Talek: a Private Publish-Subscribe Protocol

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***Abstract*—Modern applications share user-generated data over the cloud, often exposing sensitive information. In this paper, we present Talek, a private publish-subscribe (pub/sub) system that shares user data through potentially untrustworthy servers, while hiding both the content of data being shared as well as the communication pattern among its users. Talek is designed with two goals that distinguish it from the prior work in private messaging. First, Talek is designed with the strong security goal of *access sequence indistinguishability*, where clients leak no information to adversarial servers that might help an adversary distinguish between two arbitrary-length client access sequences. Second, our system aims to be practical for general-purpose workloads, from one-to-one messaging to one-to-many news feeds. To achieve these properties, we introduce two novel techniques. *Oblivious logging* combines ideas from frequency hopping, cuckoo hashing, private information retrieval, and timestamp ordering to support private reads and writes to logs stored on servers. *Private notifications* provide a private and efficient mechanism for subscribers to learn which topics have new messages without polling. We demonstrate a three-server Talek cluster that achieves a throughput of 566,000 messages per minute for a community of 32,000 users with 5.57-second end-to-end latency on commodity servers, a 3–4 order of magnitude improvement over related work with similar security goals.**

I. Introduction

Many applications depend on cloud servers to send data between users, giving cloud operators full insight into the communication patterns of the application's users. Even if the underlying data is encrypted, network metadata, such as HTTP headers, can be used to infer which users share data, when traffic is sent, where data is sent to, and how much is transferred, potentially allowing an adversary to infer the contents of the communication [40]. In an age where remote hacking, insider threats, and hidden government requests are common, protecting the privacy of communications requires that we achieve security guarantees against a stronger threat model. For some users, such as journalists and activists, protecting communication patterns is critical to their job function and personal safety.

In this paper, we present Talek, a private publish-subscribe (pub/sub) system. Talek provides user applications a single-writer many-reader log abstraction that is efficient and general-purpose, storing asynchronous messages on potentially untrusted servers. Pub/sub is a useful communication pattern for a wide range of applications, including group messaging, news feeds, or data synchronization, without requiring direct user coordination. Clients create logs of messages, which groups of trusted users may read at a later time. As long as clients and at least one server are uncompromised, running authentic versions of the software, Talek prevents a cloud operator from learning anything about the communication patterns of these users. Combined with encryption, developers can conceal both the *contents* and *metadata* of users' application usage from cloud servers.

Recent research has made great strides in improving the state of private messaging, for both point-to-point messaging [1], [2], [57], [64] and anonymous broadcast [15], [16], [17], [47], [66]. Many systems offer security guarantees rooted in k-anonymity [62], plausible deniability [39] or differential privacy [25], [26]. Talek focuses on a stronger security goal based on *access sequence indistinguishability*, where two arbitrary-length client access sequences are indistinguishable to the server, and thus the server learns no information about which users may be communicating. Existing systems based on indistinguishability are either impractical due to prohibitive network costs [4], [33], [35], [52], or are custom-tailored for specific applications [8], [38], limiting their applicability across different workloads.

Talek provides a practical design for a general-purpose private pub/sub system with strong security goals based on indistinguishability of access patterns. Talek is designed to be network bandwidth efficient — usable with mobile clients reading and writing asynchronously to many pub/sub topics, each modeled by a log of messages.

Talek is based on private information retrieval (PIR) [13], [20], [32], but PIR by itself is not enough to support a a general-purpose private pub/sub system. We add two novel techniques:

- *Oblivious logging* combines PIR with the ideas behind frequency hopping [27], [24], cuckoo hashing [54], and timestamp ordering [7] to construct a real-time pub/sub message broker that can deliver messages with provable unlinkability between publishers and subscribers.
- *Private notifications* allow subscribers to determine which topics have new messages without polling for changes or revealing anything about their subscription list.

With oblivious logging, all clients issue identically sized random-looking read and write requests to servers at a fixed rate. Within a group of clients reading and writing to a shared topic, a shared secret determines the pseudorandom and deterministic sequence of locations for topic messages. The topic writer places new messages in locations that appear random to the adversary. Any subscriber with the topic secret can follow the pseudorandom sequence, reading new messages without coordination with other users. Talek relies on private

information retrieval (PIR) to read the message stored at a location without disclosing to the server which location is being read. We apply updates and reads consistently across PIR servers using timestamp ordering. To support message asynchrony, we insert messages into a cuckoo hash table. This data structure allows us to densely pack messages and to resolve collisions without disclosing information to the adversary. Each server only stores the latest n messages it sees, purging older messages. Choosing a larger value for n means data is stored on the database for longer, at the cost of more expensive reads.

With private notifications, subscribers periodically retrieve a *global interest vector*, which privately and efficiently encodes the set of all topics with new messages. Subscribers use the global interest vector as a private notification of changes, which can be used to locally prioritize reads. Servers maintain the global interest vector without being able to discover anything about its contents.

In our system, the developer chooses l independent servers to host replicas of the data. Talek's security model assumes at least one of the servers is honest. Our guarantees hold for arbitrary behavior by the other servers, who may collude, share secrets, and send faulty responses to clients. An adversary could control the network, all other clients, and $l-1$ servers without impacting the security of the system.

We do not guarantee liveness; a single faulty server can deny all use of the system. Because clients connect directly to Talek servers, we also do not hide when users are online. We expect the system to be used for communication among groups of trusted users. It is not appropriate for anonymous broadcast content (e.g. a public blog), that would be better served by other mechanisms.

We have implemented Talek in Go and evaluated the system on a 3-server deployment using Amazon EC2. Our source code is public. Our evaluation shows that for a messaging workload where users send and receive 256-byte messages every 5 seconds, we can support 32,000 concurrent users sustaining a total throughput of 566,000 messages per minute with an average end-to-end latency of 5.57 seconds. Further, our design is compatible with horizontal scale-out to support higher message rates and/or more users, although this is left for future work. PIR-based reads are the primary bottleneck on total system performance, as the server-side computational cost of a single read operation scales with the size of the database. In all, we show that we can achieve 3–4 orders of magnitude better performance than comparable systems with the same security goals.

The paper highlights the following contributions:

- Oblivious logging is a new approach to achieving our security goal of indistinguishability of access patterns, by efficiently storing logs of messages on the server in a way that looks random to an adversary. (Sections IV and V)
- Private notifications securely encode the set of new messages, allowing clients to prioritize reads to topics. (Section VI)
- Implementation and experimental evaluation of Talek, which applies these two techniques in an end-to-end pub/sub system with practical performance. (Sections VII and VIII)

II. Background

A. Publish-Subscribe Model

Publish-subscribe is a general messaging pattern, where messages are not programmed with specific receivers. Instead, users create topics and publish messages to these topics. A set of servers, called message brokers, store and forward messages to topic subscribers. Pub/sub systems are typically not used directly by end-users. Instead, application developers incorporate the model in order to share data through pub/sub servers.

Talek associates a secret with each topic. Subscribers are granted access to topics by receiving a secret from the publisher. These secrets are shared using an in-band mechanism called *control logs*, which we elaborate in Section V-C. A subscriber uses the secret to find and decrypt messages placed on the server by the publisher.

As a practical example, a group messaging application could use topics to store messages for each group of users. Although Talek only supports single-writer many-reader logs, we can emulate many-to-many communication by creating a log for each writer. Users publish to their own log and each member of the group subscribes to all logs of the group. As another example, a topic could be used to model a microblog or news feed. Similarly, a topic could be used to store a sequence of moves in a mobile game. Pub/sub systems are ideal for applications where many readers need to read the same message, but they can also be used for one-to-one messaging.

In our system, a Talek service can be shared across many applications, masking which application a user is accessing. Any particular instance of Talek has a fixed read rate, write rate, and message size. Thus, we anticipate developers will choose an instance of Talek with configuration parameters appropriate to the application needs.

B. Threat Model

Figure 1 illustrates a system with mutually distrusting clients located across a wide-area network, sharing data through Talek services, each hosted in a unique data center. We use the term, server, as an abstraction of a unique Talek service controlled by an independent administrative domain.[1] The adversary's goal is to build a statistical model of users who are likely to be communicating together.

Talek assumes the adversary controls all but one of a set of servers. Clients do not know which server is honest. The adversary can also control the network and generate an unbounded number of clients. We assume message storage capacity is scaled to the number of clients. We assume all servers are collecting information about all client network requests, such as the source, operation type, parameters, timing,

[1]Our design allows each independent server to be implemented across multiple machines for scalable performance and fault tolerance, but that is beyond the scope of this paper.

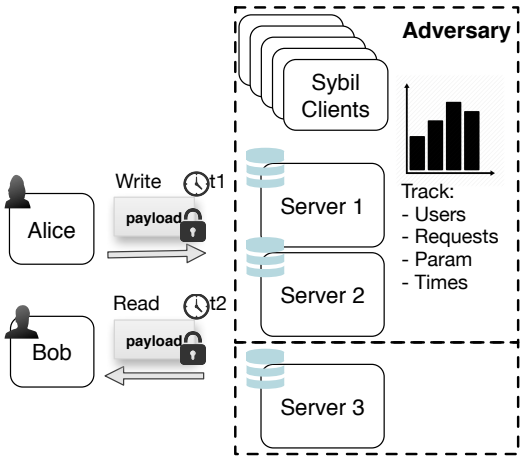

Fig. 1: System and threat model in Talek. We assume the adversary can control all but one of l servers in the system ($l = 3$ in figure). Clients send network requests directly to the servers. Adversarial servers are free to record additional data, such as the source, type, parameters, timing, and size of all requests to link users who are likely to be communicating together.

and size of requests. The Talek protocol ensures correctness and unlinkability, even when adversarial servers and clients exhibit arbitrarily malicious behavior, such as if they collude, share secrets, and send faulty responses to clients. Our security guarantees must hold even as clients are observed over long periods of time.

We assume clients who wish to share data know each others' public keys or have the ability to share a secret through an out-of-band channel [48]. Talek is designed to work with groups of trusted users. We assume that publishers trust their subscribers not to disclose topic secrets when they grant access to a topic. Malicious subscribers can collude with any server to expose the publisher of any topics to which they were granted access. However, clients colluding with servers are prevented from exposing other subscribers of the same topic.

During normal operation, all servers must be available and reachable by all clients. Any single server can deny all use of the entire system by refusing to respond or by responding with faulty information. Adversarial clients can also degrade service by mounting a denial of service attack.

We assume the existence of secure encryption, key-exchange protocols, signatures, hash functions, and random number generators. We further assume that each server's public key is known to all users. These issues are orthogonal to the properties Talek is designed to provide [63].

C. Security Goals

Informally, our security goal is to *require that any subset of $l-1$ servers can learn nothing about the access pattern of any user*. We define our security goal of *access sequence indistinguishability* more formally in Appendix A. To the adversary, an idle user is indistinguishable from a user communicating with other users. In addition to indistinguishability between two access patterns by the same client, the protocol should also leak no information that helps the adversary determine which users may be communicating together. These properties must hold regardless of how long a client is observed. We cannot hide IP addresses or when a user is online or offline from the system, because users are directly interacting with the servers. However, this must not undermine our security goal.

Definition 1. *(Access Sequence Indistinguishability) We say that the system provides access sequence indistinguishability if for any polynomial-time probabilistic adversary, the adversary's advantage in the security game of Appendix A is negligible in the security parameter.*

Access sequence indistinguishability provides one of the strongest definitions of privacy available. It is stronger than k-anonymity [62], where the adversary can narrow the user to one of k, where k is a subset of all users. It is also stronger than plausible deniability [39], where information leakage is allowed up to a certain confidence bound. Most systems that rely on these assumptions are vulnerable to statistical attacks that deanonymize users as they use the system over long periods of time.

Let seq denote a data access sequence by a client:

$$seq := [(\tau_1, op_1, k_1), \ldots, (\tau_n, op_n, k_n)]$$

where each τ_i denotes the time that an operation op_i is made, which can be a `Publish` or `Poll` to topic, k_i. Given a data access sequence, the client generates a series of network requests to the servers. Let

$$events := [(\tau'_1, req_1, par_1), \ldots, (\tau'_n, req_n, par_n)]$$

denote the sequences of events seen by a server from the client. Network request req_i arrives at time τ'_i with parameters par_i.

Informally, we achieve our security goal by designing the system such that

1) The schedule of requests seen by the server, $\{\tau'_i, req_i, par_i\}$, is independent from the data access sequence, seq. Requests are made by all clients at a fixed rate regardless of whether the client actually needed to perform a `Read` or `Write`.
2) All parameters, par_i, look random from the perspective of any $l-1$ set of servers. Dummy request parameters look indistinguishable from parameters of legitimate requests.

D. System Goals

In order to be practical for modern workloads, Talek must also satisfy the following goals:

Scalable: The system should support large numbers of ephemeral clients over a wide-area network, comparable to the application workloads supported by other privacy-preserving systems.

General Purpose: The system should be able to support a wide-range of pub/sub workloads, from point-to-point messaging to one-to-many news feeds.

Low Latency: High-priority messages should be delivered on the order of seconds, in order to support instant messaging.

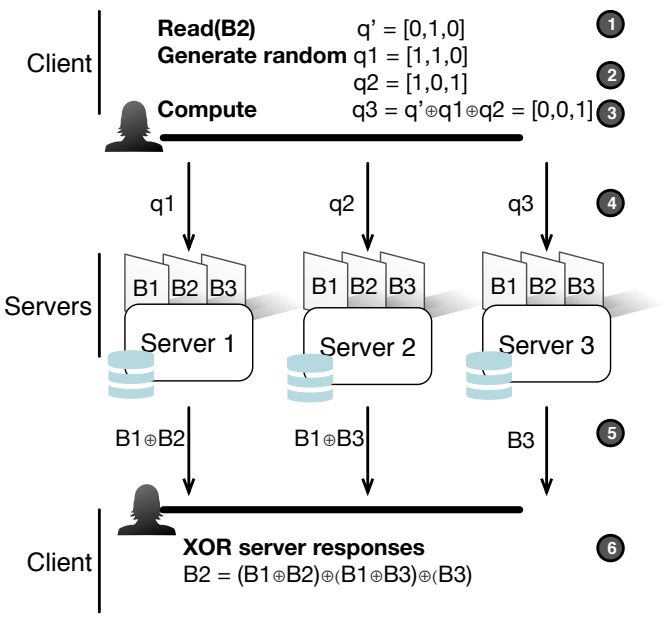

Fig. 2: Information-theoretic PIR example. Each client sends a random request vector to each server, except for one, which receives the XOR of the other random requests plus the true request. Each server responds with data equal in size to a single data block. As long as some server does not collude, the remaining servers cannot determine q', which of n blocks the client is retrieving.

E. Private Information Retrieval (PIR)

Talek uses the privacy guarantees of PIR in the context of a general-purpose pub/sub protocol. PIR allows a single client to retrieve a block from a set of storage replicas without revealing to any server the blocks of interest to the client. There exist two major categories of PIR techniques, computational PIR (C-PIR) [46] and information-theoretic PIR (IT-PIR) [13], [32], [20]. Talek is compatible with both varieties. However, C-PIR has been shown to be orders of magnitude more expensive in computation and network usage, making it impractical for the types of application workloads we target. This trade-off comes with the benefit of supporting a stronger threat model. With C-PIR, privacy is preserved even when all servers collude. In this paper, we focus on IT-PIR due to its better performance.

In order to gain an intuition for the performance and cost of IT-PIR, we illustrate the protocol with an example (Figure 2). Let l represent the number of servers in the system, each storing a full copy of the database, partitioned into equal sized blocks. While IT-PIR generalizes to arbitrary numbers of servers and blocks, the example in Figure 2 contains $l = 3$ servers and $n = 3$ blocks ($\{B_1, B_2, B_3\}$).

1) Suppose a client wanted to read the second block, $\beta = 2$, encoded by the bit vector, $q' = [0, 1, 0]$, which consists zeros and a one in position β.
2) The client generates $l-1$ random n-bit request vectors, q_1 and q_2.
3) The last request vector is computed by taking the XOR of the vectors from (1) and (2), $q_l = q' \oplus q_1 \oplus \ldots \oplus q_{l-1}$.
4) The client then sends q_i, to server i for $1 \leq i \leq l$. Because request vectors are generated randomly, this reveals no information to any collection of $< l$ colluding servers.
5) Suppose the server receives $q_i = [b_1, \ldots, b_n]$ and B_j represents the j^{th} block of the database. Each server computes R_i, the XOR of all B_j for which $b_j == 1$ and returns R_i to the client.
6) The client restores the desired block, B_β, by taking the XOR of all R_i. $B_\beta = R_1 \oplus \ldots \oplus R_l$

IT-PIR has desirable network properties: a client sends one request vector to each server and receives one block from each server. These requests and responses appear random to the network and the servers, assuming at least one server is honest. However, IT-PIR can be a computationally expensive operation, as the server's work to reply to a single request scales with the size and number of blocks in the system. The size of a client request scales with total number of blocks and the client work scales with the number of servers. IT-PIR also requires consistent snapshots across servers, with equal sized blocks in the data structure.

While PIR allows a client to read privately, in a read-/write system it is equally important to allow clients to write privately. Ostrovsky and Shoup introduced the notion of private information storage (PIS) [53], which allows a client to write to a row to a database of n rows without revealing which row was updated with poly-logarithmic communication complexity. In contrast, Talek aims to construct a pub/sub read-write mechanism with writes that take $O(1)$ time. We answer the following questions in designing our pub/sub system:

- *Random writes*: How can publishers write into the system in a way that appears random to the server? (Section IV)
- *Consistent Snapshots*: How do we maintain consistent snapshots across servers despite updates, for PIR operations to work over? (Section IV)
- *Garbage collection*: How do we constrain the size of the database to keep PIR operations tractable? (Section IV)
- *Zero coordination*: How do subscribers leverage PIR without coordinating with the publisher? (Section V)
- *Notifications*: How do we minimize the need to poll for new data? (Section VI)

III. Design Overview

Client Overview: Our system achieves our security goal by *requiring all users to behave identically from the perspective of any colluding set of $l-1$ servers*. Figure 3 illustrates how the system is organized; Figure 4 enumerates the interfaces and client/server state; Figure 5 lists constants that parameterize the design. Developers link their application to the Talek client library, calling `Publish` and `Subscribe` on the *client developer interface (CDI)*. When a function is called on the CDI, Talek places it on an internal *request queue*, which gets translated into privacy-preserving `Read` and `Write` network requests by the *network protocol interface (NPI)*. Every user issues equal-sized requests for each operation on the NPI (e.g.

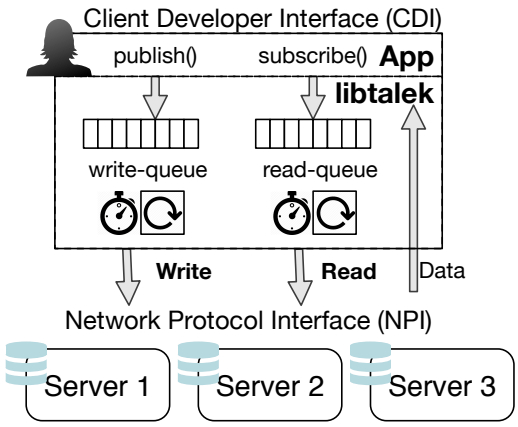

Fig. 3: Overview of the Talek architecture. All clients must behave identically from the perspective of any $l-1$ servers. Any calls by the application to publish or subscribe is internally queued by the client library, which is then translated into a privacy-preserving network request. The client library periodically issues requests with equal-sized parameters and messages that appear random to the adversary.

Client Developer Interface (CDI)
`Publish`(topic, message)
`Subscribe`(topic)

Network Protocol Interface (NPI)
`Write`(bucket1, bucket2, encryptedMsg, interestVector)
`Read`([]requestVectors) $\rightarrow$ encryptedData
`GetUpdates`() $\rightarrow$ globalInterestVector

Client State
- *topics* - List of subscribed topics
- *writeQueue* - Queue of write operations
- *readQueue* - Queue of read operations

Server State
- *log* - Global log of write operations
- *table* - Blocked cuckoo hash table

Fig. 4: Summary of Talek interfaces and client/server state

`Read` and `Write`) at a fixed rate, potentially issuing a dummy request if the respective request queue is empty. A mobile client must periodically read and write in every Talek instance subscribed to by one of its applications. While we describe the system using fixed rates for convenience, our security goals are met as long as the distribution of requests is independent from user activity.

The dummy request, including its parameters and payload, must be indistinguishable from a legitimate request. Messages are encrypted with a CCA-secure encryption scheme [6], which provides confidentiality and authenticity of messages, before being sent to the server. Thus, only the access pattern and not the contents of communication is disclosed when all servers collude. We define a globally-fixed message size, z, to which messages are split and padded to fit. Padding all messages to the size of a multimedia image would be vastly inefficient. Likewise, splitting an image into tweet-sized chunks would impose long delays. Instead, we expect Talek to be deployed according to the relative size of application messages. For example, we may run two parallel instances of the Talek protocol, one for text-based data and one for images. Because we expect Talek to be used with mobile and web applications, we can take advantage of pre-existing data types specified in the application to facilitate this categorization.

Server Overview: The server is designed to store a limited set of messages in order to allow asynchronous senders and receivers to be decoupled in time, rather than participating in synchronous rounds of communication. Because the cost of PIR operations scales linearly with the size of the database, for good performance we fix the number of messages stored on the server to n. We store the n most recent messages seen by the server, garbage collecting older messages in the system. Thus, n is directly related to the time-to-live, TTL, for a message, which dictates how tightly synchronized senders and receivers need to be. As the number of clients in the systems grows, the system must use larger values of n to support the same TTL.

In order to efficiently pack these messages into a dense data structure that is compatible with PIR, we store messages in a cuckoo hash table, with a few variations. We use a blocked cuckoo hash table [21], where each of the b buckets can store a fixed number of messages, d. Client `Write` requests explicitly specify two pseudo-randomly chosen buckets in which messages can be inserted, potentially resulting in cuckoo evictions (table rearrangement) if both buckets are full. In a `Read` request, the hash table is treated as a PIR database with each hash bucket as an entry. The client uses PIR to retrieve an entire hash bucket without revealing to the server which bucket it retrieved. Each server stores a consistent replica of the hash table in order to participate in the PIR protocol.

Blocked cuckoo hashing has a number of desirable properties for our system. Compared to chained hash tables, each bucket has an equal fixed size, a necessary requirement for PIR. With cuckoo hashing, each block is stored in one of two buckets. To handle collisions, the size of the table must be larger than n by a small overhead factor (generally less than 20% for reasonable values of the bucket size d).

A client issues at most two `Read` requests to check both buckets where a message could be stored. If the client finds the message it is looking for in the first bucket, then it can use its next `Read` request for another task, rather than querying the second cuckoo hash location. From the server's perspective, the client is simply issuing a stream of opaque PIR requests.

Topics Overview: In order to support clients reading and writing to multiple topics without online coordination, oblivious logging allows a publisher to hide legitimate messages in the client's stream of random writes. Within a topic modeled by a single-writer many-reader log, the publisher and subscribers share a secret topic handle. Exposure of the topic handle (e.g., by an untrustworthy subscriber) would expose the publisher's write pattern, but not those of other subscribers, since subscribers always read via PIR. The topic handle is

Globally Configured		
l	constant	Number of servers
n	constant	Number of messages stored on server
b	constant	Number of server-side buckets
d	constant	Depth of a bucket
z	constant	Size of a single message
w	constant	Per-user rate of writes
r	constant	Per-user rate of reads

Dynamically Measured		
m	variable	Number of online clients
TTL	$n/(m*w)$	Lifetime of a message on the server
$load$	$n/(b*d)$	Load factor of the server hash table

Fig. 5: Variables in the system, including those manually configured by the developer and dynamic behavior measured at run-time.

used with a pseudorandom function family, PRF, to generate a deterministic sequence of buckets, called a *log trail*. A publisher stores new encrypted messages along the log trail, which appears random to the adversary. Subscribers use PIR to retrieve messages along this sequence.

In order to avoid the need to poll for new messages, private notifications (§ VI) provide an efficient mechanism for subscribers to learn about new messages on the server. Along with each write, clients submit a Bloom-filter-based *interest vector*, which privately encodes the topic and sequence number of the message. Servers combine the interest vectors of all messages currently in the database to form a *global interest vector*, which privately encodes which messages are currently stored on the server. Clients periodically retrieve the global interest vector, which is used to locally determine which topics have new messages in order to prioritize reads. Regardless of the results of the global interest vector, the client must continue to read and write on its periodic schedule, even if there are no new messages to retrieve.

The next few sections describe each aspect of the system more formally. We first consider how Talek works with m idle online clients and l servers, illustrating the data structures, network requests, and a framework for security (Section IV). In later sections, we expand on this design to hide legitimate traffic among these requests using oblivious logging (Section V) and private notifications (Section VI).

IV. Talek with Idle Users

Figure 6 contains pseudocode for the server. Online clients issue dummy `Read` and `Write` requests at fixed rates of r and w respectively. We choose an arbitrary server to be the *leader*, $\mathscr{S}_0$, with the rest of the servers forming the *follower* set, $[\mathscr{S}_1, \ldots, \mathscr{S}_{l-1}]$. All `Read` and `Write` requests are directed to the leader and forwarded down the chain of followers.

Talek is further configured with a window size, n, such that messages older than the most recent n are garbage collected and deleted. It is possible for clients to miss a message if they fail to read a message before it is garbage collected. In this case, subscribers can request retransmissions as described in Section V-C.

A. Cryptographic Assumptions

Each server has a public-private key pair, pk, sk, generated using an algorithm $PKGen()$. We assume the public key of each server is known to all clients. We write $PKEnc_{pk}(text)$ for the encryption of $text$ under pk, and $PKDec_{sk}(cipher)$ for the decryption of $cipher$ under sk. Clients also have access to an efficient symmetric encryption scheme that provides *authenticated encryption with associated data* (AEAD). The associated data is authenticated, but not included in the ciphertext. We write $Enc_k(text, ad)$ for the encryption of $text$ with key k and associated data ad, and $Dec_k(cipher, ad)$ for the decryption of $cipher$. Our implementation uses an IND-CCA2 [6] RSA encryption scheme and AES-GCM for symmetric encryption. Let $PRF(key, input)$ denote a pseudorandom function family. For the purposes of this description, let $|$ denote tagged concatenation.

B. Strawman: Chained Hash Tables

We first consider a strawman approach to designing the server. Clients periodically write into pseudo-random positions on the server. Suppose we model the server's state as a table of b buckets, where clients explicitly specify to the server, in which bucket a write is placed. To make reading oblivious to the server, clients then use PIR to retrieve an entire bucket. In order to prevent clients from overwriting each other's messages, the server must have a mechanism for handling collisions.

One way to deal with collisions is to use chaining, where each bucket is a linked list of values. Because PIR requires elements of equal size, buckets would need to be padded to the length of the largest bucket. In the worst case scenario, a bucket could contain the entire database.

Another way to deal with collisions is to use open addressing, where the table is allocated to be much larger than the number of messages. Each bucket stores only one item; if a bucket is full, the server rehashes the key to find the next empty bucket. In the face of collisions, client reads would then use PIR to successively probe to find the message of interest. Unless the table is intentionally sparse, raising the overhead of computing PIR reads, a particular client could need to probe many buckets to reach its desired element. Since the read rate is fixed for all clients and all reads must complete before the message is garbage collected, only very low write rates could be supported.

C. Write: Cuckoo Hashing

Talek organizes server-side state into a blocked cuckoo hash table [21], where each server's storage is organized into b buckets, each bucket storing d messages, each of size z. PIR requests fetch an entire bucket of size $O(dz)$. Figure 7 illustrates the server-side data structures. Cuckoo hashing has a number of desirable properties for PIR-based reads. In practice, the number of messages stored, n, is chosen as a fraction of the capacity of the cuckoo table, $b \cdot d$. This fraction is set to ensure with high probability, that a message will fit with minimal rearranging of the cuckoo table [21].

```
//GlobalState
globalLog ← Array()                          ▷ Global log of write operations
seqNo ← 0                                    ▷ Global sequence number
hashtable ← BlockedCuckoo(b, d)              ▷ b buckets of depth d

1: //Writes the data into one of two buckets
2: function WRITE(buckets,data,interestVec)
3:     if isLeader() then
4:         seqNo ← seqNo + 1
5:         Append operation to globalLog
6:         Forward operation to follower servers with seqNo
7:     else
8:         Insert operation into globalLog at given seqNo
9:     end if
10:    Remove n-th oldest element from hashtable
11:    hashtable.insert(buckets[0], buckets[1], data)
12: end function
```

```
1: //Performs a PIR-based read
2: function READ(bucketVector)
3:     return bucketVector · hashtable
4: end function
```

```
1: //Returns the global interest vector
2: function GETUPDATES
3:     v ← BloomFilter()
4:     for all e ∈ last n elements of globalLog do
5:         v ← v ∪ e.interestVec
6:     end for
7:     return v
8: end function
```

Fig. 6: Pseudocode for server-side RPC handlers (NPI). The NPI was designed such that all parameters for any operation reveal no information about the user's application usage. Writes are serialized by the leader and replicated in global order to the follower servers. When writing, clients explicitly specify the two potential hash table buckets into which data is inserted. When data is read using a PIR protocol, we expose a blocked cuckoo hash table with the n most recent messages in the log and return full buckets. For simplicity, we only describe the original IT-PIR algorithm, which we show is equivalent to the serialized PIR algorithm in Section IV-D

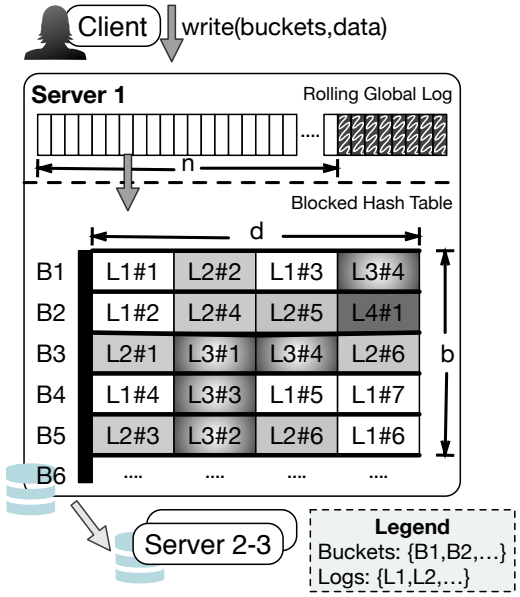

Fig. 7: Oblivious logging data structures and workflow. The leader serializes all write operations into a global log, assigning each message a globally unique sequence number. Server-side state is replicated to all other servers from the leader. In order to garbage collect old messages, we keep only the latest n messages. Client writes specify two random buckets in which the message can be placed, forming a blocked cuckoo hashing scheme. Topic logs are spread across the hash table, which can be read by the subscribers using PIR.

- PIR requires buckets be of equal size. Talek's blocked cuckoo hash table is configured with a fixed depth, d.
- Individual PIR operations are relatively expensive. Cuckoo hashing bounds the maximum number of client probes to 2.
- The cost of a PIR request scales linearly with the size of the database. Cuckoo hashing enables dense placement of messages in a pre-allocated data structure with minimal wasted space.

Because cuckoo hashing is a random algorithm and PIR requires consistent replicas across all servers, a shared random seed enables all servers to achieve identical state as long as items are inserted in the same order. The leader assigns each incoming request a global sequence number and replicates each message to the other servers. The global sequence number is used to determine the order in which messages are inserted into the hash table.

Client `Write` requests are generated using the following protocol. A client, $\mathscr{C}$, periodically issues random `Write` requests to the server. $\mathscr{C}$ is preconfigured with a randomly chosen k_{idle}, which is used to generate the i-th random number by $PRF(k_{idle}, i)$, and an idle encryption key k_{enc}. Similarly, all servers share a key k_{cuckoo}, used to generate random values in the cuckoo algorithm below. The i-th client request is generated as follows:

1) $\mathscr{C}$ chooses two random buckets,

$$\beta_1 = PRF(k_{idle}, i|1) \mod b$$
$$\beta_2 = PRF(k_{idle}, i|2) \mod b$$

where b is the number of buckets.

2) $\mathscr{C}$ encrypts a random z-length bit-string,

$$data = Enc_{k_{enc}}(PRF(k_{idle}, i|3) \mod 2^z)$$

and submits the request, $\beta_1|\beta_2|data$, to the leader, $\mathscr{S}_0$

3) Upon receiving the request, $\mathscr{S}_0$ forwards the request to all other follower servers, $\mathscr{S}_1 \ldots \mathscr{S}_{l-1}$, each following the cuckoo algorithm in steps 4–7.
4) Each server deletes the n-th oldest element from the hash table.
5) The server inserts $\beta_1|\beta_2|data$ into the bucket at either β_1 or β_2 if there is spare capacity in either bucket.
6) If both buckets are full, choose a bucket, β_e, either β_1 or β_2 using randomness from k_{cuckoo}. Let $\delta_e = \beta_1|\beta_2|data$.
7) Repeat the following until all values find a valid position
   a) Try to insert δ_e in β_e if the bucket has spare capacity.

b) If not, randomly evict an entry in β_e and insert δ_e in its place.
c) Let δ_e equal the evicted value and β_e equal its alternate bucket location.

Correctness: The leader is only responsible for assigning a global sequence number, which does not affect security nor correctness. If the leader misrepresents the global sequence number of a message (e.g. by giving a different sequence number to different follower servers), it could cause those replicas to become inconsistent. Because any follower could also deny service by failing to respond, the leader is in no more privileged a position to affect correctness or liveness of the system. In Section V-C we describe how clients detect misbehavior.

Performance: Cuckoo tables have a maximum capacity that is lower than the size of the table, $b \cdot d$. To store more messages, the data structure needs to be rebuilt with larger values of b or d. The ratio of the maximum capacity of the cuckoo table to the allocated space is known as the *load factor*. The load factor is a function of the bucket depth, d. For example, the load factor for $d = 1$ is less than 0.5, such that you must allocate twice as much memory as the number of items in the table. The load factor grows asymptotically towards 1 as d increases [21].

In Talek, the number of buckets b and the depth of each bucket d can be configured to suit a particular workload. Clients issue `Reads` with a random b-bit request vector and receive a $O(d)$-sized bucket in response. A smaller value for b and higher d allows the developer to more densely pack the hash table and use smaller request vectors in PIR requests, with the trade-off that the network overhead is larger. This configuration can be more appropriate for frequent writes of small messages in applications such as messaging. Conversely, a high value of b and low value of d resembles a traditional cuckoo hash table, resulting in a lower load factor, but better bandwidth utilization. This configuration is appropriate for infrequent writes of large messages, such as for images.

D. Read: Serialized PIR

In order to reduce the network costs of `Read` requests to the client, we use a *serialized* variation of PIR, which offloads work from clients to the leader. The client sends each server's encrypted request to the leader and receives a single response from the leader. We use one-time pads to preserve the confidentiality of each server's results, while allowing the leader to combine them on behalf of the client. In contrast, traditional PIR requires that the client receive messages from each server, such that the client combines each server's response by itself. This improvement in client network usage comes with the trade-off that the leader needs to do extra work and a slightly higher latency. Note that this does not affect the amount of bandwidth necessary to send client requests to each server.

A client, $\mathscr{C}$, periodically issues random PIR requests to the server as follows:

1) $\mathscr{C}$ chooses a random bucket to read and generates b-bit PIR request vectors for each server, $\{q_0, \ldots, q_{l-1}\}$, where b is the number of server-side buckets.
2) $\mathscr{C}$ generates a high-entropy random seed for each server, $\{p_0, \ldots, p_{l-1}\}$
3) $\mathscr{C}$ encrypts each server's parameters with its respective public key and generates a `Read` request, $PKEnc_{pk_0}(q_0|p_0), \ldots, PKEnc_{pk_{l-1}}(q_{l-1}|p_{l-1})$
4) $\mathscr{C}$ sends this request to the leader, $\mathscr{S}_0$, who forwards it to the remaining follower servers
5) In parallel, each server, $\mathscr{S}_i$, decrypts its respective PIR request vector, q_i and computes its response, R_i
6) Each server, $\mathscr{S}_i$, also computes a random one-time pad, $P_i = PRF(p_i)$, from the seed parameter. This one-time pad should be of equal size to R_i
7) Each server, $\mathscr{S}_i$, responds to the leader with $R_i \bigoplus P_i$.
8) $\mathscr{S}_0$ combines the server responses and responds to $\mathscr{C}$ with $R_0 \bigoplus P_0 \bigoplus \ldots R_{l-1} \bigoplus P_{l-1}$
9) $\mathscr{C}$ restores the bucket of interest by XOR'ing this response with each server's one-time pad, $R_0 \bigoplus \ldots \bigoplus R_{l-1}$

Security: This serialized variant of PIR is functionally equivalent to the traditional PIR scheme described in Section II-E. As long as the adversary only has access to $l - 1$ servers' secret keys, it cannot decrypt the honest server's request vector and reconstitute the secret request. Similarly, each response is combined with a random one-time pad, which prevents the adversary from learning any information from any individual server's response. Because each server's one-time pad is computed from a shared secret with the client, the client can restore the desired value.

Theorem 1. *Serialized PIR (Informally)*

1) *Security: As long as there exists at least one server's secret key that is unknown to the adversary, the adversary learns nothing of the user's secret request.*
2) *Correctness: The client receives the contents of the bucket corresponding to its request.*

E. Security Analysis of Idle Sequences

By definition, the access sequence, seq_i, of each client is a null list. For each client, the adversary observes $events_i$, a log of randomly generated requests. In the protocol as described thus far, $events_i$ is completely independent from seq_i. While we use fixed rates for `Read` and `Write` for convenience, our security goals are met as long as the rates are independent. For example, if requests follow a Poisson distribution between the hours of 9am and 5pm for every user, our security properties still hold. In the next section, we discuss how legitimate accesses are hidden among this cover traffic in a way that is indistinguishable to the adversary.

V. Oblivious Logging

The goal of *oblivious logging* is to translate secret calls to `Publish` and `Subscribe` on the client developer interface (CDI), into random-looking `Write` and `Read` network

```
{
  topicId: uint128,
  seed1: uint128,
  seed2: uint128,
  encKey: byte[]
}
```

(a) Topic Handle

```
Encrypt ({
  topicId: uint128,
  seqNo: uint64,
  value: byte[],
  signature: byte[],
}, encKey)
```

(b) Message Payload

Fig. 8: Schema of the topic handle and a message payload. The topic handle is a shared secret between a trusted group of publishers and subscribers, used to reconstitute a topic log from the servers. Each message payload in the topic log is encrypted with a shared encryption key.

requests on the network protocol interface (NPI). Critically, these `Write` and `Read` requests must look indistinguishable to the adversary from the cover traffic described in Section IV. In this section, we describe *topic logs*: single-writer, many-reader logs stored on Talek servers. A topic log is only ever written by its creator, but it may be read by many clients. Figure 9 contains pseudocode for the client.

A. Topic Handles and Messages

When a user creates a new topic log, Talek generates a *topic handle*, which contains a unique ID, id, encryption key, k_{enc}, and two seeds, k_{s1} and k_{s2}, as shown in Figure 8. The topic handle is a shared secret between the publisher and subscribers of a topic. All messages are encrypted with k_{enc} using a CCA-secure symmetric encryption scheme, $Enc_{k_{enc}}(message)$. We further assign all messages in a topic log a sequence number, $seqNo$. The two seed values are used in conjunction with a pseudorandom function family, $PRF(seed, seqNo) \in \{0 \ldots (b-1)\}$, to produce two log trails, unique and deterministic sequences of bucket locations for writes.

B. Scheduling Requests

When a publisher wants to publish a message, M, with sequence number $seqNo$ to a topic, the Talek client library does the following:

- On the next periodic random `Write` request, $\beta_1|\beta_2|data$, replace its parameters with the following:

$$\begin{aligned} \beta_1 &= PRF(k_{s1}, seqNo) \mod b \\ \beta_2 &= PRF(k_{s2}, seqNo) \mod b \\ data &= Enc_{k_{enc}}(M) \end{aligned}$$

Similarly, when a subscriber reads the next message in a topic at sequence number, $seqNo$, they do the following:

1) On the next periodic random `Read` request, replace it with a PIR read to the first bucket,
$$PRF(k_{s1}, seqNo) \mod b$$
2) If the returned bucket is missing the message, on the following periodic random `Read` request, replace it with a PIR read to the second bucket,
$$PRF(k_{s2}, seqNo) \mod b$$
3) Attempt to decrypt every message in the bucket using $Dec_{k_{enc}}(M)$ and return the result if found

For both `Write` and `Read`, legitimate requests must follow the same periodic schedule as when idle in Section IV. To the adversary, writes look indistinguishable from the idle case. Topic handles allow subscribers to find the latest content with coordination. Because reads are done with PIR, many subscribers can read the same log or poll the same bucket repeatedly without revealing any information.

C. Control Logs

In order to facilitate control messages between users, we automatically generate a *control log* between every pair of users that share at least one topic. We expect the topic handle for the control log to be generated and exchanged out of band when public keys are exchanged and verified. The control log is used by the Talek system to send retransmission requests, bootstrap new topic logs by exchanging new handles, and other control messages to coordinate between users.

Clients also use a control log to periodically send low-priority messages to itself. If these messages are lost, it serves as a hint to the client of a denial of service attack. A limitation of our work is that it does not give clients the ability to determine which server is misbehaving.

D. Security Analysis

We more formally prove the security of oblivious logging in Appendix A. Informally, we prove the security by reduction to cryptographic assumptions. For `Read`, we rely on the security properties offered by PIR. PIR queries that correspond to legitimate requests are indistinguishable from a PIR query for a random item [13]. For `Write`, we rely on the security properties of a PRF and our encryption algorithm. We use an IND-CCA secure encryption algorithm for message payloads. For any `Write`, the bucket locations are generated by a PRF, using either the topic handle's seed values, (k_{s1}, k_{s2}), or the idle seed, k_{idle}. In both cases, the output is indistinguishable from a random function. [34].

A malicious client still has the ability to try to deny service by deviating from the protocol and choosing a fixed bucket to DoS. Generally, a malicious client's ability to DoS is limited by the fixed `Write` rate, the number of Sybil clients, and the size of the database, n. We rely on the self-balancing nature of cuckoo hash tables, such that messages in the DoS'ed buckets will be evicted to their alternate locations.

As part of our threat model, we assume that the publisher trusts their subscribers. Topic handles can expose a publisher if shared with adversarial servers, by observing the users that write to the log trail. Even so, PIR continues to protect the privacy for any subscribers, even if topic handles are exposed to the adversary. Publishers must only use each output from $PRF(seed, seqNo)$ for any sequence number once.

```
//GlobalState
topics ← Map()                          ▷ Latest sequence numbers seen for each topic
readQueue ← Queue()
writeQueue ← Queue()

function PUBLISH(topic, message)
    Enqueue operation to writeQueue
end function

function SUBSCRIBE(topic)
    Add topic to topics
end function

function PERIODICWRITE
    if writeQueue.isEmpty() then
        Send a random write to the leader
    else
        topic, data ← writeQueue.dequeue()
        seqNo ← topics[t.id]++
        bucket1 ← PRF(t.seed1, seqNo)
        bucket2 ← PRF(t.seed2, seqNo)
        data′ ← Enc_{topic.key}(data)
        intVec ← BloomFilter()
        intVec.insert(topic.id|seqNo)
        leader.Write([bucket1, bucket2], data′, intVec)
    end if
end function

function PERIODICREAD
    if readQueue.isEmpty() then
        Send a random read to each server
    else
        topic, seqNo, seedChoice ← readQueue.dequeue()
        seed ← (seedChoice == 1)?topic.seed1 : topic.seed2
        data, query_l, query′ ← [0 . . . 0]
        query′[PRF(seed, seqNo)] ← 1                          ▷ secret
        for each server in followers do
            query ← RandomBitString(numBuckets)
            data ← data ⊕ server.Read(query)
            query_l ← query_l ⊕ query
        end for
        query_l ← query_l ⊕ query′
        data ← data ⊕ leader.Read(query_l)
        if data contains (topic, seqNo) then
            return data
        else if seedChoice == 1 then
            Enqueue a read for (topic, seqNo, 2) to readQueue
        end if
    end if
end function

function PERIODICUPDATES
    globalIntVec ← leader.GetUpdates()
    for all topic ∈ topics do
        seqNo ← topics[topic.id]
        if globalIntVec.contains(topic.id, seqNo) then
            Enqueue a read for (topic, seqNo, 1) to readQueue
        end if
    end for
end function
```

Fig. 9: Pseudocode for the Talek client library. Calls to publish and subscribe are queued in a global request queue. A periodic process either issues a random request or dequeues a legitimate operation to be translated into a privacy-preserving NPI request. Messages in a topic are are written to a deterministic random order of buckets. Subscribers then use PIR to retrieve these messages. For simplicity, we describe the protocol assuming an authenticated secure channel to each server. In practice, we use a functionally equivalent serialized version of PIR described in Section IV-D.

VI. Private Notifications

In the core protocol, users poll at regular intervals for each subscribed topic log. Polling in Talek presents two problems. Because every user is forced to poll at a fixed rate to meet our security goal, message latency gets worse as the user subscribes to more topics. Secondly users have no ability to prioritize topics with new messages.

We introduce a private notification system, which allows users to efficiently determine when new messages have been published to a topic without revealing to the server their topic list. By detaching reads from notifications, clients have the ability to prioritize reads, and reduce wasted work from reading buckets with no new messages.

A. Computing a Global Update Set

With every `Write` request, the client computes a Bloom filter, called an *interest vector*, encoding the topic ID and sequence number of the message being written,

$$v.insert(topicId|seqNo) \rightarrow [b_0 \dots b_{|v|}]$$

Using h cryptographically-secure hash functions in the Bloom filter and a large random topic ID, the adversary has no ability to learn anything from the interest vector. Because the server can expect every interest vector to contain only one element, it can also filter any malicious interest vectors where there are more ones than hash functions used, $\sum_{i=0}^{|v|} b_i > h$. If the `Write` request is a dummy request, we randomly choose h bits to set to 1, with the remaining bits set to 0.

Servers maintain a *global interest vector*, computed by taking the union of all *message interest vectors* of messages stored on the server. This data structure efficiently encodes the sequence numbers of every topic with a message in the server without revealing anything to the server. Clients periodically query for the global interest vector by calling `GetUpdates`, which allows each client to independently determine which topics have new messages.

B. Security Analysis

The security of private notifications relies on the assumptions of the cryptographic hash functions used in the Bloom filter. As long as we use a topic ID with sufficient entropy, each interest vector provides an advantage in the indistinguishability security game that is negligible in the security parameter.

As shown in Figure 9, private notifications are only used to prioritize reads on the internal request queue. As such, it has no impact on the security goals of oblivious logging. It simply reorders the schedule of private requests.

Because private notifications are a parallel mechanism to oblivious logging, servers could lie about an interest vector in a way that is inconsistent with the underlying data store. In order to detect server misbehavior, we retrieve the global interest vector from every server. Because all server must work over consistent snapshots, if any interest vector is inconsistent, we know some server is misbehaving.

VII. Implementation

To demonstrate that Talek is practical, we implemented a prototype in approximately 2,800 lines of code; the source

code is online. We implemented two versions. The first, written in Go, runs entirely on the CPU. The second offloads PIR batch reads to the GPU using a kernel written in C on OpenCL. We wrote Go language bindings to share memory between the CPU implementation and the GPU. The prototype uses SipHash [5] as the pseudorandom function, RSA for public-key encryption, and AES-GCM for symmetric encryption.

VIII. Evaluation

Our evaluation addresses the following questions:

- What is the cost per operation for clients and servers? (Section VIII-B)
- How does the system performance scale with more users? (Section VIII-C)
- How does Talek compare with previous work? (Section VIII-D)
- What is the end-to-end latency of messages for different applications? (Section VIII-E)
- How does the TTL of a message depend on application workloads? (Section VIII-F)

A. Setup

All experiments are conducted on Amazon EC2 P2 instances running in a single data center. These virtual machines are allocated 4 cores on an Intel Xeon E5–2686v4 processor and 61 GB of RAM. They also include an NVIDIA K80 GPU with 2496 cores and 12 GB of GPU memory. Virtual machines are placed in a placement group with up to 20 Gbps of aggregate network bandwidth.

We use 3 servers, each running in its own virtual machine. One is chosen as the leader and the others are followers. We evaluate the system with messages sizes of 256 bytes and 1KB. We allocated an additional two VMs to run user clients. Each user client issues periodic `Read` and `Write` requests to the server. Note that the cost of a dummy request is identical to the cost of a legitimate request from the perspective of the server. Thus, we simply vary the global client read and write rates to simulate different application workloads. We validate that retrieved data is the same as what was put on the client's test driver.

While our experiments are run in a single data center, we expect the performance to be similar for a more realistic cross-data center setting. This would incur higher network latency, both to reach the leader and in communicating between servers. However, this setup does allow us to focus on the main bottleneck, the server-side computational cost of Talek.

B. Cost of Operations

To understand Talek's costs, we benchmark different components of the system. In each of the reported values, we average the outcome of 200 runs. We vary the size of messages between 256 bytes and 1 KB, as well as the number of messages on the server, $n \in \{10K, 100K, 1M\}$. We fix the bucket depth in the blocked cuckoo table to 4, such that clients must retrieve 4 messages for every message it reads. This bucket depth allows our cuckoo table to support a load factor of over 95%. The number of buckets is then set in order to allocate enough space for all the messages at the maximum load factor for the cuckoo table. Figure 10 highlights the results.

	Messages on Server (n)		
	10K	100K	1M
Client-side CPU costs			
Generate new topic handle		7753 μs	
Publish (1 KB messages)	12.3 μs	70.5 μs	840.3 μs
PIR query	65.4 μs	574 μs	6888 μs
PIR response (256 B messages)		36.5 μs	
PIR response (1 KB messages)		146 μs	
Server-side CPU costs			
PIR Read: CPU (256 B messages)	2.01 ms	34.1 ms	271 ms
PIR Read: CPU (1 KB messages)	7.87 ms	136 ms	1126 ms
PIR Read: GPU (256 B messages)	0.20 ms	2.28 ms	15.4 ms
PIR Read: GPU (1 KB messages)	2.33 ms	6.93 ms	74.2 ms
Write (256 B messages)	21.9 μs	22.5 μs	22.6 μs
Write (1 KB messages)	22.8 μs	21.1 μs	25.0 μs
Server-side storage costs			
256 B messages	6.04 MB	60.4 MB	604 MB
1 KB messages	24.1 MB	241 MB	2.41 GB
Network costs			
GetUpdates	6.01 KB	59.9 KB	599 KB
Read request	0.96 KB	9.39 KB	93.7 KB
Read response (1 KB messages)		4.16 KB	
Write request (1 KB messages)		1.08 KB	

Fig. 10: Cost of individual operations in Talek. We vary the number of messages stored on the server, n, and message sizes (256 B and 1 KB). For values that do not depend on the number of messages on the server, we write a single value in the center column.

In general, computational costs are low due to IT-PIR. Computational costs on the client are minimal. Each write encrypts the message and uses a PRF to determine the bucket location. The cost of `Publish` rises with the database size due to the Bloom filter. The cost of generating a PIR query also increases with the database size. Larger values of n translate to more buckets and larger PIR request vectors that need to be generated for each server.

For the server, we implement two versions of IT-PIR. Our CPU implementation is primarily bottlenecked by memory bandwidth to the CPU. The GPU implementation accelerates performance by 1–2 orders of magnitude by taking advantage of the inherent parallelism of PIR operations across many GPU cores and the optimized on-device memory hierarchy. Writes incur negligible cost compared to the cost of reads. In our current implementation, we store all messages twice in memory. Writes are applied to the working copy stored in DRAM. Periodically, a snapshot of this state is copied into the GPU. Read requests are batched and forwarded to the GPU for processing. The leader is free to reorder reads without violating serializability. Reads are always applied to the latest version to reach the GPU.

Network costs between client and server are minimal. Clients must submit a read request containing a b-bit vector for each server. The size of `Read` responses and `Write` requests are within a small factor of the message size. The global interest vector returned from `GetUpdates` grows linearly

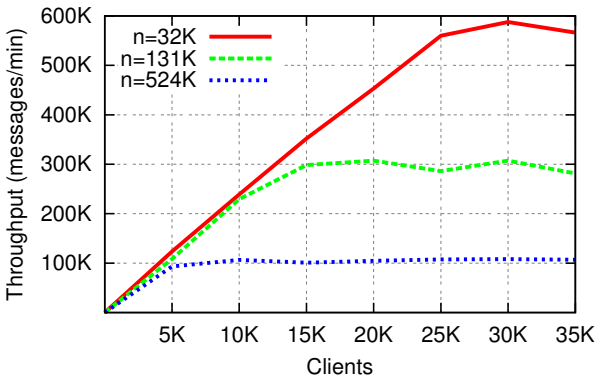

Fig. 11: Throughput of the system when varying the number of real clients. Each client issues read and write requests every 5 seconds independently. Each line represents a different value for n, the number of messages stored on the server. For larger values of n, each read requires scanning a larger table, resulting in lower throughput.

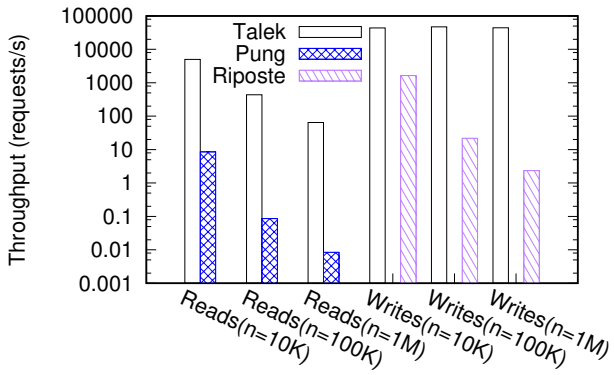

Fig. 12: Performance comparison of `Read` and `Write` handlers of various systems. Because only the code for reads was available for Pung and only the write mechanism for Riposte, we compare these respective handlers with Talek. Pung uses C-PIR, which imposes a computational cost that is 3–4 orders of magnitude higher than our IT-PIR implementation. Riposte uses a write mechanism based on a reverse variant of PIR which incurs $O(\sqrt{n})$ cost compared to Talek's $O(1)$ writes. In comparison, Talek is able to provide both higher read throughput than Pung and higher write throughput than Riposte.

with n in order to preserve a fixed false positive rate of 0.1. This cost is independent of the message size, such that its relative cost is lower for larger messages. In choosing a size for the Bloom filter, we trade off bandwidth with the false positive rate.

C. Throughput

To understand Talek's peak performance, we conducted an experiment with a simulated messaging workload. Each client sends a message every five seconds, and receives a message every five seconds. For each data point, we spawn a number of clients and measure the leader's response rate over 5 minutes, giving the system enough time to reach steady-state performance. Because writes are cheap, we rate-limit writes such that servers process equal numbers of reads and writes. This property gives readers enough time to read the message before the message is garbage collected from the server. If writes were not throttled, servers could easily accommodate a higher write throughput, while reads are bottlenecked by the PIR process on the GPU. However, this scenario would not reflect a reasonable use case, as readers would not be able to read messages before they are garbage collected.

Figure 11 shows the results for three values of $n \in \{32K, 131K, 524K\}$, the number of messages stored on the server. For small numbers of clients, the server achieves linear growth in throughput, demonstrating that the PIR operations are keeping up with read requests. The throughput is bottlenecked by the GPU's PIR process. Smaller values of n correspond to a smaller cuckoo table, resulting in cheaper PIR operations and higher throughput. We only evaluate the system with numbers of clients, m, such that $m < n$, corresponding to a message lifetime of at least one round of reads.

D. Comparison with prior work

In order to understand the relative performance between Talek with prior work, we benchmarked the `Read` and `Write` mechanisms. Figure 12 shows the relative throughput of each system.

Pung [4] is a read/write key-value based on computational PIR (C-PIR). Pung has a stronger threat model than Talek, where all servers are assumed to be untrusted. Pung's source code was not available at the time of publication and we were not able to run a direct comparison of the end-to-end system. However, Pung uses an implementation of C-PIR called XPIR [3] for reads, which we compare to our IT-PIR implementation. For 256 B messages, XPIR took $117ms$ and $11.55s$ per message for table sizes of $10K$ and $100K$ respectively. Because the memory on the test machine was exhausted at $n = 200K$, we estimate that XPIR would take $116.5s$ for $n = 1M$ by using a linear regression from measurements of $n \in \{10k, 50k, 100k, 200k\}$. XPIR imposes a computational cost that is 3–4 orders of magnitude higher than our GPU implementation. Pung uses a batching optimization to reduce costs when a client has multiple items to read. A similar optimization could be applied to Talek with similar benefits.

Riposte [15] is an anonymous broadcast system that uses PIR in reverse to anonymize writes to a database. Riposte has a weaker security goal based on anonymity within a round of communication, but does not offer privacy over multiple rounds of communication. The Riposte implementation does not include an implementation for reads. We only compare the throughput of our write handler. Riposte writes incurs $O(\sqrt{n})$ cost compared to Talek's $O(1)$ writes.

Vuvuzela [64] has a weaker security goal based on differential privacy and noise but better performance. It scales to millions of users with a peak throughput of nearly 4M messages/min using the same number of servers as Talek. Although we did not implement scaling, Talek is designed to be horizontally scalable to allow system throughput to increase by spreading buckets across servers and then combining the results. In this case, the leader and followers each consists of

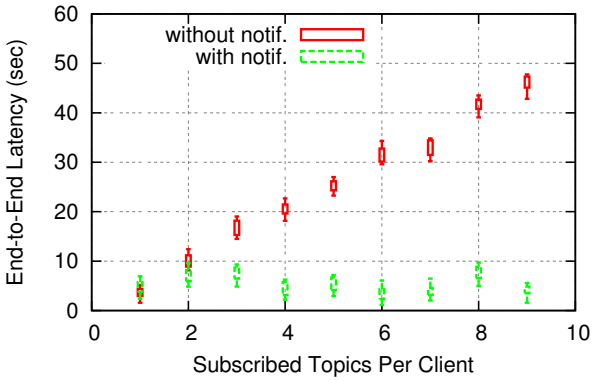

Fig. 13: End-to-end latency of message delivery when a client is subscribed to multiple topics. Each data point shows the minimum, maximum, and median out of 20 trials. Without notifications, a client must poll every topic that it is subscribed to in order to discover new messages. With notifications, clients can prioritize topics with new messages. The spread around each data point is a function of the read and write rates.

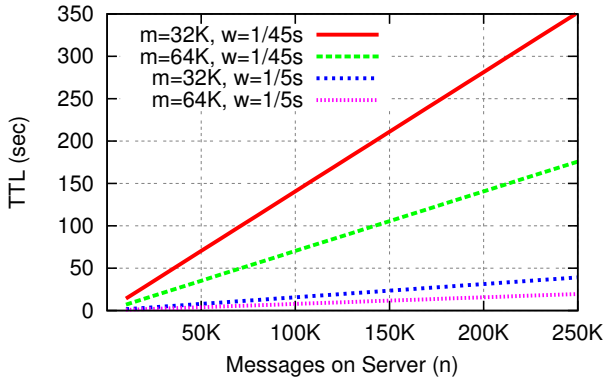

Fig. 14: The lifetime of messages on the server for different numbers of clients and write workloads. Message lifetime is directly proportional to the table size n, and inversely proportional to the number of clients and write rate. $TTL = \frac{n}{b \cdot d}$

r replicas. Writes must be replicated to every replica server; however, this would not limit performance because writes are inexpensive. Reads only require participation from one server in each replica group, which allows the system to scale for read-heavy workloads, similar to Vuvuzela.

E. End-to-End Latency with Notifications

In order to understand the latency of message delivery, we used the same messaging workload as in the throughput experiment, each user client sending and receiving messages every 5 seconds. Two additional clients are created, a sender and a receiver. We measure the end-to-end time that it takes for a message published by the sender to be seen by the receiver, varying the number of topics to which the receiver client is subscribed. Each data point highlights the spread of values, showing the minimum, maximum and median of results over 20 trials.

Figure 14 shows the results with and without private notifications. When notifications are off, the client must poll each topic in a round robin fashion until it arrives at the topic with the new message. Because the read rate is fixed, the end-to-end latency grows linearly with the number of subscribed topics. With private notifications, the receiver periodically receives a global interest vector that encodes the topic with the new message, allowing it to prioritize that read. As a result, the end-to-end latency for a single message is relatively fixed.

F. Message Lifetime

Talek is designed to support some amount of asynchrony in message delivery. Each server stores the n most recent messages or equivalently, the n/m most recent messages from each of m clients. Thus, the time-to-live (TTL) of each message depends on the write rate and the number of clients. We simulated a variety of server configurations and application workloads in Figure 14. Lower write rates improve the lifetime of messages. We would expect these types of application workloads for news feeds and other read-dominant applications. For the same number of users and TTL, lower write rates require fewer messages on the server, leading to better read performance.

IX. Related Work

PIR-based systems: Pynchon Gate [57] uses IT-PIR to allow clients to retrieve emails from any number of "distributor servers" without revealing their identity. These distributor servers update every 24-hours with a daily dump from the email server, which receives messages through a mixnet. While PIR hides the identity of which clients retrieve which messages, the email server is still aware of the communication patterns between email addresses. Talek could be used for email exchange with much lower latency and better privacy. Riffle [47] follows a similar design to Pynchon Gate, using mixnets to send messages and IT-PIR to retrieve messages. Riffle provides k-anonymity; in each round of communication the adversary learns that a message could have originated from 1 of k users. Riffle and other systems based on k-anonymity are susceptible to intersection attacks [19], [44], [50], where communication patterns can be deanonymized over time with statistical analysis of k-anonymity sets.

Ostrovsky and Shoup introduced the notion of private information storage (PIS) [53], which allows a client to write to a row to a database of n rows without revealing which row was updated. However, doing so is expensive; PIS incurred poly-logarithmic communication complexity. Riposte [15] expands on this work and applied this technique to support a scalable broadcast messaging system, but is also vulnerable to intersection attacks. Riposte writes require $O(\sqrt{n})$ messages. In contrast, by making random-looking writes to the server and relying on IT-PIR for reads, Talek write operations are cheap, $O(1)$.

DP5 [8] is an epoch-based presence system, which can be used to make users aware of their friends' online presence with strong privacy. The security of the protocol is dependent on the structure of chat presence workloads and does not generalize to

System	Security Goal	Threat Model	Technique	Application
Talek	indistinguishability	≥ 1	IT-PIR	pub/sub
Pynchon Gate [57]	k-anonymity*	≥ 1	mixnet/IT-PIR	email
Riffle [47]	k-anonymity	≥ 1	mixnet/IT-PIR	file-sharing
Riposte [15]	k-anonymity	≥ 1	IT-PIR	broadcast
Dissent [16], [17], [66]	k-anonymity	≥ 1	DC-nets	broadcast
Vuvuzela [64]	differential privacy	≥ 1	mixnet	1–1 messaging
DP5 [8]	indistinguishability	≥ 1	IT-PIR	chat presence
Popcorn [38]	indistinguishability*	≥ 1	C-PIR/IT-PIR	video streaming
Pung [4]	indistinguishability	0	C-PIR	key-value store
ORAM [59], [60], [61]	indistinguishability	0	ORAM	storage

Fig. 15: Comparison of privacy-related techniques. Security goals based on indistinguishability offer the strongest level of privacy, preventing any information leakage that would allow an adversary to distinguish between two access patterns. Prior work with indistinguishability properties are either too expensive to scale or are tailored to a single application. Systems based on k-anonymity allow the adversary to determine which of k clients a particular message originates from, opening the systems to intersection attacks [19], [44], [50] as the system is observed over long periods of time. Differential privacy only provides a formal framework to quantify information leakage and privacy bounds. The threat model column denotes the number of servers that must be honest for security properties to hold.

pub/sub. Popcorn [38] uses a combination of C-PIR and IT-PIR to construct a private read-only video streaming system over a static video database. Each of these systems leverages different sets of assumptions about application workloads to make PIR practical in their setting; in contrast, Talek provides a general-purpose mechanism to support a wide range of applications.

Pung [4] uses C-PIR to construct a key-value store with security goals based on indistinguishability, similar to Talek. Compared to Talek's threat model of at least one honest server, Pung is designed to withstand a stronger threat model, that of fully untrusted infrastructure. This threat model requires Pung use computational PIR, incurring orders of magnitude higher computational and network costs than Talek. However, Pung's client batching technique is compatible with Talek, and we plan to investigate it for future work.

Mixnet-based systems: Chaum mixnets [11], [12], [37], [41] and verifiable cryptographic shuffles [9], [30], [51] are another way to obfuscate the source of a message. Mixnets are applied to provide anonymity in a variety of applications, such as email [12], [18], [37] ISDN networks [41], voting [43], [51], data collection [9], MapReduce computations [23], social applications [11], and web proxies [29]. Mixnets are a natural fit for secure private messaging systems [63], but require messages from honest users in every round to form an anonymity set. If all other messages in a shuffle round come from the adversary, the adversary can determine the source. If a mixnet is used to access an encrypted database, unlinkability can be difficult to guarantee when the database is untrusted. Using differential privacy analysis, Vuvuzela [64] formalizes the amount of noise that honest shufflers would need to inject in order to bound information leakage at the database.

Network-level Anonymity: Onion routing [55] systems, such as Tor [22] and COR [42], are used to hide the source and destination of traffic on the Internet, such as to hide accesses to an encrypted database. While these systems perform well on the Internet today, they are designed under the assumption of a more limited local adversary. With mass surveillance, a variety of direct and indirect traffic analysis attacks are effective [28].

DC-nets: DC-nets [10], [36] are a method for anonymously broadcasting messages to a group using information-theoretic techniques. On each message transmission, all clients must broadcast random bits to every other client. Clients combine these broadcasts into a transmitted value without leaking the source of the data provided that at least one other client does not collude with the adversary. Herbivore [58] applies DC-nets to building file-sharing networks over small cliques. Dissent [16], [17], [66] extends traditional DC-nets to provide accountability mechanisms for detecting misbehaving participants. DC-nets enable effective broadcast messaging against a similar threat model to Talek, but are not a good fit for scalable pub/sub workloads because of the high network costs.

Oblivious RAM (ORAM): ORAM [33], [35], [52] is a set of protocols that allow a trusted client to access untrusted memory or storage without revealing access patterns to a strong adversary that controls all storage. Every read request requires that the client read a large portion of the database, on the order of $\Omega(\log N)$. Once a block is read, it must be re-encrypted with new randomness and moved to a new random location in the database. While recent work improve the cost of ORAM [14], [31], [45], [56], [61], [65], and offload some work onto dedicated servers [49], [59], the cryptographic security of the system depends on large reads and constant data shuffling.

X. Conclusion

In this paper, we present Talek, a general-purpose private publish-subscribe system. Talek protects both the contents and metadata of users' application usage from untrusted servers. We show that strong security goals based on *access sequence indistinguishability*, where the adversary provably learns no information about which users may be communicating, is practical with two new techniques, *oblivious logging* and *private notifications*. Our evaluations confirm that our implementation achieves 3–4 orders of magnitude better performance than previous systems with similar security goals.

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APPENDIX

We provide a security proof for Talek's protocol by reduction to the cryptographic assumptions listed in Sections II-E and IV.

A. Access Sequence Indistinguishability

Definition:

Talek consists of the following, possibly randomized, algorithms:

$Publish(\tau, \delta) \rightarrow \{\omega^0, \ldots, \omega^{l-1}\}$*:* Clients use the Publish function to generate Write requests sent to the l servers. The Publish function takes as input, a topic τ and a message δ to publish to the topic, producing a set of l Write requests, one per server.

$Poll(\tau, i) \rightarrow \{q^0, \ldots, q^{l-1}\}$*:* Clients use the Poll function to generate Read request queries sent to the servers. The Poll function takes as input a topic τ and a sequence number on the topic, producing a set of l Read requests, one per server.

$Write(\sigma, \omega) \rightarrow \sigma'$*:* Servers use the Write function to process incoming write requests. The function takes as input, a server's internal state, σ, and a write request, ω, and ouputs the updated state of the server, σ'.

$Read(\sigma, q) \rightarrow R$*:* Servers use the Read function to process incoming read requests. The function takes as input, a server's internal state, σ, and a read request, q, and outputs a function of internal state, R.

We define access sequence indistinguishability using the following security game, played between the adversary, $\mathscr{A}$, and a challenger, $\mathscr{C}$. $\mathscr{A}$ is a probabilistic, polynomial-time adaptive adversary, who is in control of the network, all but one of the servers, and an unbounded number of clients. $\mathscr{A}$ can drop any message, send arbitrary messages from any of the adversarial clients to any server, respond arbitrarily to requests, and modify any server-side state for adversarial servers. Assume the presence of authenticated secure channels between each client-server pair (e.g. with TLS).

1) $\mathscr{A}$ chooses an non-negative integer, m, and submits this number to the challenger, who spawns m clients, $\mathscr{C}_0 \ldots \mathscr{C}_{m-1}$
2) The challenger flips a coin, $b \in \{0, 1\}$, uniformly at random, which is fixed for the duration of the game.
3) For each of the challenger's clients, $\mathscr{C}_j$, $\mathscr{A}$ maintains two unique data access sequences, seq_j^0 and seq_j^1.
4) Repeat the following until $\mathscr{A}$ chooses to end the game:
   - $\mathscr{A}$ chooses the i-th operation for both sequences for all challenger clients, $\{seq_0^0[i] \ldots seq_{m-1}^0[i]\}$ and $\{seq_0^1[i], \ldots seq_{m-1}^1[i]\}$. $\mathscr{A}$ submits the operations $seq_j^0[i]$ and $seq_j^1[i]$ to the respective client, $\mathscr{C}_j$. Chosen operations can be a $Publish$, $Poll$, or $NoOp$.
   - Each client, $\mathscr{C}_j$, plays one of the two operations, $seq_j^b[i]$, into the Talek client library.
   - Adversarially controlled clients can send arbitrary requests to any server. Adversarially controlled servers can also modify its own state and respond arbitrarily.
   - $\mathscr{A}$ observes the network events, $events_j^{b'}[i]$ sent from $\mathscr{C}$'s clients to adversarial servers. These events include $Write$ and $Read$ requests.
5) $\mathscr{A}$ outputs its guess for b'.

Definition 2. *(Access Sequence Indistinguishability) We say that the system provides access sequence indistinguishability if for any polynomial-time probabilistic adversary, any challenger clients, and any data access sequences,*

$$|Pr(b = b') - 1/2| \leq negl(\lambda)$$

in the security game, where λ is a security parameter and $negl$ is a negligible function.

Practically, this definition means that an adversary would not be able to distinguish between a real user's access patterns from random access patterns of arbitrary length. It follows from this definition that the adversary should also not be

able to determine which users access the same topics, because the adversary could have chosen seq with overlapping topics across users. This security goal also prevents intersection attacks [19], [44], [50], a common problem in previous private messaging systems, where clients can be linked by observing actions over long periods of time.

Note that $\mathscr{A}$ only specifies the actions of correct users and does not specify access sequences between correct and adversarial clients. As described in Section V-D, malicious clients with a topic secret could collude with an adversarial server to de-anonymize the publisher to that topic. While this weakens $\mathscr{A}$'s power in the game, it is consistent with our goal of providing privacy guarantees to groups of trusted users. Adversarial clients can still act arbitrarily against any server.

Proof:

We consider a series of games adapted from the game above, each defined from the previous one by idealizing some part of the protocol. For game i, we write p_i for the maximum advantage, $|Pr(b = b') - 1/2|$, that $\mathscr{A}$ holds in the security game. At each step, we bound the adversary's advantage between two successive games. Technically, each of the following games consists of a series of hybrid games, where we change each of the m clients one by one.

Game 0: Consider the game defined above with an adversary $\mathscr{A}$ that chooses m challenger clients, and submits sequences with α_0 calls to $Poll$ and α_1 calls to $Write$.

Game 1: (PIR $Read$) This game is as above, except we replace the PIR request vectors, q_j, generated in $Poll$, with a bitstring $q_j \leftarrow \{0,1\}^b$ sampled at random. Let $\epsilon^{PIR}(\lambda_0, n)$ bound the advantage of an adversary breaking the PIR assumption in n calls to $Read$ with security parameter λ_0. The adversary distinguishes between the request vectors in Game 0 and the randomly sampled requests in Game 1 with advantage $\epsilon^{PIR}(\lambda_0, \alpha_0)$.

$$p_0 \leq p_1 + m \cdot \epsilon^{PIR}(\lambda_0, \alpha_0)$$

Game 2: (IND-CCA with $Write$) This game is as above, except that for each client, we maintain a table T that maps ciphertexts under key k to plaintext messages δ. $Publish$ is modified to encrypt a dummy message instead of δ and to record in T the resulting ciphertext and δ. Attempting to decrypt any ciphertext not in the table is rejected. $Poll$ is modified to retrieve plaintext from T. We can apply our IND-CCA assumption for AEAD to each key k. Let $\epsilon^{AEAD}_{IND-CCA}(\lambda_1, n)$ be the advantage of an IND-CCA adversary that performs n oracle encryptions and decryptions with security parameter λ_1.

$$p_1 \leq p_2 + m \cdot \epsilon^{AEAD}_{IND-CCA}(\lambda_1, \alpha_1)$$

Game 3: (PRF with $Write$) This game is as above, except we replace the PRF used to generate the bucket locations of $Write$s with a perfect random function. Let $\epsilon^{PRF}_{distinguish}(\lambda_2, n)$ bound the advantage of an adversary breaking our PRF assumption in n calls to PRF with a security parameter, λ_2

$$p_2 \leq p_3 + 2 \cdot m \cdot \epsilon^{PRF}_{distinguish}(\lambda_2, \alpha_1)$$

From this final game, all of the parameters in any network request have been replaced with random values. Because Game 3 involves all clients issuing periodic requests with random parameters, by definition the adversary's advantage, p_3, must be zero.

Privacy: Collecting the probabilities from all games yields:

$$\begin{aligned} p_0 \leq & m \cdot \epsilon^{PIR}(\lambda_0, \alpha_0) + \\ & m \cdot \epsilon^{AEAD}_{IND-CCA}(\lambda_1, \alpha_1) + \\ & 2 \cdot m \cdot \epsilon^{PRF}_{distinguish}(\lambda_2, \alpha_1) \end{aligned}$$

p_0 becomes negligible for large security parameters λ_0, λ_1, and λ_2.