

EphPub: Toward Robust Ephemeral Publishing

Claude Castelluccia

INRIA Rhone Alpes, France
claude.castelluccia@inrialpes.fr

Emiliano De Cristofaro

University of California, Irvine
edecrist@uci.edu

Aurélien Francillon

ETH Zurich, Switzerland
& Institute Eurecom, France
aurelien.francillon@inf.ethz.ch

Mohamed-Ali Kaafar

INRIA Rhone Alpes, France
mohamed-ali.kafaar@inrialpes.fr

Abstract—The increasing amount of personal and sensitive information disseminated over the Internet prompts commensurately growing privacy concerns. Digital data often lingers indefinitely and users lose its control. This motivates the desire to restrict content availability to an *expiration* time set by the data owner. This paper presents and formalizes the notion of *Ephemeral Publishing* (EphPub), to prevent the access to expired content. We propose an efficient and robust protocol that builds on the Domain Name System (DNS) and its caching mechanism. With EphPub, sensitive content is published *encrypted* and the key material is distributed, in a steganographic manner, to randomly selected and independent resolvers. The availability of content is then limited by the evanescence of DNS cache entries. The EphPub protocol is transparent to existing applications, and does not rely on trusted hardware, centralized servers, or user proactive actions. We analyze its robustness and show that it incurs a negligible overhead on the DNS infrastructure. We also perform a large-scale study of the caching behavior of 900K open DNS resolvers. Finally, we propose Firefox and Thunderbird extensions that provide ephemeral publishing capabilities, as well as a command-line tool to create ephemeral files.

I. INTRODUCTION

As the amount of private information disseminated over the Internet increases, so do related privacy concerns. Private data is increasingly often cached, stored, or archived, *in the cloud* and, in numerous occasions, its ownership is lost. Users are often unable to successfully delete published content: for instance, social network providers maintain daily backup tapes and do not physically erase “deleted” content from all backups [13], ascribing to the expensiveness of this operation. As a result, everlasting information may endanger user privacy and become a prey of subpoena, government surveillance, or data leaks. For instance, a college student may upload (e.g., on a social network) pictures where she/he and her/his friends are evidently drunk; even after years, pictures may regrettably re-surface, e.g., during job hunting. Similarly, a blogger may post some controversial messages, which can later compromise an election campaign or even personal safety. In essence, if private data is perpetually available, then the threat for user privacy becomes permanent.

One natural step toward enhancing privacy is ensuring data confidentiality, i.e., by encrypting sensitive content. However, besides the well-known key-distribution problem, this approach faces some challenges: (1) privacy is lost if cleartext copies of the sensitive content or the decryption keys are leaked, and (2) access cannot be revoked. In particular key holders who had little interest in the data at the time of

distribution can later decide to use the key to access the data at any future time. Consider, for example, a friend that has become an enemy, an employer that wants to dig through an employee’s past data, or subpoenas for old records. Unfortunately, not much can be done with respect to the first problem where content or keys that are leaked or redistributed. In this paper we address the later problem; namely the problem of revoking encryption keys from key holders who try to access the data after some future expiration time set by the user.

Our approach, called *Ephemeral Publishing* (EphPub), not only encrypts content, but also uses a key escrow mechanism that ensures a keys automatic erasure, after an expiration time set by the user. Our approach is similar to the concept explored by Vanish [16], where key shares are distributed on a Distributed Hash Table (DHT). Since peers store data only for a limited period of time, so called churn, key shares are eventually erased. However, DHTs are vulnerable to Sybil attacks [11]. It has been shown by Wolchok et. al. [31] that, at a reasonable cost, an attacker can collect the keys distributed over the DHT. As we will show, EphPub uses a novel key distribution mechanism based on the DNS system that avoids such attacks and also improves the usability and availability of the system.

The notion of Ephemeral Publishing is useful, for instance, in the following scenarios:

Online Social Networks (OSNs): Content published on online social networks—such as pictures or wall posts—has often time-limited value to the users. As reported by [8], users would often like to delete their content after a small period of time (e.g., a few hours or days). However, deletion is not always effective, as data is often cached without users’ knowledge by the service provider [6]. In contrast, EphPub lets a user publish encrypted content and ensures that intended recipients (e.g., OSN friends) can access decryption keys – hence, content – only within a specific period of time, assuming the OSN friend has not cached the decryption key for future use. While EphPub cannot prevent OSN friends from caching content or decryption keys for future access to the data, it can prevent friends from viewing data in the future if they did not cache the key or the content (e.g., they had no interest in the data at the time and did not access the content or key)¹.

¹ Our implementation of EphPub never caches unencrypted keys or content, which means users cannot access the content after the key expires.

Outsourced Data: Web users increasingly outsource personal and confidential data to the cloud, e.g., using backup services, such as Dropbox. Such private data must be stored in an encrypted form to prevent access by the service provider (e.g., for data mining purposes or in response to a subpoena). However, encryption would not be effective unless all the users of the data proactively delete the decryption keys since the keys may be subject to subpoena. Note that in this case we assume there is no risk of leaks or redistribution because all users want to keep the data private. However, it requires all users to remember to delete the decryption keys they have been given. EphPub addresses this issue by distributing information that allows users to retrieve the key online. This information does not need to be deleted because it becomes useless after a fixed amount of time.

A naïve solution for the EphPub problem would be to publish encrypted content and store the corresponding encryption keys on a server that she owns so that the keys can be deleted when the content’s lifetime expires. However, this solution requires keys to be constantly accessible (thus, introducing a single point of failure), and raises additional privacy concerns as the publisher can always trace users accessing her content.

Technical Roadmap. In this paper we present Ephemeral Publishing (EphPub), a protocol aimed at guaranteeing *retroactive privacy* [16], i.e., allowing users to set an expiration time on their information and preventing an adversary from retrieving messages *after* expiration. EphPub leverages a fully-distributed and ubiquitous Internet service: the Domain Name System (DNS). We exploit its caching mechanism, as DNS resolvers cache the response to a recursive DNS query for potential further requests. These cache entries are kept for a fixed period of time, i.e., the record’s TTL (Time To Live). Once the TTL has expired, the resolver erases the record from its cache. We implement encryption keys as *ephemeral keys*. Each key is composed of *ephemeral bits*, i.e., it is divided into single bits that independently become inaccessible after a period of time.

Ephemeral Bits. To set an ephemeral bit to 1, a *recursive* DNS query for an existing domain name is performed to a DNS resolver. This resolver caches the response for as long as the domain’s TTL permits. 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 the 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 the bit 1 is read, otherwise if no response is returned the bit 0 is read. We use domain names selected 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 churn, connectivity problems, caching implementations, policies issues, failures, etc.), we use a Reed-Solomon error correction code [26].

Contributions. This paper formalizes the notion of *Ephemeral Publishing* (EphPub), by defining requirements, adversarial capabilities, and privacy goals. Then, it presents a practical and robust protocol that uses the DNS and its caching mechanism.

Our solution has several strong points compared to related work (e.g., Vanish [16]): besides being immune to Sybil attacks, (1) it allows users to set data expiration times with finer granularity (in Vanish it is bounded to DHT churn, typically 8 hours); (2) it does not require any additional infrastructure (e.g., a DHT or trusted servers); (3) it is lightweight, and does not force users to install extra software (e.g., DHT client), thus, it can be deployed on smartphones. Further, we propose two prototype implementations: a command-line tool to create files that can be decrypted only before expiration time, and a stand-alone Firefox and Thunderbird extension that makes any web text ephemeral. The source code of our implementations is available at <http://code.google.com/p/ephpub/>. Finally, in the process of designing our EphPub solution, we analyze the behavior of DNS cache resolvers: our measurements show that, from a dataset of 225K resolvers, 10% behave as recommended by the IETF.

Once again, we stress that the goal of EphPub is to protect information privacy against third-party service providers, government surveillance, and future subpoena. EphPub is *not* designed to safeguard published content from targeted attacks, e.g., within content’s lifetime. It does not provide a DRM-like mechanism that prohibits recipients from copying or republishing content, *before* expiration time. In other words, aiming at preventing data access *after* expiration time, EphPub proposes a new automated technique (i.e., without user proactive intervention) geared for time-bounded content.

Paper Organization. The rest of the paper is organized as follows. In Section II, we define system model, requirements, and privacy properties. Then, we describe the EphPub protocol in Section III and analyze its security in Section IV. Next, Section V presents the details of our prototype implementations, Section VI presents our extensive experimental analysis, and Section VII overviews relevant related work. Finally, Section VIII concludes the paper and discusses future work.

II. PRELIMINARIES

In this section, we model system assumptions and requirements. Finally, we present adversarial models and our formal definition of retroactive privacy.

System Model. An Ephemeral Publishing (EphPub) system involves a sender, S , and one or more receivers. For ease of discussion, and without loss of generality, in the rest of the paper, we assume a single receiver R . S sends to R *time-bounded* messages M . 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 . 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 $t_v = t + T_v$. EphPub also involves an encoding function $Encode(\cdot, \cdot)$. Specifically, $Encode(M, t_v)$ 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 and R . The function $Decode(\cdot)$ denotes the inverse operation, i.e., $Decode(Encode(M, t_v)) = M$.

System Requirements. We require that a practical and robust Ephemeral Publishing (EphPub) protocol meets the following minimum requirements. Specifically, it should:

- 1) Guarantee *retroactive privacy*, which we define under two different adversarial models (below).
- 2) Work for synchronous and asynchronous communications. The sender and receiver could have intermittent 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 services, and not on yet-to-be deployed services or infrastructure. In addition, to avoid single points of failure or trust, it should not depend on centralized services or require the existence of specific hardware or devices, such as a TPM (Trusted Platform Module).

Assumptions. We rely on the following assumptions. (i) S and R securely erase the plaintext message M or key material from their local storage. (ii) Messages are only stored or transmitted encrypted. (iii) S and R know the expiration time t_v .

Retroactive Privacy against a Weak Adversary. A weak adversary (W-ADV) has access to the same primitives and services as any user S and R . She 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. Further, *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 obtain information exchanged between S and R .

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

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 $b \in \{0, 1\}$, computes $\text{Encode}(M_b, t_v)$, and transfers it from Ch_S to Ch_R according to EphPub.
3. W-ADV may inject, replay, and modify messages in the communication between Ch_S, Ch_R .
4. **After time t_v ,** W-ADV accesses $\text{Encode}(M_b, t_v)$.
5. W-ADV outputs b' (and wins if $b' = b$).

An example of such adversarial setting is an investigation authority wishing to obtain emails previously sent or received by a user, e.g., Alice. The authority may obtain a court order to seize Alice's PC, as well as to subpoena emails stored by Alice's email provider. That is, even if email messages were encrypted, the authority may obtain the related keys. However, the authority is assumed not to (constantly) monitor the communication channel used to exchange emails.

Retroactive Privacy against a Strong Adversary. 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 .

Formally, we say that EphPub is *retroactive-private against a strong adversary* if any efficient strong adversary S-ADV can win the following game with probability non-negligibly over 1/2. The game is between S-ADV and a two-sided challenger $Ch = (Ch_S, Ch_R)$:

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

An example of this stronger adversarial setting is a company concerned with behavior of one of its employees, e.g., Bob. The company may obtain his emails from the internal mail server and seize Bob's PC, but it may also log all traffic in corporate network.

III. THE EPHPUB PROTOCOL

In this section, we describe our EphPub construction, which relies on DNS caching. Our intuition is 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. Each bit of the key is *distributed* on separate DNS cache resolvers. Entries in the DNS cache expire according to their Time-To-Live (TTL), thus, the encryption key can no longer be recovered.

A. Building Blocks

DNS Caching. DNS Caching allows to reduce the load on individual DNS resolvers [22]. After a successful name resolution (following a DNS query), the DNS resolver keeps the record in cache for the time specified in the record's *Time-To-Live* (TTL) value (in seconds). This speeds-up responses to subsequent queries, since these 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 [3]. We will present the results of our own measurements in Section VI.

Open DNS Resolvers. The Internet features a large number of open DNS resolvers² – devices that respond to DNS queries on port 53. EphPub relies on open DNS resolvers allowing recursive queries and performing caching. In the rest of the paper, we denote them as *DNS cache resolvers*. During our experiments, we collected 900,000 open DNS resolvers' IP addresses scanning arbitrary address ranges. Our study reveals that more than 10% of the identified open DNS resolvers perform caching properly. As Dagon et al. [7] estimated the number of open recursive DNS resolvers to 17 million, we could estimate the number of open DNS cache resolvers to 1.7 million. For additional measurement studies on the DNS, we refer to [19], [29].

²A DNS resolver is open if it provides resolution for clients outside of its administrative domain. This is not to be confused with the OpenDNS company.

B. Ephemeral Bits

We now describe how EphPub encodes ephemeral bits: the existence (resp., the absence) of a record in a particular resolver'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, $dname_i$, to a DNS cache resolver, res_i . The resolver replies with the domain's record and caches the response for a period of time corresponding to domain's TTL³. 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 $\{dname_i, res_i, t_v\}$ (being $t_v = t + T_v$). 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 $dname_i$ to res_i . If $dname_i$ is in the cache, res_i replies with the corresponding entry and the bit is read as 1. If the entry is not in the cache the bit reads as 0.

If a DNS request is performed once t_v has passed, res_i will reply with an empty record, i.e., the bit will read as 0 independently of its original value.

C. Protocol Description

We now extend our approach to implement ephemeral bits to distribute (resp., retrieve) an entire encryption (resp., decryption) key.

Message Encryption. First, the sender selects a random n -bit key k , for a semantically secure cipher, such as AES. k_i denotes the i -th bit of the key. Then, the sender encrypts a message M , under key k , and produces the corresponding ciphertext, CT .

Key Distribution. The distribution of ephemeral key bits over DNS cache resolvers is illustrated in Fig. 1. Note that this instantiates the $Encode(\cdot, \cdot)$ function introduced in Section II. The sender S generates $Rs = \{res_1, \dots, res_n\}$, a list of n random (different) DNS cache resolvers, and $Dn = \{dname_1, \dots, dname_n\}$, 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; then, it verifies if $dname_i$ is already in the cache of res_i , through a non-recursive DNS request of $dname_i$. If res_i replies with a valid record, $dname_i$ is discarded, otherwise it is added to Dn .

Note that the list of random domains is precomputed and distributed to users. Specifically, we generate a random IP address, execute its reverse lookup, and check whether the corresponding domain name had a satisfactory TTL⁴. Next, for each bit k_i of the key such that $k_i = 1$, S performs a recursive DNS request of the domain name $dname_i$ to the DNS cache resolver res_i . Consequently, the resolver resolves

³To ease exposition, we assume for now that TTL is equal to the desired validity period, T_v .

⁴An example of domain names is: softbank126060235192.bbtec.net. Also, one could use existing databases of host names, e.g., robtex.com.

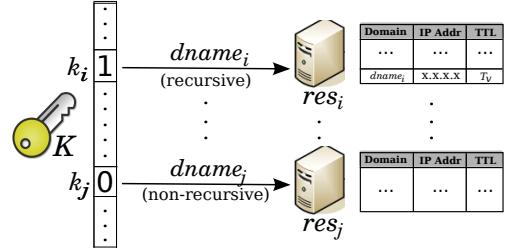


Fig. 1: EphPub Key Distribution.

the domain name, replies to the sender, and populates its cache with the corresponding record.

EphPub Object. The sender S builds the *EphPub Object* (EPO), defined as the output of the $Encode(\cdot, \cdot)$ function, introduced in Section II and instantiated above. Thus, we define $EPO(M, t_v) = \{CT, Rs, Dn, t_v\}$, i.e., the EPO is composed of the ciphertext (CT), the list of DNS cache resolvers (Rs), selected domain names (Dn), and content expiration time, 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 resolvers (res_1, \dots, res_n), respectively.

Key Retrieval. Upon reception of the EPO, i.e., $EPO(M, t_v) = \{CT, Rs, Dn, t_v\}$, the receiver checks whether the current time is smaller than t_v . If this is the case, she reconstructs the key k' as follows. The retrieval of key bits from DNS cache resolver (at a time $t+d$, s.t. $t+d < t_v$) is also illustrated in Fig. 2. For each domain name $dname_i$, ($i \in 1, n$), the receiver performs a non-recursive request to the DNS cache resolver res_i . If res_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, she decrypts the ciphertext CT to retrieve the message M . These operations instantiate the $Decode(\cdot)$ function introduced in Section II.

Note that the message is **never** transmitted or stored in cleartext, but only in its encrypted form, specifically, in its “EPO” form. This guarantees that the message M cannot even be retrieved with a forensics analysis on the hosts after t_v . Remark that, after the message validity time t_v , the DNS records will be removed from the cache of the DNS resolvers listed in Rs . Thus, the key will “disappear” and the ciphertext can no longer be decrypted.

D. EphPub+: Extending EphPub Against a Strong Adversary

In case the EPO is transmitted over a communication channel, the confidentiality of the channel becomes relevant. Consider the case of the strong adversary presented in Section II: such an adversary may eavesdrop on the communication channel, get hold of the EPO before expiration time, and hence retrieve the ephemeral key and the message M . We extend the EphPub protocol above to be robust even in presence of a strong adversary. Besides executing the EphPub protocol, the sender super-encrypts the EPO, using, for instance, an asymmetric encryption scheme, such as PGP, and the receiver's long term public key. Note that, if there are several receivers,

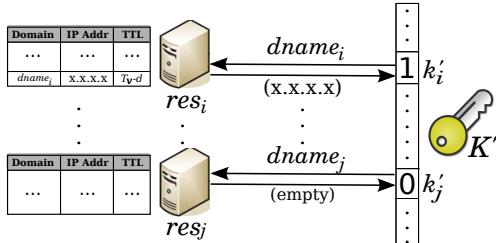


Fig. 2: EphPub Key Retrieval.

broadcast encryption techniques [5] can be used to minimize related overhead. In the rest of the paper, we will refer to EphPub+ as the protocol enforcing super-encryption of the EPO prior to transmission, and we refer to $\mathcal{E}(EPO)$ as the encryption of the EPO.

Remark. One additional potential concern with respect to a strong adversary is related to monitoring (cleartext) DNS messages between the sender and the cache resolvers. Because of this, queries to the DNS resolver have to be performed in random order. Thus, assuming 128-bit keys, a strong adversary monitoring a server’s DNS traffic learns the Hamming weight of the key (i.e. the number of ones), which corresponds to reducing the entropy of the key by roughly 5 bits⁵.

If this marginal reduction of the key strength is problematic, slightly increasing the key allows to compensate for it. For example, using a key of 134-bits provides slightly more than 128-bits of security when the Hamming weight of the key is known to the adversary. Alternatively, the sender can tunnel DNS requests, e.g., using Tor [10]. Note that, as a positive side effect, the use of Tor provides higher anonymity, as DNS requests cannot be correlated to senders.

E. Handling Errors and Erasures

Bit *errors* may occur in the ephemeral key: for instance, if a resolver is re-started while its cache is populated with one record used by EphPub, the corresponding bit will be decoded as a 0, instead of a 1. A bit can also flip from 0 to 1 if the corresponding record is requested by another user, after the sender performed key distribution. Note that the probability of this event is negligible if the domain name is selected at random, among a virtually unlimited number of host names, e.g., if wild-card domains are used. Finally, *erasures* occurs when the corresponding bit cannot be set, for example when a resolver does not reply during key retrieval.

To address potential errors and erasures, we use error correction codes [20], which make data resilient to a defined number of errors. Specifically, we use Reed-Solomon (RS) codes [26]. We select a (63, 55) RS code allowing to correct between 8 and 48 erasures or between 4 and 24 errors (depending on where the errors occur, since symbols are 6 bits long) or a combination of those, within the capacity of the error correction code. The use of this code in EphPub

⁵In average [21], the key search space for a key of size m with known Hamming weight is of $\sum_{m=0}^n \frac{\binom{n}{m}}{2^n}$.

increases the number of DNS requests only by 20%, e.g., for a 128-bit key, the increase is from 128 to 176. Note that the receiver needs to fetch the *correction bits* only when errors or erasures are present. Our experiments show that the Reed-Solomon code guarantees accurate key decoding with very limited overhead. If needed, error correction capabilities can be tuned by changing the parameters of the code, allowing higher reliability or more efficient network usage.

IV. SECURITY ANALYSIS

In this section, we analyze the security and privacy provided by EphPub. We also discuss several attacks that may target the EphPub protocol as well as potential issues that might be used to compromise system’s security.

A. Retroactive Privacy in EphPub

Theorem 1. *EphPub is a retroactive-private in presence of a weak adversary.*

Proof (Intuition). We observe that no efficient weak adversary, W-ADV, targeting an EphPub execution, has a non-negligible advantage over 1/2 in the game introduced in Section II. 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 $EPO(M_b, t_v)$, at time $\tau > t_v$, i.e., after the EPO has expired. Intuitively, an adversary accessing an expired EPO retrieves the ciphertext of the target message, the list of DNS cache resolvers with the related queried domain names. Assuming the underlying encryption scheme is semantically secure, the ciphertext does not reveal any additional information, unless the corresponding key is retrieved. Recall that EphPub uses the expiration of DNS cache records to encode the key: this inherent property of DNS resolvers causes significant challenges to attackers that do not target their attacks prior to data expiration. Indeed, although the EPO still contains the list of DNS cache resolvers that were used for key storage, these resolvers no longer contain key information. In fact, even if resolvers are subpoenaed or subject to forensics, related key bits would not be present in the cache. Thus, after the TTL has passed, attackers cannot learn whether the domain name has ever been in the cache. Also, observe that, since the receiver erases the encryption key and the message M before its expiration time, potential compromise of the receiver does not help the attacker.

As a result, the adversary cannot use information obtained from an expired EPO to recover the original message, thus, EphPub is *retroactive-private*.

B. Retroactive Privacy in EphPub+

Theorem 2. *EphPub+ is a retroactive-private in presence of a strong adversary.*

Proof (Intuition). We remark that no efficient strong adversary, S-ADV, targeting an EphPub+ execution, has a non-negligible advantage over 1/2 in the game introduced in Section II. Recall that S-ADV has access to the communication between Ch_S and Ch_R , as opposed to W-ADV. Thus, the advantage

for S-ADV may derive both from accessing $EPO(M_b, T_v)$ at time $\tau > t + T_v$ and from accessing $\mathcal{E}(EPO(M_b, T_v))$ at any time before $t + T_v$. However, one can reduce the retroactive privacy in presence of S-ADV to the security of the encryption scheme \mathcal{E} *and* the retroactive privacy in presence of W-ADV. Indeed, $\mathcal{E}(EPO(M_b, T_v))$ is a ciphertext produced using a secure encryption scheme (as discussed in Section III-D), hence, it is straightforward to show that, if S-ADV has a non-negligible advantage in distinguishing M_b given the knowledge of $\mathcal{E}(EPO(M_b, T_v))$, then S-ADV can be used to break the security of the underlying encryption scheme. In fact, since the adversary's view is again restricted to $EPO(M_b, T_v)$ *after* expiration time $t+T_v$, we can use the same arguments of Theorem 1.

C. Infeasibility of Key Recovery Attacks

Brute Force Attack. In order to reconstruct an EphPub key, an attacker may attempt to crawl all existing DNS cache resolvers with DNS requests, and try to identify some bits of the key. However, since the number of DNS cache resolvers and, especially, that of all possible domain names is extremely large, this approach is not feasible. Note that, in early 2011, <http://www.whois.sc/internet-statistics> reported 126 million active registered domain names. Moreover, relying on a sufficiently large set of wild-card domains would virtually remove any limit.

DNS Infrastructure Infiltration and Sybil Attacks. An additional adversarial strategy could involve infiltration in the DNS infrastructure, somehow similar to the Sybil attack, performed against the DHT used by Vanish [31]. Recall that, in a Sybil attack, an attacker controls several hosts that generate many virtual identities, hence, she receives a very large portion of the traffic. However, DNS resolvers are uniquely identified by their IP addresses and do not have virtual identities. A Sybil attack or an infiltration attack on the DNS infrastructure would require either (i) a very large number of public IP addresses pointing to a few hosts, (ii) a very large number of hosts acting as DNS resolvers or (iii) compromising or obtaining traffic logs of a large amount of the DNS resolvers.

We argue that those options are far from being viable. In fact, unless the attacker controls an extremely significant portion of DNS resolvers used to store the key of the target EPO, the amount of information that the attacker could learn is very limited. Since resolvers are chosen at random, e.g., among a million servers, an attacker that compromise a fraction of those would obtain, on average, the same fraction of key bits. That is, controlling 100K resolvers would lead to recovering only 10% of key bits.

Also note that an attacker cannot use newly deployed resolvers or compromised bots, which are often unstable and online for a relatively short period of time. In fact, in the design of EphPub, we make sure that resolvers are picked from a list that is generated and maintained conservatively (see Section VI).

D. Denial of Service

We now consider potential DoS attacks against EphPub. We identify two scenarios. In the first one, the attacker knows the EPO and her goal is to prevent the receiver from recovering the message. In the second scenario, the attacker is not focusing on a specific target, whereas, her goal is to attack the entire EphPub service.

Attacking a known EPO. An attacker with access to an EPO has a couple of potential approaches to prevent decryption. First, all key bits could be flipped to 1 by performing recursive DNS requests of all the EPO 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 caches of DNS resolvers, which have finite memory. As a result, an attacker could launch a DoS to EphPub 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 almost impossible. For DNS cache resolvers with cache size limitations⁶ the attack would be feasible at the cost of a huge number of DNS queries. Finally, the attacker could perform a DoS attack on the DNS cache resolvers themselves, by flooding them with bogus DNS requests. Note that as for most of Internet protocols, DoS (or even worse, DDoS) attacks are very difficult to prevent and are in general unrelated to the privacy of the system. One natural countermeasure is to always enforce EphPub+, i.e., super-encrypting the EPO, so that an attacker would not have access to the DNS information.

E. Traffic to Top Level Domains and Root Servers

When a bit is stored in a DNS cache resolver, the resolver will need to walk the DNS hierarchy to resolve the hostname's components it does not currently have in cache. Assuming a completely empty cache, the following steps will be performed by the DNS cache resolver to resolve the hostname "*sub.domain.tld*":

- A root server R_i , among R_1, \dots, R_n , is queried for *sub.domain.tld*. R_i 's will answer the addresses of the authoritative servers for *tld* (Top Level Domain servers), e.g., T_1, \dots, T_n .
- A TLD server T_j is queried for the record *sub.domain.tld*. It will answer the list of authoritative servers for the domain *domain.tld*, A_1, \dots, A_n
- Finally, an A_k 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 (or a list of DNS resolvers in case there is further sub domain delegations).

During the above process, the key might be disclosed to R_i , T_j , even if they are not malicious themselves, their network traffic might be logged, e.g., for forensics purposes. If an

⁶Note that BIND9 has an option to limit cache size `max-cache-size`, however it has been reported to be nonfunctional.

attacker gets access to the logs of all root and/or all TLD servers involved, she can then retroactively recover the original message from an EPO.

An effective counter-measure is to “pre-fetch” TLD and domain records, independently of the value of the bit to store, by performing a recursive query for an arbitrary record of the same domain, e.g., `www.domain.tld`. This will force the cache resolver to obtain the records for `tld` and `domain.tld`. Therefore, this will only expose a hostname independent of the hostname actually used to store EphPub bits. Also, the information received by root and TLD servers is the same, independently of the value actually stored in the DNS cache. Our prototype implements “*pre-fetching*” by default, this has a moderate impact on the performance and overall network load, as it performs requests independently of the value of the bit to store.

F. 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 could allow to recover the entries (i.e., key bits), after their normal expiration date. This analysis would reveal parts of a key that should not otherwise be available. Fortunately, only BIND versions older than 4.9 lack a regular cache cleanup [2]. In our experiments, there were only 4 out of 90K resolvers which were fingerprinted as using BIND versions before 4.9, thus, we excluded them. More recent BIND versions define a 1-hour default cleaning interval. Expired entries encoding the key bits are therefore removed from the cache with at most one hour delay.

DNS Poisoning Attack. The DNS system has been the target of well-known attacks, such as DNS cache poisoning [18]. 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 [30] in order to redirect queries to malicious resolvers. This attack does not interfere with EphPub as long as records can be cached by resolvers, 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. EphPub is not affected by the deployment of DNSSEC since these extensions do not impact the DNS caching mechanisms EphPub is built on.

DNS Proxying. A few enterprise networks and ISPs implement transparent DNS proxying [4] to reduce bandwidth overhead. While not recommended, DNS transparent proxying forces a sender to use the DNS resolver chosen by the ISP. The DNS proxy intercepts any incoming DNS request and redirect them to the configured resolver. As a result, a sender cannot select the DNS resolver to resolve her request and, therefore, EphPub cannot operate. A similar problem arises

when full packet capture and storage is performed within a close network distance to the sender or receiver. In this case, captured packets, together with the EPO, can result into recovering the message. However, these problems can be addressed by tunneling EphPub’s DNS requests, e.g., using Tor [10].

V. THE EPHPUB PROTOTYPE

We have implemented an EphPub 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 – the source code of our implementations is available at <http://code.google.com/p/ephpub/>.

Backend. The crucial component in EphPub is the software layer responsible for performing DNS queries to distribute/retrieve key bits. In the EphPub prototype, this layer has been implemented in Python, enhanced by the open-source PyDNS module (<http://pydns.sourceforge.net>) for DNS queries. Given the simplicity of DNS queries, EphPub can easily be ported to any other system/architecture. To distribute ephemeral keys, EphPub uses randomly picked DNS cache resolvers 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. Encryption is done with AES, relying on the PyCrypto python module (<http://www.dlitz.net/software/pycrypto>) and 128-bit keys.

Frontend. Given the simple structure of our Python-based core, the development of the user interface is not limited by particular assumptions that may affect portability or usability. Besides a simple *command-line tool* for ephemeral files, we developed a *Firefox and Thunderbird extension* prototype, using the python support provided by the *pyxpcomext* extension (<http://pyxpcomext.mozdev.org>). Therefore, all DNS operations are performed from within the extension. This extension allows: (1) the sender to encrypt any web content using EphPub and publish the corresponding EPO, (2) the receiver to open an EPO and decrypt the corresponding information (as long as that expiration time is not passed).

Usability. The EphPub functionality is completely included in a stand-alone Firefox and Thunderbird extension, i.e., we do not require the user to install or launch any additional background software, as opposed to Vanish [16]. We believe that this is crucial in order to improve the usability of the solution. Specifically, the Vanish Firefox extension requires an underlying DHT backend (i.e., Vuze) that needs to be launched independently. This also involves potentially “invasive” operations, such as the installation of the Java Virtual Machine. In contrast, our prototype only requires installing the Firefox or Thunderbird extension, thus, it addresses a larger variety of potential users and devices.

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 can take 5-10 minutes according to [16], and it may increase, as we have experienced, depending on local network configuration. Furthermore, we stress that P2P-based solutions may be prevented by firewalls and network filters, whereas, EphPub uses simple DNS queries, which are unlikely to be firewalled.

VI. MEASUREMENTS & EXPERIMENTS

We now overview our measurements, performed over several months, to select DNS cache resolvers, and present our experimental analysis of EphPub’s efficiency and robustness.

A. DNS Cache Resolvers

EphPub uses a set of randomly chosen DNS cache resolvers to distribute encryption keys. Thus, the related software layer must be equipped with an appropriate list. Although EphPub addresses potential errors and failures using error correcting codes, we need to assess DNS resolvers’ reliability to minimize error rate. To this end, we build a list containing the highest possible ratio of resolvers 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 entire TTL time and not longer. Since an accurate list of such resolvers would evolve over time, we design EphPub to mirror this evolution by providing users with automatic periodical updates.

We now overview our methodology. We remark that it might be worth investigating how to maintain an optimal dataset, e.g., drawing from existing studies, such as [7], [19], [29].

Initial DNS Resolvers Dataset. We started from a list of 900K IP addresses responding to DNS queries, from a previous probing performed several months earlier. We re-probed these addresses and obtained a list of ~225K active IP addresses. We validated this list by verifying whether the addresses answered to DNS queries throughout a period of 2 months and filtered those addresses 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. This way, we built a dataset of ~130K DNS cache resolvers.

TTL Compliance. Next, we focused on selecting cache resolvers that register the correct TTL. Indeed, looking at the TTL of the resolution answer returned after a recursive query, we noticed that some resolvers ignore the domains’ TTL, as already pointed out by [7]. After a 4-week observation, we reduced our dataset to ~80K resolvers to exclude misbehaving resolvers. Finally, we made sure that DNS cache resolvers used by EphPub 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 with non-recursive queries. Following a conservative strategy, we discarded resolvers that generated failures or premature cache entry removals after an observation time of 4 weeks. As a result, our

final dataset includes ~25K *reliable* resolvers. We summarize our measurements in Table I.

Experiment	Dataset	Fail	Pass
Initial dataset	900K	675K	225K
Correctly perform cache	225K	95K	130K
Cache correct TTL	130K	50K	80K
Cache persistence	90K	65K	25K

TABLE I: Building a dataset of reliable DNS cache resolvers.

B. Domain Names

One of our requirements is to let users actively and accurately control message expiration time. In EphPub, this time is related to key expiration time, thus, to the cache entries’ TTL. To this end, EphPub performs recursive queries only on domains that have the desired TTL. Recall that the set of domains is generated at random, as described in Section III-C. Although the RFC1912 [3] 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 confirm 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 II. As a result, our current techniques limit expiration time to 1 week. In many cases such a lifetime is enough for the application we consider (e.g., the *Online Social Networks* scenario in Section I). Also, note that this is a significantly larger interval than prior work: in Vanish [16], key shares are deleted after (typically) 8 hours, due to DHT churn. However, we acknowledge that it is an interesting open challenge how to support even longer expiration times, e.g., by periodically (and automatically) re-initializing ephemeral keys⁷.

TTL	domains
1200 [20m]	13,595
1800 [30m]	7,269
3600 [1h]	201,789
7200 [2h]	171,685
43200 [12h]	180,144

TTL	domains
86400 [24h]	998,450
172800 [2days]	77,326
259200 [3days]	12,317
432000 [5days]	13,450
604800 [7days]	42,142

TABLE II: Number of most frequent occurrences of TTLs over 2 million random domains.

C. EphPub Robustness

We now evaluate the robustness of EphPub system: we test distribution and retrieval of EphPub 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 EphPub protocol introduced in Section III-C. We fixed the encryption key size to 128 bits

⁷In cases where longer lifetimes are needed, it is possible (although not very efficient) for the source of the content to extend the expiration time of the DNS entries, by refreshing the cache after expiration, or to create a new EPO and distribute the new EPO to users.

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 Section III-E, obtaining a 176-bit encoding, denoted with e_1, \dots, e_{176} . Next, for each e_i , we wrote e_i on the randomly picked cache resolver res_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 resolvers. For each (res_i, d_i) , we performed a non-recursive DNS query to cache resolver res_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 Reed-Solomon decoding.

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 resolvers, i.e., whether $e'_i = e_i$.
- 2) The key bits effectively used for encryption/decryption, after applying error correction code.

Fig. 3 presents the results of our experiments (averaged over 100 trials). 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.

One potential concern regarding EphPub's robustness may be related to its resilience to errors due to collisions in writing ephemeral bits. However, one can make collision nearly impossible using wild-cards. Nonetheless, one can estimate the probability of a collision (without using wild-cards), using the birthday problem. Specifically, we model the probability of having at least one collision as $p(n; d) = 1 - e^{-n(n-1)/2d}$, where n is the number of EphPub documents with same expiration time and generated within the same time frame, and d is the product between the size of cache resolvers' dataset (i.e., $25K$ in our experiments) and the number of domain names with the specific TTL. For instance, considering documents with 24-hour expiration time, using our dataset of $25K$ cache resolvers and $1M$ random domains with 24-hour TTL, and assuming $n=10K$, we obtain $p(n; d) \approx 10^{-3}$. Also, recall that our error correction code can correct between 4 and 24 errors (see Section III-E). These numbers correspond to a small to medium deployment. Scaling to a larger number of users would require more DNS servers⁸ and the use of wildcard DNS domains to completely avoid the birthday paradox problem.

We conclude that the EphPub prototype is robust and accurate enough for real-world deployment. Nonetheless, a more accurate and extensive profiling of the DNS cache resolvers may further reduce the percentage of bit flipping.

⁸Based on work from Dagon et. al. [7] we estimate that 1.7 million DNS servers on the Internet would be suitable

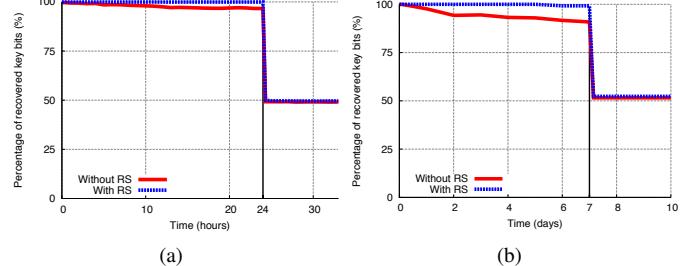


Fig. 3: Percentage of EphPub key bits correctly recovered with expiration times, respectively, 24 hours (a) and 7 days (b). *Before expiration time*, key bits are correctly recovered. *After expiration time*, key bits 1 (on average 50% of key bits) flip to 0 and are no longer correctly recovered. Whereas, key bits 0 (the other 50% of key bits) conserve their value. The resulting key is a dummy sequence of 0's and can no longer be used for valid decryption. Note that lines are plotted as the interpolation over periodical key retrievals.

D. Performance Evaluation

We now analyze the performance of EphPub to confirm that our approach is fast enough to be used in practice. In addition, we discuss several ideas to optimize our implementation. Measurements are done 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.

Key Distribution. The main operations involved in distributing EphPub keys are the generation of valid random domains with intended TTL and DNS (non) recursive queries. (We do not consider cryptographic operations, since symmetric key encryption is 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 resolver 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 overhead, it is possible to execute multiple instances of this operation in parallel. However, as described in Section III-C, the random domain generation is performed ahead of time, and not online. Nonetheless, we measure the overhead that users would experience if they want to independently generate the domains at run-time. 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 almost twice the number of bits to store, when using 128-bit encryption keys and Reed-Solomon codes), our prototype requires around 5s 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 6 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. Time to retrieve the key bits from DNS caches depends on the the delay of executing non-recursive queries, which is much smaller compared to recursive queries. In our experiments, it takes only about 1s to retrieve 176 key bits.

Additional DNS traffic. One possible objection to the EphPub system could be that it generates additional traffic towards DNS resolvers. 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 homepage 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 [1], IPv6 and IPv4 requests, etc.). When compared to these very common actions, the network and DNS usage of EphPub 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 resolver used will receive at most two DNS requests, which is a negligible workload. Also, the generated network traffic is quite limited: we measured that storing/retrieving a key on the resolvers generates at most 32KB of DNS traffic, corresponding to the worst case of having all bits set to 1 (given that an average request/response amounts to 180 bytes).

Message Overhead. The information contained in EPOs naturally generates a message overhead. Indeed, beyond the ciphertext, assuming the use of a 128-bit key and the Reed-Solomon error correction technique (see Section III-E), the EPO contains 176 IP addresses for the DNS cache resolvers (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 EPO at 4KB. According to the measurement work presented in [17], this overhead would be equal to less than one tenth of the average email size – approximately 60KB. Nonetheless, as this information is textual, the use of compression algorithms would remarkably reduce related overhead.

VII. RELATED WORK

Forward Secret Privacy. *Forward Secret Privacy (PFS)* [9] is the property ensuring 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. 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 guarantee retroactive privacy. In fact, messages are not time-bounded, hence, the receiver or any party obtaining the key can always decrypt messages without any restriction of time.

Ephemeralizer. The introduction of a trusted third party for erasing data on behalf of users has been proposed by *Ephemeralizer* solutions [23], [24], [25], [28]. Users delegate deletion of protected content to third parties (dedicated servers) that destroy the data or the encryption keys after a specified timeout. Again, this violates one of our main goals, i.e., to avoid the introduction of one or more trustworthy, always-on, and centralized services that might be compromised. For instance, recall the case of the Hushmail email encryption service, which was secretly providing the cleartext content of encrypted messages to the U.S. government [27].

Vanish. Similar to Vanish [16], EphPub aims at providing retroactive privacy, even if data storage is not trusted, compromised or stolen. However, as discussed in Section I, the Vanish architecture is vulnerable to Sybil attacks [31]. Authors of Vanish have proposed countermeasures to this specific attack [15]. However, as discussed in [31], this has only raised the bar for the attacker, due to the vulnerability of DHTs to Sybil attack, thus, leaving as open question whether or not DHTs are the best choice for key-share storage.

Observe that the main flaw of Vanish design is that DHTs are assumed to be resistant to crawling. On the contrary, monitoring all DNS resolvers is realistically infeasible. Further, EphPub provides several improvements in terms of robustness and usability. First, it allows users to select the expiration time: by choosing domain names matching desired lifetime period, users assign their content a more precise expiration time (while in Vanish this is assigned by the specific DHT implementation and due to network churn, unless using a so-called “refreshing proxy” that re-pushes key shares). Also, as we show next, given its simple nature, EphPub does not require users to install any additional software (e.g., DHT client). Thus, it can be easily ported on any architecture and deployed even on mobile phones. Indeed, researchers are already advocating efficient solutions to guarantee retroactive privacy, for instance, in *location sharing* applications over smartphones [14].

VIII. CONCLUSION & FUTURE WORK

This paper formalized the concept of Ephemeral Publishing (EphPub) and presented a novel efficient and robust solution to it, based on the caching mechanism of the DNS. It is transparent to existing applications and services and lets the sender to control data’s lifetime with relatively finer granularity than prior work [16]. Our EphPub technique uses a Reed-Solomon error correction code to minimize the error ratio. Our experimental analysis attests to EphPub’s efficiency and shows that the protocol correctly handles ephemeral keys. Measurements conducted over several hundred thousands open DNS resolvers may be of independent interest. We estimated the number of resolvers suitable for EphPub to 1.7 million.

We also proposed a command-line tool and a Firefox and a Thunderbird extension prototypes that implement EphPub. Our software improves, by design, the usability of previous work [16]. Our implementations use a list of selected DNS cache resolvers that minimize error rates. Nonetheless, EphPub users can build their own set of random resolvers.

EphPub guarantees that published content cannot be decoded after its expiration time, i.e., after that, an adversary cannot retrieve the decryption key, hence, she cannot reconstruct the content. Note that this guarantee holds even if the adversary controls (or compromises) the sender and the receivers, and tries to recover the key or the plaintext from their memory. Indeed, we assume that senders (resp., receivers) never store plaintexts and encryption/decryption keys, after publishing (resp., reading) the content, and before the expiration time. While one may consider this to be a “strong” assumption, observe that EphPub’s retroactive privacy guarantees are useful even without this assumption. In fact, EphPub ensures that expired content cannot be retrieved by the types of attackers (similar to *honest-but-curious* adversaries), envisioned in EphPub applications. For instance, recall the examples from Section I: even if plaintexts are not erased by the publisher, an employer is still prevented from crawling social networks, blogs and forums, or cached data to access expired content published by his employees.

We emphasize that EphPub does not protect against a user that copies or redistributes decrypted content, although the EphPub software is designed not to store it on local memory.

EphPub represents an initial foray into DNS-based Ephemeral Publishing, thus, much remains to be done. Future work includes a deeper analysis of existing DNS monitoring systems, a large-scale evaluation on the DNS load, and investigating alternative approaches based on other caching mechanisms of today’s Internet (e.g., web caching).

We also acknowledge that, if EphPub was to be used by a high number (e.g., millions) of users, it could impose a remarkable and unwanted traffic on the (open) DNS cache resolvers. Thus, it is unclear how resolvers’ administrators will react. Nevertheless, we hope that the privacy protection offered by systems like EphPub will result into a community effort, where users may contribute by providing DNS resources. One prominent example of this practice is the Tor Project [10], where a volunteer network of servers route Internet traffic in order to conceal a user’s location or web usage.

ACKNOWLEDGMENTS

The authors would like to thank our shepherd James Griffoen for his very helpful feedback and editorial suggestions, Daniele Perito for providing us the initial list of DNS servers as well as Vincent Jugé and the anonymous reviewers for their insightful comments and help to improve this article.

REFERENCES

- [1] The Linux man-pages project, Linux Programmer’s Manual. <http://www.kernel.org/doc/man-pages>, 2011.
- [2] P. Albitz and C. Liu. *DNS and Bind*. O’Reilly Media, Fourth edition, 2001.
- [3] D. Barr. Common DNS operational and configuration errors. *IETF, Network Working Group, Request For Comments, RFC 1912*, 1996.
- [4] R. Bellis. DNS Proxy Implementation Guidelines. *IETF, Network Working Group, Request For Comments, RFC 5625*, 2011.
- [5] D. Boneh, C. Gentry, and B. Waters. Collusion resistant broadcast encryption with short ciphertexts and private keys. In *Crypto*, 2005.
- [6] J. Bonneau. Attack of the Zombie Photo. <http://www.lightbluetouchpaper.org/2009/05/20/attack-of-the-zombie-photos/>.
- [7] D. Dagon, N. Provos, C. Lee, and W. Lee. Corrupted DNS resolution paths: The rise of a malicious resolution authority. In *NDSS*, 2008.
- [8] Danah Boyd. Risk Reduction Strategies on Facebook. <http://www.zephoria.org/thoughts/archives/2010/11/08/risk-reduction-strategies-on-facebook.html>, 2010.
- [9] W. Diffie, P. C. van Oorschot, and M. J. Wiener. Authentication and authenticated key exchanges. *Designs, Codes and Cryptography*, 2(2), 1992.
- [10] R. Dingledine, N. Mathewson, and P. Syverson. Tor: The second-generation onion router. In *USENIX Security*, 2004.
- [11] J. Douceur. The sybil attack. In *IPTPS*, 2002.
- [12] D. Eastlake. Domain Name System Security (DNSSEC) Extensions. *IETF, Network Working Group, Request For Comments, RFC 2535*, 1999.
- [13] Facebook, Inc. Facebook’s Privacy Policy. <http://www.facebook.com/policy.php>, 2011.
- [14] J. Freudiger, R. Neu, and J. Hubaux. Private Sharing of User Location over Online Social Networks. In *HotPots*, 2010.
- [15] R. Geambasu, J. Falkner, P. Gardner, T. Kohno, A. Krishnamurthy, and H. Levy. Experiences building security applications on DHTs. Technical report, UW-CSE-09-09-01.
- [16] R. Geambasu, T. Kohno, A. Levy, and H. Levy. Vanish: Increasing data privacy with self-destructing data. In *USENIX Security*, 2009.
- [17] L. H. Gomes, C. Cazita, J. M. Almeida, V. A. F. Almeida, and W. M. Jr. Characterizing a spam traffic. In *IMC*, 2004.
- [18] A. Klein. BIND 9 DNS cache poisoning. <http://www.trusteer.com/list-context/publications/bind-9-dns-cache-poisoning>, 2007.
- [19] J. Kristoff. DNS - Open Recursive Name Server Probing. <http://condor.depaul.edu/jkristof/orns/>, 2011.
- [20] D. MacKay. *Information theory, inference, and learning algorithms*. Cambridge Univ Press, 2003.
- [21] T. S. Messerges, E. A. Dabbish, and R. H. Sloan. Examining smart-card security under the threat of power analysis attacks. *IEEE Trans. Comput.*, 51:541–552, May 2002.
- [22] P. Mockapetris. Domain Names - Implementation and specification. *IETF, Network Working Group, Request For Comments, RFC 1035*, 1987.
- [23] S. K. Nair, M. T. Dashti, B. Crispo, and A. S. Tanenbaum. A Hybrid PKI-IBC Based Ephemerizer System. In *ISC*, 2007.
- [24] R. Perlman. File system design with assured delete. In *SISW*, 2005.
- [25] R. Perlman. The Ephemerizer: Making data disappear. *Journal of Information System Security (JISec)*, 2005.
- [26] I. Reed and G. Solomon. Polynomial codes over certain finite fields. *Journal of the Society for Industrial and Applied Mathematics*, 8(2):300–304, 1960.
- [27] R. Singel. Encrypted E-Mail Company Hushmail Spills to Feds. <http://www.wired.com/threatlevel/2007/11/encrypted-e-mail/>, 2007.
- [28] Y. Tang, P. Lee, J. Lui, and R. Perlman. Fade: Secure overlay cloud storage with file assured deletion. *Security and Privacy in Communication Networks*, 2010.
- [29] The Measurement Factory. DNS Surveys. <http://dns.measurement-factory.com/surveys/>, 2011.
- [30] US CERT. Multiple DNS implementations vulnerable to cache poisoning. <http://www.kb.cert.org/vuls/id/800113>, 2008.
- [31] S. Wolchok, O. Hofmann, N. Heninger, E. Felten, J. Halderman, C. Rossbach, B. Waters, and E. Witchel. Defeating Vanish with Low-Cost Sybil Attacks Against Large DHTs. In *NDSS’10*.