PriFi: A Low-Latency Local-Area Anonymous Communication Network

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Abstract— Popular anonymity protocols such as Tor [15] provide low communication latency but are vulnerable to traffic-analysis attacks that can de-anonymize users. Traffic-analysis resistant protocols typically do not achieve low-latency communication (e.g., Dissent [58], Riffle [30]), or are restricted to a specific type of traffic (e.g., Herd [34], Aqua [33]).

In this paper, we present PriFi, the first practical protocol for anonymous communication in local-area networks that is provably secure against traffic-analysis attacks, has a low communication latency, and is traffic agnostic. PriFi is based on Dining Cryptographer’s networks [6], and uses a 3-layer architecture which removes the usual anonymization bottleneck seen in mix networks: packets sent by the clients follow their usual path, without any additional hop that would add latency.

As a second contribution, we propose a novel technique for protecting against equivocation attacks, in which a malicious relay de-anonymizes clients by sending them different information. In PriFi’s architecture, this is achieved without adding extra latency; in particular, clients do not need to gossip or run consensus among themselves. Finally, we describe a technique for detecting disruption (jamming) attacks by malicious clients and a blaming mechanism to enforce accountability against such attacks.

We have fully implemented PriFi and evaluated its performance with well-known datasets. Our analysis is twofold: first, we show that our architecture tolerates well client churn; second, we show that the system can be used in practice with minimal latency overhead (e.g., 70ms for 50 clients), and is compatible with delay-sensitive application such as VoIP.

I. INTRODUCTION

Many organizations such as companies and universities use local area networks (LANs or WLANs) to provide Internet access to their members. Unfortunately, eavesdropping on those networks is particularly easy: due to the broadcast nature of WLANs (and depending on the LAN architecture), curious members such as rogue employees, IT administrators, and malware can all see and record other users’ data. Encryption only partially solves the problem, as today’s solutions such as TLS often leak the source and destination of the communication. Moreover, many traffic-analysis attacks have successfully inferred parts of encrypted content on Internet traffic [22, 3], VoIP traffic [5], and arbitrary traffic [27]. Along with the knowledge of the sender/recipient, such attacks can be used to track individual user activities.

A scenario in which this is of particular concern is humanitarian organizations. Information exchanged on their networks can be very sensitive, and the identity of the communicating people can be of vital importance (e.g., in totalitarian regimes or conflict areas). For the most critical information, some organizations actually do not use electronic communication, but send members in person. For information that cannot justify this method, members of the organization essentially accept the risks and use emails. Within large organizations, the risk of having one malicious endpoint or rogue user is certainly non-negligible.

For security- and privacy-conscious users, few good solutions exist. Using an external VPN service hides the traffic on the network up to the VPN exit but requires to trust the VPN provider, which often is not more trustworthy than the original organization. The most popular anonymous communication network, Tor [15], can be used both as an encrypted tunnel to exit the organization network and as a way to protect the sender/receiver identity. Yet, both aforementioned solutions are not designed to protect users against traffic-analysis attacks [43, 26]. In practice, they raise the cost of such attacks but do not offer strong protection.

Anonymous communication techniques could in principle help harden WLANs against traffic-analysis attacks by making many users’ and devices’ network traffic indistinguishable. Current anonymity mechanisms, however, suffer from a tension between communication latency and traffic-analysis resistance: known techniques either focus on low latency and bandwidth costs while remaining vulnerable to traffic analysis [15, 16], or provide traffic-analysis resistance at the expense of high latency [19, 58].

In this paper, we present PriFi, a low-latency anonymous communication protocol for local-area networks with provable anonymity and resistance against traffic-analysis attacks. PriFi’s anonymity sets are organized around LANs and WLANs (abbreviated (W)LANs afterwards), e.g., a organization/company/university network. Users connected to PriFi are assured their communication is anonymous and indistinguishable from the traffic of other users and devices on the (W)LAN. PriFi uses the Dining Cryptographer’s Network (DC-net) protocol [6] as a strong anonymization primitive.

PriFi is traffic-agnostic (i.e., it is suitable for all-purpose communications), similar to a VPN service but with strong privacy and tracking resistance. Users can make use of the Internet transparently; in particular, PriFi’s low-latency communication allow users to communicate via voice and video calls (e.g., VoIP), or use latency-sensitive applications (e.g., streaming) on top of PriFi.

The PriFi ecosystem consists of a set of clients who wish to anonymously make use of the Internet with the help of
an untrusted relay, and a set of servers, all but one of which are untrusted. The clients anonymize their traffic with cryptographic material that they share with every server and send the traffic to the relay, who acts as a middleman between the clients and the servers. The relay aggregates the ciphertext messages to produce an anonymous cleartext message which is then sent to the Internet. Upon receiving a response from the Internet, the relay broadcasts it to all clients, achieving both sender and receiver anonymity.

The three-layer architecture (i.e., client/relay/server) of PriFi forms a communication tree that eliminates the need for costly client-to-server communication. In fact, this architecture removes an important latency bottleneck usually seen in mix-nets [7], where the data sent by the clients goes through several servers. Such servers often have a high latency (e.g., 100ms) to the clients; in that case, the servers latency is directly added to the overall latency experienced by the clients. In PriFi, the client’s data packets remain on the network path they would have taken without PriFi, with no extra hop, and in particular do not go through the servers. As a result, even if the servers are geographically dispersed around the world, their existence adds security but not latency, because they only “stream” ciphertexts to the relay from outside the latency-critical path. This design dramatically reduces the latency experienced by the clients. Additionally, our architecture leverages on the broadcast nature of WLANs to ensure receiver anonymity with no additional cost.

PriFi’s low-latency design introduces two important security challenges. First, the relay is responsible for all downstream data; a malicious relay can try to deanonymize clients through equivocation, i.e., by sending different response messages to different clients and analyze their subsequent behavior. Moreover, malicious clients may attempt to perform disruption attacks (i.e., jamming) on the virtual anonymous channel provided by PriFi, causing a denial of service. PriFi employs novel solutions to both challenges without introducing extra latency to the communication.

Contributions. The main contributions of this paper are:

- a low-latency architecture for traffic-analysis-resistant anonymous communication in local-area networks,
- a technique for protecting against disruption attacks by malicious clients,
- a technique for protecting against equivocation attacks by a malicious relay,
- an analysis of the impact of churn on DC-net-based systems;
- an open-source, tested and maintainable implementation of PriFi,
- an evaluation of our implementation with realistic datasets.

Paper Organization. In Section II, we present the related work, and briefly introduce DC-nets [6] and their challenges as an anonymization primitive. In Section III, we define the threat model and introduce PriFi. Then, we present the basic version of the protocol in Section IV We describe the protocols for preventing disruption attacks and equivocation in Sections V and VI. Section VII is a discussion of practicality challenges for PriFi (e.g., client churn and scalability to large networks). Section VIII describes our implementation of PriFi and experimental results, including the impact of churn on DC-nets. Finally, we conclude and state our open problems in Section IX.

II. BACKGROUND AND RELATED WORK

A. Practical Anonymity

VPNs are a popular way to achieve anonymity in the Internet; due to their low latency, they can support most network protocols. While convenient, VPNs offer limited anonymity protection, e.g., the VPN provider could be coerced or compromised, or a global adversary could break a user’s anonymity using traffic analysis techniques. As a result, a significant number of solutions have been proposed to provide stronger anonymity guarantees [48].

For stronger traffic-analysis protection without a single point of failure, several efforts rely on mix-networks techniques [7] [13, 44, 55]. However, they provide small anonymity sets, as they are generally less convenient due to their high latency. Moreover, they are vulnerable to several attacks that break their anonymity guarantees [41, 40]. Solutions based on onion routing [15, 8, 37] tend to be more popular due to their low latency overheads. Tor [13], the most widely deployed anonymous routing protocol, reports anonymity sets in the order of millions of users. However, Tor, and similar protocols, are not resistant to traffic analysis attacks and global adversaries [28, 29]. Thus, we can assume that Tor offers a large but weak anonymity set. In addition, there are solutions that provide strong anonymity guarantees and high scalability by using additional techniques such as differential privacy [55], private information retrieval [30, 11] and secure multi-party computation [11, 31]. However, these solutions are designed for particular applications such as file sharing [33, 19], VoIP [34] and messaging/microblogging [11, 50, 55, 32, 31]. Hence, they are not as convenient for the users as a VPN or Tor, which arguably hinders both adoption and the strength of the provided anonymity.

Another technique is Dining Cryptographer’s networks (DC-nets) [5] that provides anonymous communication with provable traffic-analysis resistance. Aside the original design, DC-nets have been re-used in several anonymous communication networks [9, 58, 10], and have been extensively studied [20, 54, 21, 18, 17, 28]. However, DC-nets have high-latency and communication overheads and scale poorly. Dissent protocols [9, 58] address these limitations, but for group-communication scenarios (mesh network).

PriFi builds on the ideas of Dissent to provide traffic-analysis resistance and low-latency to VPN-like scenarios, by relying on the notions of local-area anonymity and wireless networks. Moreover, PriFi offers a novel solutions to well-known DC-nets’ challenges: disruption protection and churn handling.
B. DC-nets Challenges

**Disruption Protection.** DC-nets are known to be vulnerable to disruption attacks (i.e., jamming) from malicious insiders, because their encrypted messages are malleable and an adversary on the network can flip bits in other client’s plaintexts. Different solutions have been proposed: both Dissent [9] and Verdict [10] have proactively verifiable constructions that prove the correctness of the ciphers, while Dissent in Numbers [58] describe a blame mechanism to retroactively find and exclude a disruptor. These disruption protection mechanisms, however, have significant performance costs: the blame mechanism in Dissent in Numbers require minutes to hours to find a disruptor, and the verifiable DC-net used in Verdict [10] is computationally intensive and hence does not allow frequent communication rounds.

**Churn Handling.** DC-nets have a particular relationship with churn, i.e., clients joining or leaving the network. Unlike other anonymity networks, the disconnection of any client invalidates the current communication and forces re-transmission of the data. This is due to the design of the protocol: in the phase of recovering a message \( m \) using ciphertexts from all the nodes, a single missing ciphertext prevents the recovery of \( m \). This is a fundamental limitation of DC-nets that cannot be easily removed. Dissent in Numbers [58] propose a solution to eliminate the cost of churn when a client disconnects, however, it requires coordination among a set of servers, which can be costly if the servers are in different jurisdictions (i.e., PriFi' scenario). Also, such solution does not address the costs of clients joining the network.

**Schedule.** A DC-net creates an anonymous channel shared between its clients. If many clients try to transmit at the same time, collisions will occur. As retransmissions are usually costly, previous works [9] [58] [10] use some form of scheduling to prevent honest clients from communicating at the same time. Dissent [9] relies on an internal-shuffle mechanism that divides the client ciphers into slots. Dissent in Numbers and Verdict [58] [10] use a Neff-Shuffle [39] to organize clients into time slots.

**Impact of topology.** The initial DC-net design [6] requires a shared secret between every pair of members, which can be seen as a flat topology (only made of clients). Dissent in Numbers [58] and subsequent work [10] have a more scalable two-tier topology made of clients and servers, where each client \( i \) only exchanges a secret with each server \( j \) but not with other clients. This architecture has several benefits (e.g., reducing the total number of keys), yet has a major negative impact on latency: it requires several server-to-server rounds of communication to handle client churn, maintain integrity of messages, and ensure accountability of participants.

III. System Overview

In this section we present PriFi’s design goals and assumptions, general architecture and threat model.

**Goals.** PriFi’s five main design goals are:

| (G1) Anonymity: | an adversary should not be able to guess users’ identities or attribute an honest user’s message to its author with a probability significantly better than random guessing. If all but one user colludes, no anonymity is possible. |
| (G2) Traffic-analysis resistance: | PriFi should not leak information that could help an adversary to break the anonymity of honest users. |
| (G3) Low latency: | the delay introduced by PriFi should be small enough to support network applications with different quality of service (QoS) requirements, e.g., e-mail, instant messaging, web browsing, VoIP and videoconferencing. |
| (G4) Accountability: | misbehaviors, including denial of service (DoS) attacks, by any party should be traceable without affecting the anonymity of honest users. |
| (G5) Scalability: | PriFi should be able to support small to large (i.e., hundreds to thousands of users) and geographically distributed organizations. |

**System Model.** Consider a set of \( n \) clients (or users), who want to anonymously make use of the Internet. The clients are connected to the Internet through a local-area network, where they connect to a relay (e.g., a router) that can process normal traffic in addition to running our protocol (see Figure 1). Outside the local-area network, there is a set of \( m \) servers whose role is to assist the relay in the anonymization process. These servers might be distributed around the world, preferably across different jurisdictions, to maximize diversity and collective trustworthiness. Therefore, the connections between the servers and the relay are high-latency. We define as HIGH_LAT the latency between the servers and the relay, and LOW_LAT the latency inside the (W)LAN. Moreover, we define downstream communication as the data from the Internet to one of the clients, and upstream communication as the data from one of the clients towards the Internet.

**Threat Model.** We say a node (client, server or relay) is honest...
if it follows our protocol faithfully and does not collude or leak sensitive information to any other node. A node controlled by the adversary is malicious (or dishonest); malicious nodes can deviate arbitrarily from the protocol and can collude with each other to de-anonymize honest clients and disrupt the communication.

In our model, the relay can be malicious, i.e., it might actively try to de-anonymize honest users. However, the relay is considered trusted for availability. That is, the relay will not perform actions that affect the availability of PriFi communications such as delaying, corrupting or deleting clients’ messages. In our scenario, the relay is the gateway to Internet (e.g., a WLAN router), and could perform those availability attacks on any traffic anyway (e.g., simply drop all packets); PriFi does not make the situation any different. Moreover, such attacks can be easily detected by clients and cause them to report the relay and/or to switch to a more reliable relay.

Clients can be malicious, but our model requires at least two honest clients (otherwise, de-anonymization is trivial). Unlike the relay, malicious clients can conduct disruption attacks in which they jam the communication channel by sending invalid messages in every round of the protocol. While such an attack does not compromise honest clients’ anonymity, they can cause indefinite communication blackouts.

The servers follow the anytrust model \([58]\): at least one server is honest, and they are all highly available. This means that clients are not required to know or choose which server to trust. Malicious servers can try to de-anonymize honest clients or perform disruption attacks.

We assume that the servers and the relay are protected against external DoS attacks through well-known defense mechanisms such as server provisioning or proofs-of-work. Such attacks are common to any distributed system and therefore not addressed in PriFi. In addition, we assume that all nodes communicate using non-private but authenticated channels; the adversary can observe all such messages when in transit. End-to-end content privacy can be achieved via orthogonal, well-understood content encryption mechanisms such as TLS. Moreover, assume that asymmetric and symmetric key encryption algorithms, key-exchange schemes, signature schemes, and hash functions are all correctly implemented and configured. Finally, we assume that there is a public-key infrastructure (PKI) already in place.

Usage. From the point of view of a client who is using the organization’s PriFi network to communicate with other members or the Internet, PriFi is similar to a low-latency VPN service: it receives data from and sends data to the applications running on the user’s computer. The relay acts as the other end of the VPN, relaying data between the Internet and the clients. However, unlike traditional VPN services, the relay is not trusted; it might maliciously (possibly by colluding with other untrusted entities) attempt to de-anonymize the clients.

Servers. To anonymize traffic, PriFi uses servers to reduce the amount of computation, communication and storage needed by each client. In DC-nets, these amounts depend on the number of other nodes with which each client shares a secret. In practice, we expect the number of servers to be much smaller (e.g., 5) than the number of clients (e.g., 100), so each client needs to share secrets with only a small group of nodes. Additionally, those servers are used to organize the clients in an ordered schedule needed for communication (see Section \([IV]\)). Finally, the servers participate in the protocol protecting against internal disruptions (see Section \([V]\)).

Critical latency path. The main technical contribution of PriFi is a new DC-net protocol redesigned so that these remote servers, while adding to the security of all PriFi clients, do not add to their communication latency. End-to-end latency of connections between users and local or remote sites they are accessing is dominated purely by “single-hop” communication via the PriFi relay. Even if the servers are geographically dispersed around the world, their existence adds security but not latency, because they only “stream” ciphertexts to the relay from outside the latency-critical path.

IV. Basic PriFi Protocol

In this section, we present the general concepts used in the PriFi protocol, its operational details and an optimization to reduce the latency overhead introduced by the servers. In subsequent sections, we explain how to extend the basic PriFi protocol to deal with disruption (Section \([V]\)) and equivocation (Sections \([VI]\)) attacks.

A. General Concepts

The protocol is executed jointly by the clients, servers, and the relay to anonymize messages sent by the clients to the Internet. The protocol proceeds in time slots such that only one client – the slot owner – is allowed to send an \(\ell\)-bit anonymous message to the Internet in each time slot. A schedule consists of \(n\) ordered time slots, each corresponding to one of the clients; each client has the opportunity to send an \(\ell\)-bit message exactly once during a schedule. An epoch is the timespan where the configuration (i.e., share secrets and schedule) does not change. At the beginning of each epoch, a new schedule is established. Epochs expire after a predetermined period of time (e.g., 10 minutes) to prevent clients from using the same slot for an extended period, thus reducing the chances of adversary linking upstream messages to a particular slot. Epochs can also expire due to network churn, e.g., clients connecting or disconnecting from the system. Figure \([2]\) illustrate these concepts.

PriFi uses DC-net-based anonymization only for the upstream traffic. To anonymize the downstream traffic, the relay encrypts each downstream message with the ephemeral public key of the receiver (generated during the Set-up phase described next). The relay then broadcasts the encrypted downstream message to all clients. Thus, only the intended client will be able to decrypt the downstream message without compromising its anonymity.
Fig. 2. Illustration of time slots, schedules and epochs for \( n = 3 \) clients \( A, B, C \). The labels show the slot owners.

Finally, PriFi is closed-membership system. Before the protocol starts, we assume that each client and each server holds a public/private key pair, and that the relay holds a roster of all the public keys. This enables the relay to verify the membership of the clients. To defend against intersection attacks, anonymous credentials can be used to prove membership (Section VII).

B. Protocol Phases

The PriFi protocol consists of four main phases:

Set-up Phase. In this phase, the relay first authenticates all clients using their public keys. Then, each client \( c_i \) runs a key exchange protocol with each server \( s_j \) to agree on a shared secret \( r_{ij} \), which is only known to both of them. This secret is later used to seed a pseudorandom generator (PRG) to obtain a stream of pseudorandom bits, the pads, from which the clients and the servers will compute their ciphertexts. Using this approach, clients and servers do not need to generate a shared secret for every slot. Figure 3 illustrates the relationship between shared secrets, pads and ciphertexts for a client \( i \).

Schedule Phase. After setup, all nodes (clients, servers and the relay) jointly perform a Schedule phase to assign one client to one slot. Note that this binding must remain secret, otherwise there would be no anonymity. Our protocol outputs a schedule where each client can recognize its own slot, but no the slot of other clients.

First, each client generates an ephemeral public/private key pair. Second, the relay collects all the clients’ ephemeral public keys as a sequence \( N \). Third, all the servers sequentially shuffle \( N \) using a verifiable shuffle protocol \( [9] \), each one sending its result and proof to the next server via the relay. Finally, after the last server finishes running its verifiable shuffle protocol, the relay holds a random permutation \( \pi \) consisting of fresh pseudonyms for the public keys in \( N \); \( \pi \) represents the schedule, as it indicates when clients can send upstream data, i.e., their slot. A client can recognize its own pseudonym by using its ephemeral private key, but other parties cannot link the ephemeral public key to the fresh pseudonym.

Anonymize Phase. After the Schedule phase, all nodes continuously run the Anonymize protocol (see Protocol 1). This protocol occurs in rounds; one round (or instance) of the Anonymize protocol corresponds to one slot in the schedule.

In each round, all servers compute one ciphertext and send it to the relay. Each server ciphertext is an XOR of \( n \) pseudo-random \( \ell \)-bits pads generated using a PRG seeded with the shared secret \( r_{ij} \) of each client. Likewise, each client computes an \( \ell \)-bits ciphertext, computed as the XOR of \( m \) pads, and sends it to the relay. The client owning the slot creates a slightly different ciphertext: in addition to XORing the \( m \) pads, the slot owner also XORs its \( \ell \)-bits upstream message \( x \). In practice, \( x \) is an IP packet with obfuscated source address. If the slot owner has nothing to transmit, it sets \( x = 0^\ell \).

Once the relay receives the \( m+n \) ciphertexts from all clients and servers, it XORs them together to obtain \( y \). If the protocol is executed correctly, \( y \) should be equal to \( x \), as all pads are included exactly twice. If \( y \) is a full (and valid) IP packet, the relay forwards it to its Internet destination (with the relay’s IP address as the source address, i.e., the relay act as a proxy). If it is a partial packet, the relay buffers it, and completes it in the next schedule.

At this point, the relay has computed exactly one upstream message \( y \), and possibly sent it to its Internet destination. To complete the current round of Anonymize, the relay broadcasts one downstream message \( z \) to all clients. The content of \( z \) is whatever data the relay needs to send to the client: either an immediate answer to \( y \), or an answer to a previous upstream message \( y' \). Notice that \( z \) is of arbitrary length, thus easily supporting downstream-intensive scenarios.

In short, a round of Anonymize consists of exactly one exchange among all clients and the relay (\( n \) client ciphertexts upstream, yielding 1 upstream message \( y \), and 1 downstream message \( z \)). Hence, clients are in lockstep, and remain synchronized with the relay.

Resynchronization Phase. In the case of churn, e.g., if any client or server disconnects, or a new client requests to join the PriFi network, the relay broadcasts a Set-up request to all nodes. Upon reception, each node finishes the current Anonymize round, and re-runs both the Set-up and Schedule phases. Hence, a resynchronization signals the start of a new epoch. Network churn can significantly affect performance, a well-known problem for DC-nets-based protocols. We propose some optimizations to address this concern (Section VII).

C. Servers Optimization

Servers should be located in various jurisdictions to reduce the risk of coercion by authorities; this implies large latencies.

\(^2\)One notable exception: if the round was disrupted, discussed in Section VII.
Protocol 1 Anonymize phase for a given round $t$

**Notations:** Let $C_1, ..., C_n$ denote the clients, $R$ denotes the relay, $S_1, ..., S_m$ denote the servers, and $\ell$ denotes the bit-length of ciphertexts sent by clients and servers to the relay in each time slot.

1. **Server Ciphertext Generation.** Each server $S_j$ computes an $\ell$-bit pseudorandom pad $p_{ij}$ for each client $C_i$ using a PRG seeded with $r_{ij}$. The server then computes its ciphertext $s_j$ from
   $$s_j \leftarrow p_{ij} \oplus ... \oplus p_{im}$$
   and sends it to $R$.

2. **Client Ciphertext Generation.** Each client $C_i$ performs the following steps:
   a. Generate an $\ell$-bit pseudorandom pad $p_{ij}$ for each server $S_j$ using a PRG seeded with $r_{ij}$
   b. Let $\pi$ denote the permutation generated by the Schedule phase, and $x_i$ denote $C_i$’s next $\ell$ bits of data. Compute and send a ciphertext $c_i$ to $R$ such that
      - if $t \mod n = \pi(i)$ (i.e., $c_i$ is the slot owner), then $$c_i \leftarrow x_i \oplus p_{i1} \oplus ... \oplus p_{im}$$
      - Otherwise, $$c_i \leftarrow p_{i1} \oplus ... \oplus p_{im}$$

3. **Plaintext Reveal.** $R$ collects the ciphertexts $s_1, ..., s_m$ from the servers and $c_1, ..., c_n$ from the clients and computes
   $$y \leftarrow s_1 \oplus ... \oplus s_m \oplus c_1 \oplus ... \oplus c_n$$
   $R$ sends $y$ to the Internet.

4. **Message Broadcast.** $R$ broadcast a downstream message $z$ to each $C_i$. If $R$ has no data for any client, $z$ is a 1-bit message.

V. DISRUPTION PROTECTION

A well-known weakness of DC-nets is that a single malicious member can anonymously jam communications, either completely or selectively. In this section, we describe how PriFi deals with such a threat.

A. Background

In PriFi, a malicious client or server can transmit arbitrary bits – instead of just the XORed ciphertext defined by the protocol – to corrupt the upstream messages of other clients without leaving a trace. Affected client(s) can detect such an attack and switch to a different relay. However, a moderately powerful adversary could feasibly infiltrate groups at a large portion of relays in a given region. Hence, the affected client(s) might be forced to use a weaker communication channel. Previous DC-net-based protocols include protection mechanisms against such attacks (see Section II), however such mechanisms are inefficient (e.g., minutes to hours to find a disruptor) and are not compatible with PriFi’s topology. Hence, we designed a new disruption-protection mechanism for PriFi.

B. Protocol Overview

PriFi’s disruption-protection protocol relies on three steps:

**Attack detection.** During the Schedule phase (see Section IV), the relay establishes a shared secret, $r_{iR}$, with each client. For instance, the relay can generate a unique share secret per client and encrypt it with the corresponding client’s public key (i.e., the pseudonym used in the schedule). The server broadcasts the encrypted shared secrets and the clients decrypt them with their corresponding private keys. The client owning the current slot uses this shared secret to compute the HMAC of the upstream message, $HMAC(r_{iR}, x)$. Next, the client sends the upstream message and its HMAC to the relay. The relay validates the HMAC to find evidence of a disruption attack. If the validation fails, the relay indicates, via the downstream message, that a disruption has been detected and that, in the same slot of the next schedule, a verifiable DC-net [10] should be used to prevent further message corruption (for performance reasons, the relay could wait for a few schedules before requesting the use of a verifiable DC-net). Note that, by letting the relay detect disruption attacks, we remove the work and responsibility from clients. This is possible because the relay is trusted for availability (see Section III, i.e., the relay will not perform attacks or collude with other parties to reduce availability.

**Finding flipped bits.** Only one flipped bit is needed to identify and exclude the malicious client or server. More precisely, the relay needs to find a bit that was 0 in the original message but got flipped to 1 (using a bit that was 1 and got flipped to 0 leaks information about the slot owner). For this purpose, the affected client will resend the original upstream message in her next slot, but using a verifiable DC-net (to prevent further disruption). Next, the relay compares the original and corrupted upstream messages to find the position $p$ of a
flipped 0-bit. Once such a bit is found, the relay will stop
the communications (i.e., the Anonymize protocol) and send a
signed request to all clients and servers to reveal the individual
bits from their different pseudorandom pads at position $p$ for
the disrupted round; clients will reveal one bit per server and
servers will reveal one bit per client. If no flipped 0-bit is
found, the relay stops the disruption protection protocol and
communications are not interrupted, i.e., the attack is detected,
but the disruptor cannot be traced without breaking anonymity
guarantees. To reduce the chances of a disruptor flipping only
1-bits (e.g., the adversary could guess parts of the content
in the upstream message), the client can XOR the upstream
message with the shared secret $r_{IR}$. Therefore, the adversary
will have only 1/2 chance of flipping a 1-bit.

Finding the disruptor. Once the relay receives all the bit-
revealing messages, it proceeds to check if a client or server
revealed values that do not match with the value sent in the
bit position $p$ during the disrupted round. If the values do not
match, the corresponding client or server is the disruptor and
is excluded from the system. If no mismatch is found, then
the relay proceeds to compare the bits revealed by the clients
with the bits revealed by the servers. There must be, without
loss of generality, a difference among one of the bits that one
of the clients and an one of the servers revealed (otherwise,
the round was not disrupted). After identifying a mismatch
between a client and server, the relay requests that they reveal
their shared secret $r_{ij}$, along with a zero-knowledge proof
showing that it was computed correctly. The relay verifies the
proofs and seeds the PRNG with the secrets to generate the
pad for the disrupted round. At this point, the relay will be
able to determine which one, the client or the server, disrupted
the round and exclude it from the system. Revealing the shared
secrets does not compromise anonymity, as it never happens
between two honest parties.

VI. Equivocation Protection

PriFi’s architecture introduces an important challenge: an
untrusted relay can equivocate by sending different down-
stream messages to different clients to de-anonymize them.
For example, in an unencrypted communication (e.g., a DNS
request), the relay can slightly modify the downstream mes-
gage for each client. These unique messages might affect the
messages sent in subsequent rounds (e.g., the contacted IP
in the case of a DNS request), so the relay might be able to
determine which client sent the request, based on their
subsequent behavior. By default, PriFi uses a round-robin
schedule in a given epoch; thus, de-anonymizing one slot de-
anonyms a slot owner for the whole epoch, as the schedule
does not change within one epoch.

Equivocation example. Client $C_1$ and $C_2$, both honest, are
connected to a malicious relay, and they collectively run the
PriFi protocol. On the first round, the relay decodes a
DNS request for a given domain. As the request was sent
through PriFi, it is anonymous, and the relay does not know
whether $C_1$ or $C_2$ sent it. However, the relay can, instead
of broadcasting the same DNS answer to $C_1$ and $C_2$, send
two different answers to $C_1$ and $C_2$, containing IP$_1$ and IP$_2$,
respectively. Later on, the relay decodes a request to IP$_2$
and it can guess that $C_2$ made the request (along with the original
DNS request), as it is unlikely that $C_1$ has knowledge of IP$_2$.

A. Protocol Overview

PriFi protects against relay equivocation attacks without
adding extra latency. This is achieved by encrypting clients’
upstream messages in such a way that the resulting ciphertexts
depend on the history of downstream messages in a epoch. As
a result, the relay can only decrypt an upstream message if all
clients agree on the downstream messages they have received
in the current epoch. If the clients disagree, the relay will not
be able to decrypt the upstream message from the current and
future rounds. In such case, the relay is required to issue a
special command to reset the history of all clients and restore
the communications. Such a command should be issued rarely
and, clients should be suspicious of it. Hence, the relay has
no incentive to try an equivocation attack, which would be
detected by clients and would affect the availability of the
service.

The protocol works as follows. In each round, the slot owner
encrypts its upstream message with a fresh random key and
includes a blinded version of this key in its upstream message.
The key is blinded with a value computed by raising the
downstream history value to a secret exponent derived from the
client’s pads. The downstream history consists of the crypto-
graphic hash of the previous downstream history concatenated
with the most recent downstream message, hence, it depends
on all past downstream messages. Moreover, the downstream
history is “bound” to the client’s pads via exponentiation in
a cyclic group, where the Discrete Logarithm Problem
(DLP) and the Decisional Diffie-Hellman assumption (DDH)
hold. Other clients also send contributions and, if all clients
have similar downstream history, the relay will be able to
unblind the key and decrypt the upstream message. When
new clients join the system, the relay provides them with
the current downstream history value during the setup phase.
The downstream history can only be reset by the relay via a
reset-history command broadcasted to all clients; thus, the
downstream history is kept across epochs.

B. Protocol Description

Protocols 2, 3 and 4 are run by each node as part of the
Anonymize phase (see Protocol 1 in Section IV) for
equivocation protection.

Let $F_q$ denote a finite field of prime order $q$, $G$ denote
a multiplicative group of order $q$ with generator $g$ such that
the DLP and the DDH assumptions hold in $G$. Also, let $M_i$
denote the message that client $i$ wants to send to the relay. Let
$H : \{0, 1\}^* \rightarrow \{0, 1\}^\ell$ be a cryptographic hash function, and
$F_1 : \{0, 1\}^\ell \rightarrow G$ and $F_2 : \{0, 1\}^\ell \rightarrow F_q$ be publicly-known
one-to-one functions that are efficiently computable and in-
vertible.
Protocols

**Protocol 1** Equivocation Protection – Client

Consider $m$ servers, $n$ clients and a client $C_i$ with a plaintext $x_i$ and an empty downstream history $h_i$.

1. Upon receiving a downstream message $d_i$ from the relay, $C_i$ sets $h_i \leftarrow H(h_i|d_i)$.
2. If $C_i$ is the slot owner, it picks a pseudorandom key $k_i \in_R \{0,1\}^n$, sets $x'_i \leftarrow x_i \oplus k_i$ and sends $(k_i, c_i)$ to the relay, where
   \[
   k_i \leftarrow F_1(k_i) \cdot F_1(h_i) \sum_{j=1}^m F_2(H(p_{ij})), \quad (1)
   \]
   \[
   c_i \leftarrow x'_i \oplus p_{i1} \oplus \ldots \oplus p_{im}.
   \]
3. If $C_i$ is not the slot owner, then it sets
   \[
   k_i \leftarrow F_1(h_i) \sum_{j=1}^m F_2(H(p_{ij})), \quad (2)
   \]
   \[
   c_i \leftarrow p_{i1} \oplus \ldots \oplus p_{im},
   \]
   and sends $(k_i, c_i)$ to the relay.

In Protocol 2 the client encrypts $x_i$ (i.e., the upstream message) as $x'_i$, and blinds $k_i$ with its downstream history. The blinding also uses the hash of the pads (unknown to the relay), so the relay is unable to unblind the key without the contribution (and agreement) of all clients. In Protocol 3, the server sends an additional value $\sigma_j$ to the relay, used to unblind $k_i$. In Protocol 4 the relay unblinds the key and decrypts the upstream message. The correctness of these protocols is shown in Appendix A.

**Protocol 2** Equivocation Protection – Client

Each server $S_j$ sends $(\sigma_j, s_j)$ to the relay, where
\[
\sigma_j \leftarrow - \sum_{i=1}^n F_2(H(p_{ij})), \quad (3)
\]
\[
s_j \leftarrow p_{ij} \oplus \ldots \oplus p_{nj}.
\]

**Protocol 3** Equivocation Protection – Server

The relay starts with an empty downstream history denoted by $h$.

1. Upon receiving a downstream message $d$ for the clients, the relay sets $h \leftarrow H(h|d)$.
2. Upon receiving $(k_i, c_i)$’s from all clients and $s_j$’s from all servers, the relay decrypts the owner’s message from:
   \[
   k \leftarrow F_1(h) \sum_{j=1}^m s_j \prod_{i=1}^n k_i \quad (4)
   \]
   \[
   y' \leftarrow c_1 \oplus \ldots \oplus c_m \oplus s_1 \oplus \ldots \oplus s_m
   \]
   \[
y \leftarrow y' \oplus F_1^{-1}(k).
   \]
3. The relay sends $y$ to the corresponding Internet address.

C. Discussion

**Malicious behavior.** A malicious client or relay might try to falsely accuse the other. For example, to frame the relay, a malicious client might pretend to have received a downstream message different from other clients. Also, a malicious relay might pretend that an honest client is sending wrongly-computed $k_i$ to cause a DoS. These problems can be solved by simply requiring that both clients and servers sign every message they send. When a problem occurs, honest nodes are protected from incorrect blaming, assuming that no party can forge signatures.

A malicious client or server might also send a wrongly computed $k_i$ to cause an anonymous DoS. Note that signing messages cannot prevent such an attack because the relay is unable to validate the correctness of the $k_i$ values. To detect this attack and trace the disruptor, the relay can proceed as follows. First, we assume that the blinding key has a recognizable structure, e.g., a header. When the relay runs the protocol it will detect the DoS attack by checking the structure of the blinding key $k$ obtained. If the blinding key’s structure is incorrect, the relay determines that an attack is in place and follows a procedure similar to the disruption protection protocol (Section V). That is, the relay stops the communications and sends a signed request to all clients and servers asking them to reveal the hash of the pads $H(p_{ij})$ used to compute their current $k_i$ values. If there is a mismatch between a $k_i$ and the $H(p_{ij})$ values sent by a client or server, then this client or server is considered the disruptor. Otherwise, the relay compares the $H(p_{ij})$ values revealed by the clients with those revealed by the servers. There must be a difference, WLOG, among one of the $H(p_{ij})$ values revealed by one client and one server. After identifying a mismatch between a client and a server, the relay requests that they reveal their shared secret $r_{ij}$, along with a zero-knowledge proof showing $r_{ij}$ was computed correctly. To generate the pads for the disrupted round, the relay seeds the PRG with these secrets. At this point, the relay will be able to determine which one, the client or the server, disrupted the round and exclude it from the system.

VII. Practical Considerations

Here we describe how PriFi handles four practical issues: client churn, anonymous authentication, quality-of-service (QoS) for different client types and scaling to large networks.

A. Handling Client Churn

Client churn can have a significant effect on the performance of DC-net based protocols, including PriFi. For example, the disconnection of a single client invalidates all the ciphertexts in the current round. We define two types of client churn: (1) graceful churn, where clients gracefully announce to the relay their intent to connect or disconnect from PriFi; and (2) abrupt disconnections, where clients abruptly disconnect from PriFi without sending any warning to the relay.

PriFi uses a delay-and-reconfiguration approach to handle graceful churn without communication disruption. The key idea is to execute the resynchronization phase, triggered by a client gracefully connecting or disconnecting, in parallel to the current Anonymize phase, thus maintaining the communications. That is, the joining or disconnecting client $c$ sends...
a request to the relay, which starts in background a new Set-up and Schedule phases with the new set of clients \( C' \), while maintaining the current Anonymize phase with the old set \( C \). Once each client of \( C' \) starts the new Anonymize phase (hence, clients in both set run two concurrent Anonymize protocols), the relay stops the old Anonymize phase concerning \( C \). This approach enables interruption-less handling of graceful client churn, by temporarily using more CPU time and network messages on all the nodes.

We argue that the CPU cost is negligible: The relay does only one additional signature check; each server has to run an additional verifiable shuffle protocol, yet by design servers are well-provisioned servers able to handle several PriFi networks in parallel. Each client has to generate two new pairs of keys, which could be intensive on low-power devices; we envision that clients could generate these keys in advance, keeping them ready in case a churn occurs. All the nodes then have to exchange this information over the network, yet it is a constant and small number of messages, and the total communication is only in \( O(m + n) \), where \( m \) is the number of servers and \( n \) is the number of clients.

In the case of abrupt disconnections, if a client disconnects unexpectedly, it disrupts the current Anonymize round, and the upstream message \( x \) is lost. The delay-and-reconfiguration approach is not applicable in this scenario: all nodes need to stop, and perform a new Set-up and Schedule phase. In PriFi, this is the only event when the communications stops. We evaluate the effect of client mobility and churn in more detail in Subsection VIII-A.

B. Anonymous Authentication

Even if an adversary cannot directly link messages to a client, it can run intersection attacks by monitoring the set of online clients (usually public information), and correlate it with the anonymous message sent. This scenario is especially plausible in the case of members of an organization identifying themselves to access the network.

To solve this problem, PriFi uses the Deniable Anonymous Group Authentication (DAGA) [50] protocol, an anonymous authentication mechanism. During authentication, members prove that they own a private key that corresponds to one of the group public keys, without revealing which one. Other alternatives could fit PriFi [45], but DAGA has the benefit of providing deniable anonymous authentication, further protecting clients from coercion. With anonymous authentication, an adversary is unable to easily tell whether a client is online. Hence, PriFi offers stronger tracking-resistance than other anonymous communication channels.

C. Providing QoS

To support different QoS levels, PriFi enables clients to subscribe to channels with different bitrates. Each channel is an isolated instance of the PriFi protocol, but runs with different speeds and payload sizes. In this way, constrained devices (e.g., suitable IoT devices, battery-powered devices) only join “slow” PriFi channels that require little computation and more powerful devices join both slower and faster channels. Channels correspond to categories of traffic, for instance “e-mails”, “web browsing”, “VoIP” and “video conferencing”. With this approach, a device that has no VoIP capabilities can save resources by joining only the appropriate channel.

Devices connected to several channels participate in the anonymity set of those channels, but probably only communicate using the fastest. The benefit for this approach is increasing the anonymity set of slower channel, but let us analyze the cost of being active in several channels. Assuming an order of magnitude difference in terms of latency between channels (e.g., web browsing at 100ms, VoIP at 10ms latency), joining an additional slower channel only adds 1 message every 10 messages on the fast channel, a tolerable cost for high-end devices.

This approach causes a well-known tension between anonymity and performance. That is, having all devices in one anonymity set provides better anonymity, yet might be completely impractical for a whole class of devices (e.g., battery-powered smartphones). Hence, we propose to accommodate more devices by splitting the anonymity set in parts. The size of the partitions, the number of channels and their parameters are highly dependent on the security needed, the number of active devices and their requirements; finding the appropriate balance is outside the scope of this work.

D. Scaling PriFi to Large Networks

Up to this point, we discussed the deployment of a single PriFi setup (i.e., one relay, a few servers and many clients). The relay, which can be implemented in a wireless access point, has a certain number of radio interfaces and can only support a limited number of clients; for a rough estimate, last generation dual-band wireless access points usually support up to 200 clients [52]. Hence, the current PriFi design does not scale (yet) to large companies and university campuses.

Multiple relays. The most straightforward solution is to install several PriFi networks in parallel. In practice, this means installing several relays, in a very similar way as current wireless setups for large companies or universities. Note that these relays can use the same servers, so in theory no scaling is needed there. The major difficulty comes from our threat model, that requires at least two honest clients. With multiple relays (each having a distinct anonymity set), if the two honest clients are connected to different relays (i.e., anonymity sets), they would have no anonymity at all.

A second, orthogonal concern is the ability of a relay to evict clients. As stated before, a relay is trusted for availability (Section III). However, in a multiple-relay scenario, malicious relays could deny service or slow down honest clients to affect client’s anonymity. Suppose that at a given physical location, a client can choose between two relays, \( R \) and \( R' \). \( R \) is malicious and it has two honest clients connected (i.e., other clients are malicious and colluding with the relay). \( R \) evicts one of the honest clients, e.g., claiming that the client is slowing down the network, leaving only one honest client with no anonymity. In a single-relay scenario, this attack would
have been detected (the evicted client is likely to complain), whereas in a multiple-relay scenario, the evicted client is likely to automatically connect to \( R' \).

Management servers. Both problems boil down to the fact that relays have too much power in that scenario, with respect to moving clients among anonymity sets. This issue can be solved by introducing a set of management servers. We assume the management servers to be in the anytrust model [57]. These management servers will perform the DAGA [50] authentication protocol and assign freshly-authenticated clients to relays. The assignment process will provide clients with a ticket, signed by the management server(s), specifying the relay the client can connect to. Moreover, management servers can use the RandHound protocol [51] (i.e., distributed randomness in the anytrust model) to randomly and securely assign new clients to relays.

Using the management servers, at the very least, a relay evicting a client becomes visible, as the client will have to request a new ticket to the management servers. Hence, there will be a trace of which relay evicted an anonymous client. Clients have administrative solutions (e.g., complaining to the IT services) and proofs (i.e., the issued tokens and the signed eviction request from the relay) of the abnormal behavior. Finally, the management servers’ logs can be automatically analyzed for abnormal behaviors (e.g., several clients suddenly leaving a relay) and trigger the appropriate administrative responses.

VIII. Evaluation

A. Client churn

We first evaluate the impact of client churn (i.e., when a client connects or disconnects) in PriFi. In conventional DC-nets, if any client goes offline, all other clients must recompute and exchange the shared secrets before the communication can continue. Worse, the current communication round become indecipherable, forcing the other clients to resend their payload the next round. Hence, churn in DC-net induces (1) re-transmissions and (2) global downtime where no one can communicate. While re-transmissions are acceptable with PriFi’s small and frequent rounds (e.g., 10–100KB of payload each 10ms), too frequent churn could prevent delay-sensitive applications (e.g., VoIP, streaming) to be run on top of PriFi.

Previous systems that use DC-nets (e.g., [9, 58]) argued how churn was tolerable. Our contribution here is the first analysis of the impact of churn in a realistic scenario where nodes are mobile. In other words, we analyze the practicality of deploying a DC-net in a Wireless scenario (e.g., an Internet cafe), and show the availability of the network.

Dataset. For characterizing node mobility, we used a well-known dataset [42] from CRAWDAD [12]. It contains 4 hours of wireless traffic, recorded in a university cafeteria. Those traces contain the Data Link layer, and show the devices’ association and disassociation requests. With respect to PriFi, this dataset represents a pessimistic scenario, since node mobility is likely higher in a cafe than in an office or classroom.

The dataset contains 254 occurrences of churn over 240 minutes, in which there are 222 associations (33 unique devices) and 32 disassociations (12 unique devices).

Dataset analysis. Each device (dis)connection induces a re-synchronization (i.e., Setup + Schedule) time of \( D \) milliseconds, where \( D \) depends on the number of servers \( M \) and clients \( N \), and the latency needed to contact them. We use the following approximation: 10ms for the clients (i.e., emulating a busy LAN), and 100ms for servers (located outside the LAN). Figure 4 shows typical values for \( D \), which is in the order of seconds. Depending on the strategy, this time \( D \) is either direct downtime, or not if the re-synchronization happens in background. We analyze three strategies:

1) the naïve approach kills the communication for every churn, and devices experience a downtime of \( D \)

2) the abrupt disconnections approach uses the graceful approach presented above for connections (which can be enforced by the relay), yielding 0 downtime for connections, but assumes a worse-case scenario were all nodes disconnect abruptly (e.g., they do not cooperate, or they experience some network failure), yielding a downtime of \( D \).

3) the graceful only assumes no abrupt disconnections. It is an ideal scenario that cannot be guaranteed (e.g., in case of a device running out of battery), but we envision to come close to this scenario, especially since users have incentive to cooperate to maintain a good QoS for everybody.

We display in Table I three metrics for each of these strategies: the first metric is the raw number of communication

| TABLE I |
| --- |
| Applying the "Cafe" Dataset to PriFi |
| Interruptions | Availability [%] | MCD [s] |
| Naïve | 254 | 98.72792 | 1.55147 |
| Abrupt Disconnections | 32 | 99.81778 | 0.82 |
| Graceful only | 0 | 100 | 0 |

![Fig. 4. Network downtime (i.e. where no communication can happen) in case of abrupt disconnection, averaged 10 times, with 95% percentiles. The time is lower-bounded by the latency to the \( M \) servers.](image-url)
interruptions, which directly comes from the node mobility in the dataset. The second metric is the network availability percentage, computed as \( \frac{\text{total time}}{\text{downtime}} \). The last metric is the maximum continuous downtime, the longest network interruption if PriFi is used with the aforementioned dataset. This last metric has direct impact on usability: a PriFi user doing a VoIP call might experience audio/video freezes for the duration of the downtime.

**QoS and availability.** Using PriFi in the ‘cafe’ scenario represented by the dataset [42] would slightly decrease network availability, as churn induces global downtime. However, over 4h, between 0 and 32 global loss of communication occur, and the network availability ranges between 99.82\% and 100\%, depending on the disconnection types. Assuming PriFi clients have incentives to disconnect gracefully (which improves the situation for everyone at a minimal cost), only network failures and other hardware problem yield global downtime. The longest disconnection period is 0.82s in the worst case, which is noticeable by the users using time-sensitive applications (e.g., VoIP), but hopefully is a bearable cost for anonymity.

**Anonymity metrics.** In Figure 5 we display the size of the anonymity set versus the time, i.e., among how many participants a PriFi user is anonymous at any point in time. This is an essential anonymity metric that quantifies anonymity.

In particular, the variations are interesting, as they show user mobility. A high variance means that while connected, a user risks being less anonymous if unlucky (and many people disconnect suddenly); should the size of the anonymity set drop to 1, anonymity would be lost.

In the analyzed scenario, we start by removing the uninteresting linear component which indicated that over the duration of the experiment, more people joined the cafe than left. Then, we display the difference, in percentage, between the actual anonymity set size and the baseline tendency. We see that size of the anonymity set does not vary more than \( \pm 8\% \); The mean number of users is 50, hence, the worst-case of “anonymity loss” in that scenario is of 4 users, which is tolerable in an anonymity set of 50 users.

### B. PriFi Evaluation

We implemented a prototype of PriFi in Go [24], and made the source code publicly available [1]. We evaluated the performance of our prototype on the Deterlab [14] infrastructure (the topology is provided in the repository). All experiments below are reproducible with a few simple commands, e.g., ./PriFi.sh simul-vary-nclients. Finally, the raw logs and scripts to recreate the plots are available in a separate repository [2].

**Latency.** Figure 6(a) shows the latency of the PriFi system, i.e., the time needed for an anonymized packet to be sent by the client, decoded by the relay, and sent back to this same client. In this experiment, one random user is responsible for measuring those “pings”, while others only participate in the protocol without sending data (i.e., the number of active user is 1, anonymous among all users). The latency increase linearly, from 40ms for 30 users (e.g., a small company) to 120ms for 100 users, and scales well with the number of clients.

**Schedule.** A major component of the latency is the buffering of messages by the clients; having only one slot per schedule, clients must wait this slot before transmitting data. This waiting time is depicted by the red curve in Figure 6(a). To reduce the time spent waiting on the slot, we alter the scheduling mechanism and allows slots to be closed. A periodic reservation map allow clients to anonymously specify if they want to send data; if not, the round is defined as closed. The relay skips the closed rounds, which allows for shorter, more frequent schedules. For instance, if only one user wants to transmit, the relay alternates between reservation map and 1-slot schedules.

This reservation mechanism improves the situation where many users are idle. It induces additional delay in some cases, as the client needs to wait for the next reservation to open his slot, and wait again for his slot. Other scheduling mechanisms (e.g., embedded in each packet, or removing the schedule and allowing collisions) would yield different trade-offs between latency and number of users; finding the best way to divide the anonymous channel depends on many factors, and is out-of-scope of this project.

**Skype dataset.** We then replay real traces through PriFi. To validate the VoIP scenario, we selected a dataset containing Skype traces [47] from CRAWDAD [12]. One client replayed those traces through PriFi, while others were not transmitting data, and the relay recorded the time-difference between the received packets and the original traces (i.e., the latency does not include the communication to the Skype servers, but only the added latency by PriFi). The evaluation results are displayed in Figure 6(b) we see that the median value increases linearly from 25ms for 20 clients, to 75ms for 100 clients, below the one-way 150ms recommended threshold [53] and below the 250ms threshold where callers start noticing delay [25].

Figure 6(a) shows slightly higher latencies than Figure 6(b) because in the first scenario, the client has to reserve a slot and wait for it for each packet. In the Skype dataset,
once a slot has been reserved for one packet, PriFi packs as many buffered packets as possible, using more efficiently the upstream payload.

**Broadcast.** Figure 7 shows the benefits of using UDP broadcast instead of unicasting to provide receiver anonymity. We see time spent sending data increasing linearly with the number of clients in Figure 7(a) while remaining negligible in Figure 7(b). In PriFi, shorter round duration translates directly into lower latency for the clients. This experiment depicts how WLANs, which achieve broadcast naturally, compose well with anonymous communication systems providing receiver anonymity.

**Pipelining.** Figure 8 also demonstrate how pipelining can be used to reduce latency in systems where nodes wait on each other (e.g., DC-nets). In PriFi, increasing the pipelining factor allowed to decrease the experienced latency by 2.25 at no other cost.

**Usability.** The current implementation uses SOCKS proxies to tunnel the clients traffic in PriFi. As such, this prototype only supports SOCKS-compatible applications, e.g., web browsers. During an informal evaluation, we successfully loaded various webpages and streamed YouTube videos through PriFi. The interested reader can test our prototype by cloning the repository [1], and running "/PriFi.sh all-localhost".

**IX. Conclusion and Open Problems**

In this paper, we presented PriFi, an anonymous communication network that has provable security. PriFi relies on a specific, but common network topology to provide low-latency, traffic-agnostic anonymous communication. PriFi uses DC-nets with a novel topology to provide strong anonymity, and addresses two main shortcomings of similar work: client churn is handled in background, and malicious insiders are excluded quickly, orders of magnitude faster than before.

We implemented and made public the source code of PriFi, and evaluated its performance on a common infrastructure, with well-known datasets. Our experiments show that PriFi achieves low-latency (70ms for 50 clients) and would support delay-sensitive applications.
We envision PriFi being deployed in organizations, companies, and universities, protecting the users’ traffic from eavesdropping by malicious insiders or corrupted endpoints. PriFi would be transparent to the end users, facilitating adoption.

**Future work.** The current prototype need to be tested in more diverse scenarios; in particular, only empirical experiments have been made with end-to-end communications. The next logical step is to perform latency test with traces combining different traffic categories, as well as user testing, to assert the prototype stability and usability.

A second open problem is the division of the anonymous channel created by PriFi: user scheduling has a major impact on the fairness and the perceived latency for the clients. In PriFi, the scheduling policy chosen can be changed on the fly and enforced by the relay, possibly adapting to the live traffic.

Finally, PriFi could be adapted to scenarios containing resources-constrained devices (e.g., mobile phones, or IoT devices). Previous work showed how sensitive IoT traffic can be, even encrypted. PriFi could provide strong protection while being computationally lightweight in a scenario with low churn.

Fig. 8. Effect of pipelining on latency. A window $W = 7$ divides the latency by 2.25 in comparison to the naive $W = 1$ approach.

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**APPENDIX A**

**EQUIVOCATION PROTOCOL PROOF**

Let $C_o$ be the slot owner, $x_o$ be its plaintext upstream message, $x'_o$ be its encrypted upstream message, and $k_o$ be the key used to encrypt $x_o$ into $x'_o$.

We first consider the case that all clients have received the same downstream messages from the relay until the current slot, i.e., $h_1 = h_2 = \ldots = h_n = h$. By substituting equations (1)-(3) in Equation (4), and letting $P = \sum_{i,j} F_2(p_{ij})$, we have $k = F_1(k_o) \cdot F_1(h)^{-P} \cdot F_1(h)^{P} = F_1(k_o)$. Thus, the relay can correctly unblind $k_o = F_1^{-1}(k)$ and decrypt $x_o$.

Note that although the relay learns $k_o$, due to the hardness of DLP, it cannot learn any information about clients’ ciphertexts, $\sum_{j=1}^m F_2(p_{ij})$, which could be used to de-anonymize the client.

Now, consider two disjoint non-empty subsets $A,B \subset \{1,\ldots,n\}$, such that all clients $C_i \in A$ have the downstream history $h_A$ and all clients $C_i \in B$ have the downstream history $h_B \neq h_A$. From Equation (4)

$$ k = F_1(k_o) \cdot F_1(h)^{-P} \cdot \prod_{i \in A} F_1(h_A)^{\sum_{j=1}^m F_2(p_{ij})} \cdot \prod_{i \in B} F_1(h_B)^{\sum_{j=1}^m F_2(p_{ij})} \tag{5} $$

Since $F_1(h)^{-P} = \prod_{i=1}^n F_1(h)^{-\sum_{j=1}^m F_2(p_{ij})}$, and $A,B$ are disjoint non-empty subsets of $\{1,\ldots,n\}$, for any choice of $h$ in Equation (6), $k \neq F_1(k_o)$. Therefore, if there is any disagreement among the clients on the downstream history, the relay will not be able to obtain the key to decrypt the owner’s upstream message.