_i \) is discarded, otherwise it is added in the list \( Dn \).

Note that the list of random domains is precomputed and distributed to users. This list is created as follows: we generate a random IP address, execute its reverse lookup, and check whether the corresponding domain name had a satisfactory TTL.\(^5\)

Then, for each bit \( k_j \) of the key such that \( k_j = 1 \), \( S \) performs a recursive DNS request of the domain name \( dname_i \) to the open DNS cache server \( serv_i \). Consequently, the server resolves the domain name, replies to the sender and populates its cache with the corresponding record.

#### EphCom Object

The sender \( S \) builds the EphCom Object (ECO), defined as the output of the \( Encode() \) function introduced in Sec. 2.1 and instantiated above. Thus, we define \( ECO(M, t_v) = \{ CT, Sv, Dn, t_v \} \), making the ECO composed of the ciphertext \( CT \), the list of DNS cache servers \( (Sv) \), domain names previously selected \( (Dn) \), and the expiration time of the data, defined as \( t_v = t + T_v \). The ciphertext is the result of the encryption of message \( M \) using an ephemeral key whose bits are distributed over DNS cache servers \( (serv_1, \ldots, serv_n) \) by querying domains \( (dname_1, \ldots, dname_n) \), respectively.

#### Key Retrieval

Upon reception of the ECO, i.e., \( ECO(M, t_v) = \{ CT, Sv, Dn, t_v \} \), the receiver checks whether the current time is smaller than \( t_v \). If this is the case, \( R \) reconstructs the key \( k' \) as follows. The retrieval of key bits from DNS cache servers (at a time \( t + d \), s.t. \( t + d < t_v \)) is also illustrated in Fig. 2(b). For each domain name \( dname_i \), \( i \in \{1, n\} \), \( R \) performs a non-recursive request to the DNS cache server \( serv_i \). If \( serv_i \) replies with a valid record, then \( k'_i \) is set to 1, otherwise, \( k'_i \) is set to 0. Once the key is retrieved, \( R \) decrypts the ciphertext \( CT \) to retrieve the message \( M \). These operations instantiate the \( Decode() \) function introduced in Sec. 2.1.

We assume that \( S \) and \( R \) securely erase the plaintext message \( M \) and the encryption key as soon as possible (i.e., after writing or reading the message), and anyhow before \( t_v \). Note that the message is never transmitted or stored in cleartext, but only in its encrypted form, more specifically in its ECO form. This guarantees that the message \( M \) can not be retrieved by a forensics analysis of the hosts after \( t_v \), once the encryption key has disappeared. After the message validity time \( t_v \), the DNS records will be removed from the cache of the DNS servers listed in \( S \). Thus, the key will disappear and the ciphertext can no longer be decrypted.
3.4 EphCom+: Extending EphCom Against a Strong Adversary

In case the ECO is transmitted over a communication channel, the security of such channel becomes relevant. Consider the case of the strong adversary presented in Sec. 2. This adversary may eavesdrop on the communication channel, get hold of the ECO before expiration time, and thus retrieve the ephemeral key and the message. However, it is possible to extend the EphCom protocol discussed above to be effective even in presence of a strong adversary. We require that, in addition to follow the EphCom protocol, the sender also encrypts the ECO, using for example an asymmetric encryption scheme and the destination’s long term public key, e.g., using the PGP protocol [31]. In the rest of the paper, we will refer to EphCom+ as the protocol enforcing encryption of the ECO prior to sending, further we refer to $E(\text{ECO})$ as the encryption of the ECO.

We remark that only the usage of secure and authenticated communication does not yield an Ephemeral Data System, i.e., it does not provide retroactive privacy. Consider for instance secure email services, like those enforcing PGP encryption: A receiver is not “time-bounded” and can retrieve her emails at anytime. Moreover, an adversary that records encrypted emails and then compromises the receiver to obtain her PGP private key can retrieve the exchanged emails. A solution based on an authenticated Diffie-Hellman key exchange protocol would prevent the attacker from retrieving the encryption key. However, if the receiver erases the encryption key and the email after reading it, she will not be able to read it again. A possible solution would be to keep the encryption key and only erase it at expiration time $t_v$. However, this solution is not practical since the receiver might be turned off at time $t_v$, and the key might then be at risk.

3.5 Handling Errors and Erasures

There are several scenarios where bit errors can be introduced in the key. For example, if a DNS server is restarted while its cache is populated with one record used by our scheme, the decoded bit will be set to 0 instead of 1. A bit can also flip from 0 to 1 when that particular record was requested by another user after the sender performed the key distribution. Furthermore, if a server does not reply, the corresponding bit cannot be set (this is an erased bit, not an error bit). To remedy this problem, we propose to use error correction codes. Error detection and correction are well-known techniques used to ensure that data is transmitted without errors across unreliable media or networks. For more information, we refer to [21].

One trivial approach could be to use a convolutional code [7]. A convolutional code is a type of error-correcting code in which each $m$-bit information symbol to be encoded is transformed into an $n$-bit symbol. More specifically, we could use a scheme that codes each bit into a 3-bit symbol.

In the context of EphCom, we would code the bit 1 as 111, and the bit 0 as 000. Given that the DNS-cache channel is almost a Z-channel, the symbol decoding would work as follows. If the symbol 000 is received, the bit would be set to 0. For all other symbols, the bit would be set to 1.

However, this code although well-suited for EphCom, would not be optimal in terms of bandwidth. For each bit of useful data, 3 bits have to be sent and this therefore increases significantly the number of necessary DNS requests. Therefore, we use another correction technique, relying on a Reed-Solomon (RS) code [27]. We select a $(63, 55)$ RS code that allows to correct from 8 to 48 erasures or from 4 to 24 errors (depending on where the errors are, as symbols are 6 bits long) or a combination of those (within the capacity of the error correction code). The use of this code in EphCom would increase the number of requests only by 20% (for a 128-bit key, from 128 to 176), as opposed to 300% for the naïve code. Our experiments show that the Reed-Solomon code guarantees accurate key decoding with very limited overhead. Also, note that the correction capability can be tuned at will (by changing the parameters of the code) in order to increase error rate correction.

4. SECURITY ANALYSIS

In this section, we analyze the security and privacy provided by EphCom. Note that is unlikely, in any EDS, to show that retroactive privacy properties are provably-secure in a formal cryptographic sense, since it is not possible to formalize what side information is available to the adversary before expiration time. Nonetheless, our analysis is as rigorous and exhaustive as possible. Also, we discuss several attacks that may target the EphCom protocol as well as potential issues that might be used to compromise the system’s security.

4.1 Retroactive Privacy in EphCom

Theorem 1. EphCom is a retroactive-private Ephemeral Data System in presence of a weak adversary.

Proof (Sketch). We show that no efficient weak adversary W-ADV has a non-negligible advantage over 1/2 against challenger Ch in the following game (introduced for a generic Ephemeral Data System in Sec. 2.5).

1. W-ADV announces two equal-length messages $M_0, M_1$, validity starting time $t$ and expiration time $t_v = t + T_v$.

2. At time $t$, Ch randomly selects a bit $b \in \{0, 1\}$. Then, following the EphCom protocol discussed in Sec. 3, Ch produces $E(\text{ECO}(M_b, t_v))$, and transfers it from Ch$_S$ to Ch$_R$.

In a Z-channel the probability of a symbol 0 to be received as a 1 is very low.

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4 In PGP, an email is encrypted with a session key, itself encrypted with the receiver’s RSA public key.

5 The probability of this event to happen can be set a very small value if the domain name is selected properly, at random.
3. W-ADV can inject, replay, and modify messages in the communication between $Ch_S, Ch_R$.
4. At time $\tau > t_v$, W-ADV has access to $ECO(M_b, t_v)$.
5. W-ADV outputs $b'$ (and wins if $b' = b$).

First, remark that, as the weak adversary does not get any additional information during $[t, t_v]$, the only advantage for her may derive from accessing $ECO(M_b, t_v)$, at time $\tau > t_v$, i.e., after the ECO has expired.

Intuitively, an adversary accessing an expired ECO retrieves the ciphertext of the target message, the list of DNS cache servers with the related queried domain names. Assuming the underlying encryption scheme is secure, the ciphertext does not reveal any additional information, unless the corresponding key is retrieved. As a result, unless the adversary can use the information obtained from an expired ECO to recover the encryption key (which happens with negligible probability), EphCom is retroactive-private.

Recall that EphCom uses the expiration of DNS cache records to encode the key. Such an inherent property of DNS servers causes significant challenges to attackers that do not target their attacks prior to data expiration. In fact, even if the ECO still contains the list of DNS cache servers that were used for key storage, such servers no longer contain key information. Even if those DNS servers are subpoenaed or subject to forensics, the related key bits would not be present in the cache. Thus, after TTL has timed out, attackers cannot learn whether the domain name has ever been in the cache. Also, observe that, since the receiver erases the encryption key and message $M$ before its expiration time, potential compromise of the receiver does not help the attacker. $\square$

### 4.2 Retroactive Privacy in EphCom+

**Theorem 2.** EphCom+ is a retroactive-private Ephemeral Data System in presence of a strong adversary.

**Proof (Sketch).** We show that no efficient strong adversary S-ADV has a non-negligible advantage over $1/2$ against challenger $Ch$ in the following game (introduced for a generic Ephemeral Data System in Sec. 2.3).

1. S-ADV announces two equal-length messages $M_0, M_1$, validity starting time $t$ and expiration time $t_v = t + T_v$.
2. At time $t$, $Ch$ randomly selects a bit $b \in \{0, 1\}$. Then, following the extended EphCom protocol discussed in Sec. 3.4, $Ch$ produces $ECO(M_b, t_v)$, generates and transfer $E(EOC(M_b, t_v))$ from $Ch_S$ to $Ch_R$.
3. S-ADV can eavesdrop, inject, replay, and modify messages in the communication between $Ch_S, Ch_R$.

3a. At any time, S-ADV has access to $E(EOC(M_b, t_v))$.
3b. At time $\tau > t_v$, S-ADV has access to $E(EOC(M_b, t_v))$.
4. S-ADV outputs $b'$ (and wins if $b' = b$).

Recall that S-ADV has access to the communication between $Ch_S$ and $Ch_R$, as opposed to W-ADV. Hence, the advantage for S-ADV may derive both from accessing $E(EOC(M_b, t_v))$ at time $\tau > t + T_v$ and from accessing $E(EOC(M_b, t_v))$ at any time before $t + T_v$.

However, we show that we can reduce privacy in presence of S-ADV to security of the encryption scheme $E$ and retroactive-privacy in presence of W-ADV. Indeed, $E(EOC(M_b, t_v))$ is a ciphertext produced using a secure encryption scheme (as discussed in Sec. 3.4), thus, it is straightforward to show that, if S-ADV has a non-negligible advantage in distinguishing $M_b$ given the knowledge of $E(EOC(M_b, t_v))$, then S-ADV can be used to break the security of the underlying encryption scheme. Further, as the adversary’s view is restricted to $ECO(M_b, t_v)$ after expiration time $t + T_v$, we can use the same arguments of Theorem 1. $\square$

### 4.3 Key Recovery Attacks

**Brute Force Attack.** In order to retrieve the EphCom key, an attacker may attempt to crawl all existing DNS cache servers with non-recursive DNS requests, hoping to identify some bits of the keys. However, since the number of DNS cache servers and, especially, that of all possible domain names is extremely large, this approach is clearly not practical.

**DNS Infrastructure Infiltration Attack.** Another adversarial strategy could be to infiltrate the DNS infrastructure by compromising existing DNS servers, or deploying new ones. By controlling some of the DNS servers, the attacker could learn the domain names that were requested, and therefore some of the bits of the EphCom keys. However, unless the attacker controls a significant portion of DNS servers used to store the key of the target ECO, the amount of information that the attacker could learn is limited. However, such an attack is not practical since the DNS cache servers and domain names are chosen randomly.

**Sybil-like Attacks.** A variant of the Infrastructure Infiltration attack is the Sybil attack, such an attack was performed against Vanish [30] are not effective against the DNS infrastructure. In a Sybil attack an attacker controls several hosts that generate many virtual identities, and thus manages to receive a very large portion of the P2P traffic. DNS servers are uniquely identified by their IP addresses and do not have virtual identities. A Sybil attack on the DNS would therefore require either (i) a large number of public IP addresses pointing to a few hosts, or (ii) a large number of hosts acting as DNS servers. We argue that both options are far from being viable. For instance, while the Amazon EC2 platform was successfully used in [30] to attack Vanish, it would not be useful for EphCom as public IPv4 addresses usage is limited.

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to 5 public IP per account. In addition, the IP addresses of malicious DNS servers would need to be included in the default list of DNS servers that is provided with the EphCom extension. As we will discuss in Sec. 6, our filtering algorithm is quite conservative and only selects stable servers that are operational for at least one year. This prevents attacks that use newly deployed servers or compromised bots, which are often unstable and online for a relatively short period of time.

4.4 Denial of Service Analysis

We now consider potential DoS attacks against the EphCom scheme. We identify two scenarios. In the first one, the attacker knows the ECO and her goal is to prevent the receiver from recovering the message. In the second scenario, the attacker is not targeting a specific target, but her goal is to attack the entire EphCom service.

Attacking a known ECO. An attacker with access to an ECO has several potential approaches to prevent decryption. First, all key bits can be flipped to 1 by performing recursive DNS requests of all the ECO domain names. However, after this attack the records corresponding to bit 0 in the initial key will have a larger TTL than the records corresponding to bit 1. Therefore, the initial key could still be recoverable by the receiver. Second, the attacker could target the DNS server caches, which have finite memory availability. As a result, an attacker could launch a DoS to EphCom by filling caches with random entries until the entry used to store a bit is removed from the cache. However, the default Bind behavior does not limit the cache size, making this attack impossible. For DNS cache servers with cache size limitations, the attack would be feasible. Finally, the attacker could perform a DoS attack on the DNS cache servers themselves, by flooding them with bogus DNS requests. Note that as for most of Internet protocols, brute-force DoS attacks are very difficult to prevent and are in general unrelated to the privacy of the system. A simple solution to address the previously described attacks is to use EPHCOM+, i.e., PGP-encryption of the ECO, such that an attacker would not have access to the DNS information.

Attacking the EphCom Service. An attack of the whole EphCom service is much more demanding, requiring extensive DoS attacks against a significant percentage of the DNS cache servers of the Internet. Flooding servers with packets or by trying to fill up their cache would require many DNS requests and is very difficult to perform. Furthermore, this attack would impact the operation of the entire Internet and would therefore be easily noticeable.

4.5 Top Level Domains and Root Servers Logging

When an ephemeral bit 1 is stored in a DNS cache, the cache server performs a recursive request to retrieve the record corresponding to the requested domain. The server will walk through the DNS hierarchy to locate the authoritative DNS server. If the cache is empty, and the domain used is sub.domain.tld, the following steps will be needed:

- A root server $R_i$, among $R_1, \ldots, R_n$, is queried for sub.domain.tld.
- $R_i$’s answer will contain the addresses of the authoritative servers for tld (so called Top Level Domains, TLD, servers), e.g., $T_1, \ldots, T_n$.
- The request for the record sub.domain.tld. is sent to one of the tld. authoritative servers, $T_i$. $T_i$ will answer with the list of DNS authoritative servers, $A_1, \ldots, A_n$, for domain.tld.
- Finally, one of the authoritative servers, e.g., $A_i$, will be queried for the domain sub.domain.tld., and will answer with the requested record, or a negative answer if this record does not exist.\(^{11}\)

One can argue that during the above process, the key might be disclosed to third parties (here $R_i$, $T_i$ and $A_i$). Indeed, even if these servers themselves are not malicious, their network traffic might be logged, e.g., for forensics purposes. An attacker willing to open an EphCom message after its expiration date could try to exploit such logs. Assuming that each request to store a 1 is logged and that an attacker can get access to the logs of all root and all TLD servers involved, she can then retroactively recover the original message from an ECO.

A simple and effective counter-measure to defend against this attack is to use caching with a “pre-fetching” request. If a record is already cached, no further communication to the TLD and root servers is required. Therefore, a straightforward solution is – independently of the value of the bit to store – to perform a recursive query (the “pre-fetching” query) for another record of the same domain, e.g., www.domain.tld. This will force the cache server to obtain the records for tld and domain.tld. From now on, the records will be in cache and the request to store a bit to 1 will be sent directly to the corresponding authoritative server. This technique therefore only exposes a hostname independent from the one actually used in the EphCom message. Also, the information received by root and TLD servers will be the same, independently of the value stored in the cache DNS server.

This technique would also succeed if:

- tld. and/or domain.tld. records are already cached. In such a case, the reply will be made without querying the TLD or the root servers.
- the hostname www.domain.tld does not actually exist. In this case, the cache server will still make the same

\(^{10}\)Note that BIND9 has an option to limit cache size max-cache-size, however it has been reported to be nonfunctional.

\(^{11}\)This step might be repeated as many times as there are subdomains delegations under domain.tld.
requests to the root and TLD servers (and keep those records in cache), but will eventually receive a negative answer (from the $A_i$ server).

Our prototype implements this “pre-fetching” by default and has a small impact on the performance and overall network load. Indeed, without this extension, when a cache miss occurs (i.e., domain.tld and tld are not already in cache), requests would still go through the TLD and root servers. Moreover, in case of cache hit this extension would not trigger additional requests to root and TLD servers. Therefore, it only incurs one additional DNS message exchange between the DNS cache server and the client for each bit set to 1 and one additional DNS message exchange between the DNS cache server and the root for each bit set to 0. The additional load generated on the root and TLD servers is therefore not significant.

4.6 Irrelevance of Known DNS Security Issues

DNS Flushing Periods. Older versions of the BIND DNS Server do not periodically erase expired entries from the DNS cache. Therefore, a forensic analysis on such a server would allow to recover the entries (i.e., key bits) long after their normal expiration date. This analysis would therefore reveal parts of a key that should not otherwise be available. Fortunately, only BIND versions older than 4.9 lack a regular cache cleanup [5]. In our dataset there are only 4 BIND servers fingerprinted as versions 4.8 out of 90K servers. We therefore exclude them. More recent BIND DNS servers have by default a 1 hour cleaning interval. Expired entries are therefore removed from the cache and information about the expired key bits stored in the cache rapidly disappear.

DNS Poisoning Attack. The DNS system has been the target of well-known attacks, such as DNS cache poisoning [19]. In such an attack, an attacker is able to inject a fake record associating a legitimate host name to a bogus IP address. This attack is used for redirecting users to a malicious site. Variants of this attack rely on injecting fraudulent glue records together with normal response [1] in order to redirect queries to malicious name servers. This attack does not interfere with EphCom as long as records can be cached by cache servers, even if the stored values point to malicious IP addresses.

Domain Name System Security Extensions. DNSSEC have been recently designed to provide authentication and data integrity of DNS records [12]. The main idea of DNSSEC is to digitally sign answers to DNS lookups using public-key cryptography. EphCom is not affected by the deployment of DNSSEC since these extensions do not impact the DNS caching mechanisms EphCom is built on.

5. EXTENSIONS

In this section, we discuss several extensions to the Eph-

Com scheme.

Dedicated host names with tunable TTL. The current version of EphCom uses randomly chosen (but valid) domain names with adequate TTLs to encode the bits of encryption keys. This simple approach does not require any configuration work from the users. Another option would be for users to create their own domain names with TTL values corresponding to the desired key (and data) lifetime. This approach is more demanding, but several easy-to-configure dynamic DNS services could be used for this purpose (e.g., dyndns.com). This approach has at least two benefits: First, it provides more granularity since the TTL can be set to the desired lifetime. Second, it allows the user to erase a key before its expiration time by performing recursive DNS queries to all DNS cache servers that were used to code the bits of the key. This operation would set all the bits of the key to 1 and would prevent ECO decryption. Such a feature is important since it allows the sender to erase data (emails, files, etc.) that was sent by mistake. For convenience, such a system could be provided as a web service and integrated in the EphCom Firefox extension (see Sec. 7) for automated use.

Note that premature erasure of a key is not possible if domains are selected at random: although the sender could set all the bits to 1, the receiver would still be able to distinguish the bits that were initially set to 1 from the bits that were recently set to 1 from the TTL values. In fact, the recent bits 1 would have a larger TTL than the bit 1.\footnote{When performing a non-recursive request, a DNS server returns the remaining time until expiration in the TTL field.} If the user controls the domain names and its authoritative DNS servers, she can set the TTL of the domain corresponding to the bit 0 to $r_{TTL}$, where $r_{TTL}$ is the remaining TTL of the records. Then she can populate the caches, and erase all the domain names of the key from the authoritative servers. As a result, each cached record would have similar TTL value, independently of the value of the bit that it was originally coding.

However, we point out that the usage of a dynamic DNS service, such as DynDNS, should be done carefully. The cache servers query this authoritative DNS server to obtain the DNS record when a 1 is encoded. The authoritative server then learns this cache server/domain pair. If this information is available for all bits, together with the original ECO message, it would be possible to recover the message. Therefore, it is mandatory in this case to rely either on trusted servers or on a separate authoritative DNS server for each bit of the key.

While experimenting with EphCom, we realized that a few enterprise networks and ISPs implement transparent DNS proxying [6] to reduce bandwidth overhead. While not recommended, DNS transparent proxying forces a sender to use the DNS server chosen by the ISP. The DNS proxy intercepts any incoming DNS request and redirect them to the configured server. As a result, a sender cannot select the
DNS server to resolve her request and, therefore, EphCom cannot operate. A similar problem arises when full packet capture and storage is performed within a close network distance to the sender or receiver (i.e. such that it would collect a majority of the DNS messages). In this case, captured packets, together with the ECO, can result into recovering the message. However, these problems can be addressed by tunneling the EphCom’s DNS requests, e.g., using Tor [10] or open proxies. Note that, as a positive side effect, the use of Tor provides higher anonymity, as DNS requested cannot be correlated to any sender.

6. MEASUREMENTS & EXPERIMENTS

In this section, we overview our measurements performed in the process of selecting Open DNS cache servers, and our experimental analysis of EphCom.

6.1 DNS Cache Servers

EphCom uses a set of randomly chosen DNS cache servers to distribute encryption keys. Thus, the related software layer must be equipped of a list of DNS cache servers. Although EphCom is resilient to errors and failures by means of error correcting codes, it is necessary to take into account DNS servers’ reliability in order to minimize the error rate. To this end, we build a list containing the highest possible ratio of servers that: (i) successfully respond to both recursive and non-recursive queries, (ii) have a small rate of connection errors, (iii) maintain entries in the cache for the whole TTL time (and not longer). Since an accurate list of such servers would evolve over time, we design EphCom to mirror this evolution by providing users with automatic periodical updates.

We now overview our methodology to build this list. Note that it is worth investigating how to maintain an optimal dataset, drawing from existing studies, such as [8, 20, 29].

Initial DNS Servers Dataset. We started from a list of 900K IP addresses responding to DNS queries, from a previous probing performed several months ahead. We re-probed these addresses and obtained a list of ~225K IP addresses. We validated this list by verifying whether the addresses answered to DNS queries throughout a period of 4 weeks. We further filtered those that: (i) did not answer to recursive DNS queries, (ii) did not cache answers to recursive queries, (iii) did not answer to non-recursive DNS queries, (iv) performed caching or recursive resolution when receiving non-recursive queries. In this way, we built a dataset of ~130K DNS cache servers.

TTL Compliance. Next, we focused on selecting cache servers that register the correct TTL. Indeed, looking at the TTL of the resolution answer returned after a recursive query, we noticed that some servers ignore the domains’ TTL, as pointed out in [8]. After another 4-week observation, we reduced our dataset to ~80K servers. Finally, we made sure that DNS cache servers used by EphCom would successfully maintain cache entries for the intended time, i.e., domain’s TTL. Hence, we periodically performed recursive DNS queries and subsequently test the presence of the corresponding cache entry—by means of a non-recursive query. Following a conservative strategy, we discarded servers that generated failures or premature cache entry removals after an observation time of 4 weeks. In this way, we finally reduced our dataset to ~25K reliable servers.

Table 1: Building a reliable DNS cache servers dataset.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Dataset</th>
<th>Fail</th>
<th>Pass</th>
<th>Perc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial dataset</td>
<td>900K</td>
<td>675K</td>
<td>225K</td>
<td>25%</td>
</tr>
<tr>
<td>Correctly perform cache</td>
<td>225K</td>
<td>95K</td>
<td>130K</td>
<td>57%</td>
</tr>
<tr>
<td>Cache correct TTL</td>
<td>130K</td>
<td>50K</td>
<td>80K</td>
<td>62%</td>
</tr>
<tr>
<td>Cache persistence</td>
<td>90K</td>
<td>65K</td>
<td>25K</td>
<td>27%</td>
</tr>
</tbody>
</table>

6.2 Domain Names

One of EDSs’ requirements is to let users actively and accurately control message expiration time. In EphCom, this time is related to key expiration time, thus, to the cache entries’ TTL. To this end, EphCom performs recursive queries only on domains that have the desired TTL. Recall that the set of domains is generated at random, as described in Sec. 3.3. Although the RFC1912 [5] defines the TTL to potentially last up to several weeks, in practice, we find that only a negligible fraction of domains have TTL higher than 604,800 seconds (1 week).

We highlight that the range of possible TTLs a user can select is reasonably wide. To show evidence of this we generated 2 million random domains that could be successfully resolved (i.e., we generated a random IP address and performed a reverse lookup to obtain the corresponding domain name). Then, we harvested their TTL provided by the authoritative DNS server. We notice that TTLs range from 0 seconds to 7 days. The distribution of most frequent TTLs is shown in Table 2.

6.3 EphCom Robustness

In this section, we evaluate the robustness of EphCom system by testing both the distribution and the retrieval of EphCom keys. Our goal is to examine whether the keys can be successfully retrieved before the expiration time while disappearing afterwards.

To this end, we executed the EphCom protocol introduced in Sec. 3.5. We fixed the encryption key size to 128 bits and chose a desired expiration time, i.e., 24 hours and 7 days. We stored the key as follows. First, we encode the key using the Reed-Solomon code discussed in Sec. 3.5 obtaining a 176-bit encoding, denoted with $e_1, \ldots, e_{176}$. Next, for each $e_i$, we wrote $e_i$ on the randomly picked cache server $s_i$ using
The domain name $d_i$ chosen at random and having a TTL equal to the desired expiration time.

Then, at periodic intervals, we retrieved the keys from the cache servers. For each $(s_i, d_i)$, we performed a non-recursive DNS query to cache server $s_i$ for the domain $d_i$: if an entry in the cache existed, we read $e_i' = 1$, otherwise $e_i' = 0$. Finally, we decoded the key using the decoding technique of the Reed-Solomon code.

We now analyze the percentage of key bits successfully retrieved during our experiments. We measured the correctness of both:

1. The bits that were read/written on cache servers, i.e., whether $e_i' = e_i$.

2. The key bits effectively used for encryption/decryption, i.e., after applying error correction code.

Figure 3 presents the results of our experiments (averaged over 100 trials), with expiration time set to, respectively, 3, 12, and 24 hours, and 1 week. Keys could be correctly retrieved up to the expiration time, whereas right after TTL timeout all bit 1’s flip to 0 in the corresponding key. At this point, the recovered key is all 0’s (it reads on Fig. 3 as around 50% of the initial random key bits, which were initially 0’s, are correctly recovered). Clearly, this provides no information on the original key.

We conclude that the EphCom prototype provides a robust and accurate Ephemeral Data System. In particular, throughout all our experiments, almost all the errors were related to bit 1’s flipping to bit 0’s, thus making our channel a Z-
channel. In addition, a more accurate and extensive profiling of the DNS cache servers may further reduce the percentage of bit flipping, by excluding servers that are prone to errors or premature removal of cache entries.

6.4 Performance Evaluation

We now analyze the performance of EphCom in order to confirm that our DNS-based approach is fast and scalable enough to be used in practice. In addition, we discuss several ideas to optimize our implementation. Performance measurements are run on a Dell PC with two quad-core CPUs Intel Xeon at 1.60GHz with 4GB RAM, Python 2.6.2 (with pydns-2.3.3 and pycrypto-2.1.0b1) and a high-speed Internet connection. Each experiment is repeated 100 times in order to produce a significant average measure.

**Key Distribution.** The main operations involved in distributing EphCom keys are the generation of valid random domains with intended TTL and DNS (non) recursive queries. (We do not consider cryptographic operations, which are relatively fast compared to the former tasks).

Random domain generation is performed as follows: we generate random IP address and perform a reverse lookup on the local DNS server to check whether the corresponding domain name resolves and has the desired TTL. Hence, this operation involves a number of trials that is directly related to the popularity of the desired expiration time as domain TTL. Due to its limited computational and bandwidth complexity, it is possible to execute multiple instances of this operation in parallel. However, as described in Sec. 3.3 the random domain generation is performed ahead of time, and not on-line. Nonetheless, if users want to independently generate the domains at run-time, they would incur in the following overhead. Due to potential errors or failures, it is advisable to pre-generate a number of random domains strictly larger—e.g., twice as many—than the bits to store. In order to generate 320 random domains (that is twice the number of bits to store if using 128-bit encryption keys and the Reed-Solomon code), our prototype requires around 5 seconds for TTL equal to 86,400 seconds (1 day). We also measure times for less popular TTLs. To generate the same number of random domains but with TTL equal to 14,400 seconds (4 hours), the prototype requires around 1 minute.

On the other hand, the time overhead needed to store key bits in DNS caches mostly depends on the delay in executing recursive queries. Our experiments show that, executing queries in parallel (instantiating up to 64 threads), this operation takes about 8 seconds. Although, DNS queries are not computationally expensive (in our experiments, the CPU usage never went over 2% throughout the whole execution) we let the number of parallel threads be a parameter that can be set by the user according to its needs.

**Key Retrieval.** The time needed to retrieve the key bits from DNS caches is instead related to the delay of executing non-recursive queries, which is much smaller than recursive queries. In our experiments it takes only 1.5 seconds to retrieve 176 key bits.

**Additional DNS traffic.** One possible objection to the EphCom system could be that it generates additional traffic towards DNS servers. However, the generated traffic is extremely limited in comparison to the number of DNS queries generated through typical Web navigation. To illustrate this, we note as examples that opening the Firefox default home-page on Ubuntu leads to more than 50 DNS queries. Furthermore, opening the [www.cnn.com] web page generates about 140 DNS queries. The number of queries is related to several factors, such as pre-fetching performed by Firefox, the number of advertisement links, and multiple lookups for each domain (one for each domain in the search list [2], IPv6 and IPv4 requests, etc.). When compared to these very common actions, the network and DNS usage of EphCom can be considered negligible.

Moreover, performing those DNS requests in parallel (up to 64 parallel threads in our experiments) might appear as an aggressive behavior. However, each DNS cache server used will receive at most two DNS requests 13, which represents an insignificant workload. On the other hand, the network traffic is quite limited, we experimentally measured it to 64KB to store a key 14.

We acknowledge that, if EphCom starts being used by a high number (millions) of users, it could induce a potentially overwhelming traffic on the Open DNS server. However, we expect the deployment of EphCom as a volunteer-based system, where users contribute by providing DNS servers resources. This approach would be somehow similar to the Tor anonymising network [10], where users would benefit from retroactive privacy guarantees, while helping the system scale by running Open DNS servers.

**Message Overhead.** If ECOs are transmitted over a communication channel, an increased number of bytes would be exchanged between receiver and sender, due to the additional information contained in the ECO. Indeed, beyond the ciphertext, assuming a 128-bit key and the use of the Reed-Solomon error correction technique presented in Sec. 4.5, the ECO contains 176 IP addresses for the DNS cache servers (each requiring 4 bytes) and 176 domain names (each requiring approximately 20 bytes). Thus, we estimate the average size of the additional information in the ECO at 4KB. According to the measurement work presented in [15], this overhead would be equal to less than one tenth of the average email size which was reported as approximately 60KB. Moreover, since the information related to the domain name is textual, the use of compression algorithms would effectively improve space efficiency.

13One request for looking up the www.domain.tld. the second (only if the bit to store is a 1) for sub.domain.tld, as presented in Sec. 4.5
14Which corresponds to an average of 180 bytes for a DNS request or response and below the worst case of 352 requests, (a key with all bits set to one) Sec. 4.5
7. THE EPHCOM PROTOTYPE

We have implemented an EphCom prototype with a simple modular architecture made of two components: the DNS core (backend) and the user interface (frontend). In this section, we present the details of the components and the interface between them, as well as the description of our software implementations.15

Backend. The crucial component in EphCom is the software layer responsible for performing DNS queries to distribute/retrieve key bits. The simplicity of the DNS-based approach is mirrored in the agility of our software implementations. In the EphCom prototype, this layer has been implemented in Python, enhanced by the efficient open-source PyDNS module (http://pydns.sourceforge.net) for DNS queries. Note that, thanks to the simple nature of DNS queries, EphCom can easily be ported to any other system, including mobile phones. To distribute ephemeral keys, EphCom uses randomly picked DNS cache servers and domain names. The implementation of key storage is straightforward, by means of recursive and non-recursive DNS queries. As a result, the footprint of our core implementation is extremely compact. For the encryption operations, we use the AES algorithm, as of the implementation provided by the PyCrypto python module16 with a standard key size of 128 bits.

Frontend. Given the simple structure of our Python-based core, the development of any user interface is not burdened with particular assumptions that may affect portability or usability. Besides a simple command-line tool for ephemeral files, we provide, as an illustrative example, the support for ephemeral emails, using EphCom system. To this end, we developed a Firefox extension prototype, namely the EphCom Firefox Extension, that allows: (i) the sender to encrypt the content of an email using EphCom and generate the corresponding ECO, (ii) the receiver to open an ECO and decrypt the corresponding message (assuming that expiration time is not passed).

Usability. The EphCom Firefox Extension uses our underlying DNS-based approach. All the functionality is included within the stand-alone extension, i.e., we do not require the user to install or launch any additional background software, as opposed to the Vanish architecture [17]. We believe that this feature is fundamental in increasing the usability of the scheme. In particular, the Vanish Firefox extension requires an underlying Vuze-DHT-backend that must be independently launched. Furthermore, the backend installation process include potentially “invasive” operations such as the installation of the Java Virtual Machine and the P2P Vuze-DHT infrastructure. In contrast, installation of our prototype only requires installing the Firefox extension, and may thus address a larger variety of potential users and devices. Note that we use the Python Extension17, that provides Python-Mozilla bindings enabling Python to be used inside of Mozilla applications.

Availability. Our prototype does not incur a setup delay, as opposed to Vanish, where the use of the extension is subject to the Vuze backend to bootstrap. This operation takes from 5 to 10 minutes according to [17], although may notably increase depending on local network configuration. Furthermore, we stress that P2P-based solutions may be prevented by firewalls and network filters, EphCom uses simple DNS queries, that are unlikely to be firewallated.

8. RELATED WORK

Forward Secret Privacy. Forward Secret Privacy (PFS) is the property that ensures that a session key derived from a pair of long-term public and private keys will not be compromised if one of the long-term private keys is compromised in the future. PFS was originally introduced in [9]. An authenticated Diffie-Hellman (DH) key exchange protocol provides this property since the compromise of the long term key does not provide any information about the DH components that were used. However, a PFS system does not provide retroactive privacy for several reasons. First, messages are not time-bounded, hence, the receiver can always decrypt messages without any restriction of time. Furthermore, in order to prevent future compromise of the encryption keys, the receiver should erase its short-term private keys (such as its DH private component) as soon as she has recovered the message. However, this would prevent her from recovering the message at a later time (before expiration time). A possible outcome would be to keep the private key and actively erase it at expiration time, but this still violates the Ephemerality Data System requirements, as discussed in Sec. [2].

Ephemerizer solutions. Introducing a trusted third party to erase data on behalf of users has been proposed by the Ephemerizer solutions [24, 25, 26]. In these approaches, users delegate deletion of protected data to third parties that automatically destroy such data after the specified timeout. This violates one of the main goals that we set for Ephemeral Data Systems, i.e., the introduction of trustworthy centralized service that might be compromised. Recall, for instance, the case of the Hushmail email encryption service, which was secretly providing the cleartext contents of encrypted messages to the federal government[28].

Vanish. Similar to Vanish [17], EphCom aims at providing retroactive privacy, even if data storage is not trusted, compromised or stolen. However, as discussed in Sec. [1] the Vanish’s architecture is based on a P2P model vulnerable to Sybil attacks. The main flaw on Vanish design is DHs are assumed to be resistant-enough to crawling. EphCom does not suffer from such a weakness, as it is deployed on an ex-

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15The source code of our implementations is available upon request.
16Available at [http://www.dlitz.net/software/pycrypto](http://www.dlitz.net/software/pycrypto)
17Available at [http://pyxpcomext.mozdev.org](http://pyxpcomext.mozdev.org)
isting always-on and very large Internet service, the DNS, where crawling would be prohibitively expensive. Besides privacy issues overcome by the EphCom scheme, another features provides an improvement over Vanish: EphCom allows users to select the expiration time, i.e., the period of time during which data is available. By choosing domain names matching desired lifetime period, users assign their contents a precise expiration time and do not rely on any hazardous timeout that would be assigned by specific DHTs implementations or would be due to network churn.

9. CONCLUSION & FUTURE WORK

This paper formalized the concept of Ephemeral Data Systems (EDSs) and introduced a novel instantiation, EphCom. EphCom relies on the caching mechanism of the DNS: it exploits the fact that DNS servers cache the response to a recursive DNS request for potential further requests. EphCom does not rely on any TPM devices, peer-to-peer networks, or centralized servers, and is transparent to existing applications and services. Finally, it is flexible and allows the sender to closely control data’s lifetime.

We presented extensive experiments, which attest to the reliability of EphCom. We showed that, using our list of Open DNS cache servers, EphCom correctly reconstructs ephemeral keys (before expiration time). EphCom relies on a Reed-Solomon error correction code, which reduces the error ratio to a negligible probability. Also, we tested the efficiency of EphCom through large-scale experiments, and showed that the extra load generated on the DNS infrastructure is negligible. Finally, we presented a command line tool and a proof-of-concept Firefox extension that implements EphCom and improves, by design, usability and availability of previous work [17]. Although we provided a proof-of-concept implementation using a list of DNS cache servers minimizing error rates, note that EphCom users can build their own set of servers. Indeed, since the DNS servers and domain names are chosen randomly, users refusing to trust the list of servers provided by an external party may select their own list.

We showed how to implement Ephemeral Data Systems using the caching mechanism of DNS servers. Nonetheless, one may consider alternative approaches based on other caching mechanisms available in today’s Internet, e.g., web search caching. However, it is appears a challenge, for these potential solutions, to set data expiration times with fine granularity.

Future work also include further analysis of existing DNS monitoring systems (a potential threat to EphCom), and a large scale DNS load evaluation.

10. REFERENCES


