

YOUCHOOSE: A LIGHTWEIGHT ANONYMOUS PROOF OF ACCOUNT OWNERSHIP

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ABSTRACT

We explore the issue of anonymously proving account ownership (anonymous PAO) to let a prover prove to a verifier that it owns a valid account at a server without being tracked by the server or the verifier, without requiring any changes at the server's end and without even revealing to it that any anonymous PAO is taking place. This concept has applications in sensitive areas like whistleblowing. The first introduction of anonymous PAOs was by Wang et al., who also introduced the secure channel injection (SCI) protocol to realize anonymous PAO in the context of email account ownership.

In this paper, we propose YouChoose, an approach that improves upon Wang et al.'s SCI-based anonymous PAO. Unlike SCI, which demands carefully designed multi-party computation (MPC) protocols for efficiency, YouChoose works without MPC, simply relying on the verifier to selectively forward TLS records. It is faster, more efficient, and adaptable, with only a few milliseconds overhead compared to SCI's 8 seconds on top of a proxied email transaction carrying a typical email attachment such as an image file. Further, the simplicity of the YouChoose approach readily enables anonymous PAO in different settings such as various ciphersuites of TLS, account types other than email, etc., while the SCI approach needs specifically designed MPC protocols for each use case. The paper also formalizes both YouChoose and SCI into definitions for a generalized anonymous PAO.

1 INTRODUCTION

Anonymous credentials provide a powerful tool for making assertions about identity while maintaining privacy. In an anonymous credential scheme, individuals identify themselves using different pseudonyms with different organizations, preventing even colluding credential issuers and verifiers from identifying and tracking users. For example, say a person P wants to anonymously prove to a verifier V that they possess a credential from a credential issuer I . P obtains a credential from I against a pseudonym P_I they use with I , and transforms it to a credential against a pseudonym P_V they use with V . This convinces V that the credential is genuine, but even if I and V actively collude, they cannot link the pseudonyms P_I and P_V together.

However, one drawback of most existing anonymous credential schemes is that they require active participation from the credential issuer I and may not work in settings where I may be unwilling to cooperate. For instance, consider a whistleblower use-case where an employee wants to anonymously report misconduct at their organization to a journalist and the journalist wants assurance that the information is sent by a genuine employee. In this case, the employee cannot use a standard anonymous credential scheme to prove their employee status, simply because the organization would never cooperate and issue any self-incriminating anonymous credential. Depending on the use-case, infrastructural changes to support anonymous credentials may range from being actively harmful to the issuer's reputation and business interests to simply not being a priority item. Thus, a practical security goal is anonymous authentication without requiring any infrastructural changes at the issuer and, in some cases, without even letting the issuer know of any such authentication taking place.

Specifically, we focus on a specific anonymous credential called an email-based anonymous proof of account ownership (PAO).

Here, P wants to prove to V that they own an email account with I , without revealing which account. Email is ubiquitous in business, government, education and daily life. As a result, employees routinely have working email addresses within their organizations. Email-based anonymous PAO thus fits perfectly with our goal of avoiding infrastructural changes from I while anonymously proving the insider status of P to V .

An email-based non-anonymous PAO typically relies on P 's ability to *retrieve* email sent to the claimed email address (V sends a random challenge to the claimed email address and requires P to produce the challenge), but it reveals P 's email address to V . Email-based anonymous PAO was first introduced by Wang et al. [1], where they let P prove ownership of an email account at a domain without revealing their email address, by relying on P 's ability to *send* emails from the claimed email address. This allows P to prove ownership of an account at I because in the standard email infrastructure, P send emails via I 's email server (say S) that verifies P 's account credentials and forwards the emails to a recipient only upon successful authentication. In Wang et al.'s approach, the verifier V acts as a proxy sitting between P and S (see Figure 1a). P sends an email from their claimed email account, say `alice@domain.com`, to some other account they own, say `alice2@domain2.com`. V securely injects a challenge into messages sent over the secure channel such as TLS between P and S . This is done via a 2-party computation protocol called *secure channel injection* (SCI) [1] that allows P and V to jointly compute an authenticated and encrypted message containing the injected challenge, without P learning the challenge bits and V learning the message contents and session keys. Later, if P is able to produce the challenge to V (by accessing the inbox of `alice2@domain2.com` or the sent emails folder of `alice@domain.com`), then it proves to V that the email was successfully sent by S and hence P 's ownership of an account at S .

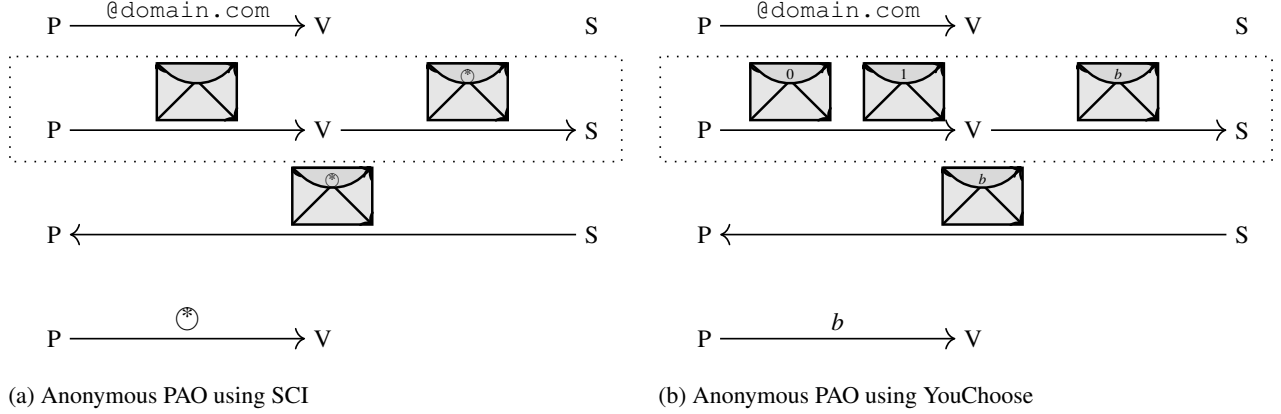


Figure 1: SCI based anonymous proof of account ownership (PAO) on the left versus our YouChoose based anonymous PAO on the right. Here, P is the prover, S is the email server of $domain.com$, and V is the verifier. \circledast represent the injected challenge; 0, 1 represent the order of the email messages and b represents the bit denoting the email forwarded by V .

YouChoose. In this paper, we introduce YouChoose, an alternative approach to anonymous PAO that is considerably lighter-weight and general than the SCI-based approach of Wang et al. The basic idea behind YouChoose is shown in Figure 1b. P sends two email messages m_0 and m_1 from $alice@domain.com$ to an account they own. V ensures that the interaction is with $domain.com$ and forwards only one of the emails m_b for a randomly chosen $b \in \{0, 1\}$. P 's challenge is to find out whether m_0 or m_1 was forwarded. If P sends the correct bit b to V , it proves with a soundness error of $1/2$ that S had forwarded the email and thus P is an eligible $domain.com$ user. Although the soundness error can be made negligibly small by repeating the above process, this would require P to send multiple emails. We optimize this by carefully designing a protocol that achieves a negligible soundness error with just one email while respecting the restrictions imposed by the underlying TLS secure channel.

The YouChoose approach is simpler, more efficient, and more general than the SCI-based approach for anonymous PAO. Since general-purpose 2-party computation (2PC) protocols for SCI are expensive, Wang et al. designed special-purpose SCI protocols by leveraging recent advancements in maliciously secure 2PC for the AES-CBC/HMAC-SHA-256 ciphersuites of TLS 1.2 [1] and in oblivious polynomial evaluation for AES-GCM. Similar efficient 2PC protocols need to be carefully designed to support other ciphersuites like ChaCha20-Poly1305 in TLS 1.3 [2]. In contrast, the YouChoose approach of selectively forwarding messages is fairly general and can be used not only with any ciphersuite in TLS 1.2 or TLS 1.3, but also for anonymous PAO beyond just email. For example, P could anonymously prove ownership of a Twitter account to V by having V selectively forward tweets submitted by P via the Twitter API. Further, since the most expensive step in YouChoose is a few simple coin tosses, it is much more efficient than Wang et al.'s specially designed SCI protocol, which incurs roughly 8 seconds overhead per session versus only a few milliseconds in case of YouChoose.

It is also interesting to note that Wang et al.'s scheme requires the prover to have exclusive access to the recipient account and is thus restricted to email-type applications. In YouChoose, the

challenge is identifying whether the first or the second email was forwarded and not the email contents themselves, so it does not require the prover to have exclusive access to the recipient account. This may be useful in applications such as the Twitter example above, where the finally posted tweets may be read by anybody.

Our main contributions are the following:

- We introduce the YouChoose approach, a simpler and more efficient alternative to SCI-based anonymous PAO.
- We formalize the general paradigm of anonymous PAO common to both YouChoose and SCI, of V acting as a proxy between P and S , securely modifying messages in the secure channel established between P and S and using these modifications as a challenge for P to prove account ownership (Section 3). Our security definitions generalize the definitions given by Wang et al.
- We propose and implement a concrete YouChoose protocol for SMTP-TLS and discuss the implementation aspects for anonymously proving email account ownership using SMTP over the TLS secure channel (Section 4). We analyze the security of the protocol in Section 5. We provide our implementation at this github link⁴ and plan to release it as open-source software.

2 RELATED WORK

Whistleblowing. Whistleblowing is crucial to educate the public of misdeeds and to call those in power to account. Therefore, it is desirable to cryptographically protect the identity of a whistleblower to allow a low-risk disclosure of wrongdoing. The use of secure messaging apps [3, 4], mix-nets [5], or onion routing systems such as the Tor network [6] allows whistleblowers to communicate anonymously with journalists. However, these systems do not provide a way for whistleblowers to prove their insider status.

A whistleblower could use group signatures schemes [7] instead which allow a member of a group (such as an organization) to

⁴Link: <https://github.com/aarav22/anon-pao>

sign a message on behalf of the group without revealing their identity. However, it violates the privacy we seek as a group manager can still identify the signer. Ring signatures [8] do not require such group manager, but nevertheless allow signing on behalf of an ad hoc group of public keys. However, this method requires that all group members possess public keys accessible via a trusted directory, hence requiring cooperation of the organization.

Anonymous credentials allow a user to prove to another party that they have a valid identity certified by some certificate authority (CA), without revealing the identity itself [9, 10, 11]. Nevertheless, the CA learns that the user wishes to use a privacy tool such as an anonymous credential, which in itself is sensitive information in use-cases such as whistleblowing.

Email-based Anonymous PAO. An anonymous PAO allows a prover to prove ownership of an account to a verifier without revealing which account. In case of email identity, instead of proving that the account owner owns a particular email address such as `alice@domain.com`, the verifier will be convinced if the prover proves that it owns some valid email address at `domain.com`.

Secure Channel Injection (SCI) [1] allows a verifier to inject a random challenge into an email sent from a prover’s email account to an account accessible only by the prover. The SCI protocol by Wang et al. depends on two 2PC protocols: 2P-HMAC and 2P-CBC, which are used to jointly compute the HMAC tag and the TLS ciphertext, respectively. However, this approach not only requires a 2PC protocol making it computationally expensive but it is currently only optimized for AES in CBC mode that lacks support in TLS 1.3.

Multi-context TLS (mcTLS) [12] is a modified version of TLS that enables middleboxes to read and/or access specific parts of a TLS connection by revealing some specific session keys to them. This modification allows for message injection similar to SCI, but it is not compatible with existing web infrastructure as it requires changes in TLS. Moreover, for mcTLS to work, the server must have full awareness of the modifications made by the middleboxes, which might arouse suspicion of a non-standard protocol execution in the server.

Maillet, as described in [13], is a censorship-circumvention system designed to enable users in censored regions to access social media websites. It employs a similar setup where the client communicates with the website through a distributed set of proxy servers, but the client needs to share its credentials among the proxies. These distributed proxies then engage in a secure computation protocol with each other to collectively compute the TLS record, facilitating authentication with the remote server. Although one might consider utilizing their protocol for anonymous PAO, if the proxy servers collude, it allows them to impersonate as the client and forge messages.

DECO [14] is a protocol that allows the client to prove to a third-party verifier that it received a certain response from the server. This could theoretically be used to anonymously prove ownership of an account if the server sends a distinct success message upon successful authentication, since the client could prove to the verifier that it received a success message. However, the way it is implemented requires the session key to be split

between the client and the verifier and thus requires a secure MPC protocol for client authentication. However, this approach does not work for email-based anonymous PAO as the SMTP standard does not require servers to send a distinct success message to the clients upon authentication.

3 FORMALIZATION OF ANONYMOUS PAO

We now formalize a generalized version of SCI-based anonymous PAO [1] where *a*) the modifications made by *V* could be more general than simply injecting messages in the secure channel between *P* and *S* and, in particular for YouChoose, include dropping of messages, and *b*) the proof is for general account ownership as opposed to just email account ownership; we characterize this general account ownership by a credential verification algorithm *CVer* run by *S* that takes as input an account credential *cred* and outputs 1 if the credential was valid and 0 otherwise (e.g., for email-based account ownership, *CVer* would take the email and password as input credential and output 1 if the email was registered at the domain and the supplied password was correct and 0 otherwise).

Formally, we say that an anonymous PAO scheme is a tuple of protocols (Setup, GenToken, Prove) between *P*, *V* and *S* defined as follows:

- $(P\langle k \rangle, V\langle \rangle, S\langle k \rangle) \leftarrow \text{Setup}(d, P\langle \rangle, V\langle \rangle, S\langle \rangle)$: This is a protocol to establish a secure channel between *P* and *S* with *V* acting as a proxy. All of *P*, *V* and *S* obtain an identifier *d* identifying *S*’s domain; neither of them obtain any secret input. *P* and *S* output a common session key *k* for the secure channel; *V* does not obtain any output.
- $(P\langle st_p \rangle, V\langle st_v \rangle, S\langle m' / \perp \rangle) \leftarrow \text{GenToken}(P\langle k, cred \rangle, V\langle \rangle, S\langle k \rangle)$: This is a protocol to generate an authentication token that *P* can use to anonymously prove to *V* that it owns a valid account at *S*. *P* supplies the account ownership credential *cred* as input, and both *P* and *S* supply the secure channel’s session key *k*. *P* sends a message *m* to the secure channel during the protocol and *S* outputs a message *m'* $\in \mathcal{M}(m)$ if *CVer*(*c*) = 1, where $\mathcal{M}(m)$ denotes the set of modifications that *V* is allowed to make on *m*; *S* outputs \perp if *CVer*(*cred*) = 0. The output *m'* acts as a token that *P* needs to obtain from *S* through an out-of-band channel. *P* and *V* output their internal states *st_p* and *st_v* to be used later.
- $(P\langle \rangle, V\langle 0/1 \rangle) \leftarrow \text{Prove}(P\langle st_p, m' \rangle, V\langle st_v \rangle)$: This is a protocol that allows *P* to prove account ownership to *V* using the token obtained from *S* at the end of the GenToken protocol. *P* and *V* supply their internal states *st_p* and *st_v* as input and *P* additionally supplies the token *m'*. *V* outputs 1 if the token is valid and 0 otherwise.

We also assume that all protocols implicitly obtain a security parameter *n* (in unary).

Security Properties. Our security properties are naturally extensions of the security properties proposed by Wang et al. [1] for SCI-based PAO. The soundness requirement (Definition 3.1) captures that the verifier accepts the proof only if the prover indeed owns a valid account with the server. This soundness requirement is more direct than the *injection secrecy* property

of [1] that provides soundness in the SCI setting. Injection secrecy requires that P does not learn the challenge injected by V during the GenToken protocol and hence implies soundness because then P can retrieve the challenge only if it has an account at S . We cannot use this definition directly because the challenge in YouChoose is which of the message pairs selected by P was dropped and hence we opt for the more direct soundness definition.

Transcript privacy (Definition 3.2) is required to prevent leakage of credential information to V and thus impersonation of P by V . Transcript integrity (Definition 3.3) prevents V from modifying the messages sent over the secure channel beyond what is allowed by the modification function \mathcal{M} . This is required, e.g., to prevent V from sending a malicious email to a modified recipient address on behalf of P . Finally, server obliviousness (Definition 3.4) captures that S remains unaware of any anonymous PAO taking place between P and V . We require that the transcript that S receives looks indistinguishable from the case when P establishes a secure connection with S and sends through the secure channel a message that follows a distribution \mathcal{D} , where \mathcal{D} denotes the distribution of messages routinely sent by account owners through S for purposes other than anonymous PAO. Thus, server obliviousness captures that the server cannot distinguish an execution of anonymous PAO with a routine communication of messages from the account owners via S .

Definition 3.1 (Soundness). For all PPT adversaries P supplying an input credential $cred$ such that $CVer(cred)$ outputs 0, the probability that V outputs 1 in the Prove protocol when S runs honestly is negligible.

Definition 3.2 (Transcript privacy). The GenToken and Prove protocols do not reveal any information about P 's account credential $cred$ or the session key k to V .

Definition 3.3 (Transcript integrity with respect to \mathcal{M}). For all PPT adversaries V , if P and S are honest and P supplies a message m to the secure channel, S cannot output $m' \notin \mathcal{M}(m)$, except with negligible probability.

Definition 3.4 (Server obliviousness with respect to \mathcal{D}). Assuming that P and V are honest, S cannot distinguish between a) an execution of Setup and GenToken where it obtains a key k during Setup and a message m' during GenToken, and b) an execution of the setup and communication steps of a secure channel established with P where P sends a message $m' \leftarrow \mathcal{D}$ to the secure channel.

Network Assumptions. We now highlight the network assumptions under which we aim to achieve the above security properties. We do not require any more assumptions than those made in Wang et al.'s work for SCI-based anonymous PAO [1]:

1. Each party can only view the traffic on their own local network. In particular, P cannot access the transcript of interactions between V and S and S cannot access the transcript of interactions between P and V . Without the first assumption, it is impossible to achieve soundness since P can readily identify the modifications sent to S without requiring an account at S . Without the second assumption, it is impossible to achieve server obliviousness.
2. No party can spoof their identities or re-route messages to nodes other than the intended recipients. Without this as-

sumption, a malicious S could spoof as V and violate server obliviousness (and identify P) or a malicious P can spoof as S and violate soundness.

3. S cannot detect a non-standard secure channel protocol by just looking at V 's IP address.

3.1 Preliminaries

In this section, we describe notation and recall some background about TLS, which acts as the secure channel for our protocol, and SMTP, which acts as the application layer protocol for establishing email account ownership.

Notation. Let $x \xleftarrow{\$} S$ denote an element x sampled uniformly at random from a set S . Given a positive integer x , let $[x]$ denote the set $\{1, \dots, x\}$. We use \perp to indicate an empty message or failure and \parallel to denote concatenation of elements.

Electronic mail and SMTP. The Internet e-mail system has three major components: *user agents*, *mail servers*, and the *Simple Mail Transfer Protocol* (SMTP). These components can be described in the context of a sender, Alice, sending an e-mail message to a recipient, Bob. A typical e-mail message starts its journey in the sender's user agent, travels from the sender's user agent to the sender's mail server (this process is called *message submission*), and travels from the sender's mail server to the recipient's mail server (this process is called *message transmission*), where it is deposited in the recipient's mailbox. The recipient could access the messages in their mailbox by logging into its mail server. Microsoft's Outlook, Apple Mail, and Mozilla Thunderbird are among the popular user agents for e-mail. Mail servers are commonly operated by the user's service provider. Webmail solutions such as Gmail blur the distinctions between mail submission and mail transfer somewhat.

SMTP is the principal application-layer protocol for Internet electronic mail. SMTP define both server-to-server and client-to-server communication patterns. While it is primarily used to execute message transmission, i.e., transfer mail from the sender's mail server to the recipient's mail server, it is also used for mail submission, i.e., sending mail from the sender's user agent to the sender's mail server. Once at the destination server, email can be retrieved using protocols such as POP3 and IMAP.

We now briefly review how SMTP submits an e-mail message from a sender's user agent to the sender's mail server. First, the client SMTP (running on the sender's user client) has TCP establish a connection to port 25 at the server SMTP (running on the sender's mail server). Once the connection is established, the client and server perform application layer SMTP handshaking: the SMTP client indicates the e-mail address of the sender and the e-mail address of the recipient. Once the SMTP client and server have introduced themselves to each other, the client sends the messages. In particular, the client issues five commands: EHLO (an abbreviation for Extended HELLO), MAIL FROM, RCPT TO, DATA, and QUIT. These commands are self-explanatory (the DATA command signals the client's readiness to send the email content, including headers and body, after which the client starts transmitting the actual email data). The server issues replies to each command, with each reply having a reply code. SMTP did originally not require authentication for message submission (i.e., user agent to mail server), but this

was added later to fight spam. If the client needs to authenticate itself before sending the email, it uses the AUTH command. The server may support various authentication mechanisms like LOGIN, PLAIN, or CRAM-MD5. The PLAIN version of the AUTH command allows a client to provide its username and password to the server in plain.

As SMTP runs over TCP, all SMTP messages travel as payload in TCP packets. TLS is a popular mechanism for enhancing TCP communications with confidentiality, data integrity, server authentication, and client authentication. TLS consists of two primary components: **Handshake Protocol** - it authenticates the communicating parties, negotiate cryptographic modes and parameters, and establish shared keying material; **Record Protocol** - it uses the parameters established by the handshake protocol to protect (confidentiality and integrity) traffic between the communicating peers.⁵ Therefore, for a comprehensive security, SMTP must run over TLS. There are two ways to negotiate an TLS session. The first is to use TLS directly. This requires a IANA-assigned dedicated port. Application layer protocols that use this method are often indicated by adding a ‘S’ at the end, e.g., SMTPS. In the case of SMTP, port 465 was initially defined for SMTPS, but was deprecated later (it is nevertheless still used).

The second major way to use TLS is to connect with TCP on the normal port first and then upgrade the connection using a protocol-specific command. This method is commonly referred to as STARTTLS. The specifications in the RFCs commonly require clients to first query a server for STARTTLS support with a specific ‘capability’ command before trying to upgrade the connection [15]. The server can confirm an upgrade; the TLS handshake follows.

Requirements for the SMTP server. (1) Auth: Only authenticated users with legitimate sender addresses can send emails using a server that is correctly setup using a valid TLS certificate and being configured as a closed relay. (2) NoEcho: For soundness, the server should not echo back received commands to the client.

4 THE YOUCHOOSE PROTOCOL

We now describe the YouChoose protocol for anonymous PAO. The high-level outline of our scheme using TLS as the secure channel and SMTP as the application level protocol is shown in Figure 2. We begin with a basic version of our protocol that works for all authenticated encryption schemes based on the MAC-then-Encrypt or Encrypt-then-MAC paradigm, such as the AES-CBC/HMAC-SHA256 ciphersuite used in TLS 1.2 (Section 4.1). However, this basic protocol does not satisfy transcript privacy under nonce-based authenticated encryption schemes such as AES-GCM used in TLS 1.2 and 1.3. Thus, we also propose a variant of YouChoose for this case in Section 4.2.

4.1 The Basic Protocol

We now describe the basic YouChoose protocol (see Figure 3). First, during the Setup protocol, P and S establish a secure

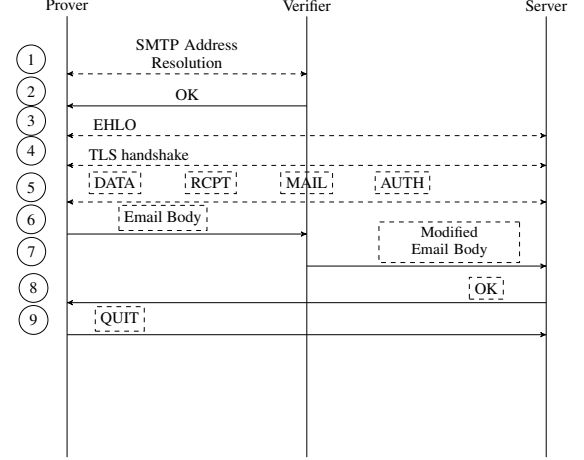


Figure 2: SMTP-TLS based anonymous PAO. Here, the dashed rectangle represents a TLS fragment. Steps 1-2 set up the prover and the verifier. Step 3 queries the server’s capabilities. Step 4 performs a TLS handshake. Steps 5-9 send the email.

channel among them with V acting as a proxy in-between. During this protocol, P and V obtain S ’s domain name d . V queries the DNS for the IP address of an SMTP server with domain name d , checks if the server supports the STARTTLS extension by making an SMTP query to this IP address, and aborts the protocol if it does not. P then initiates a TLS handshake with S with V acting as a proxy to establish a session key k for the secure channel between P and S .

During the GenToken protocol, P submits an email to the mail server S using SMTP over the TLS secure channel established above, and V drops parts of the email body such that the email finally forwarded by S allows P to construct an anonymous PAO authentication token. P first sends SMTP headers AUTH, MAIL, RCPT, and DATA to S in order to set up the email transaction, where AUTH contains P ’s email account credentials (e.g., username and password), MAIL contains the sender email address, RCPT contains the recipient email address, and DATA notifies the beginning of the email body. After this, P constructs an email body containing a sequence of challenge message pairs and V drops a randomly chosen message out of each message pair before forwarding them to S , such that S still accepts the received transcript as a valid SMTP email. As per the SMTP protocol, S forwards the email to the recipient mail server only if the credentials supplied in the AUTH header are valid. P can retrieve the contents of the forwarded email either by accessing the recipient email account or by accessing the sent emails folder of the sender email account.

During the Prove protocol, P compares the sequence of forwarded messages in the retrieved email with the original message pairs and constructs the sequence of challenge bits denoting which of the message pairs were forwarded by V . V verifies these challenge bits, completing the anonymous PAO.

Dropping parts of email body under TLS. Notice that modification or even dropping of parts of the email body by V is not allowed as per the integrity guarantees provided by the

⁵Handshake and Record Protocol correspond to the setup and communication steps of the TLS secure channel respectively.

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Setup( $d, P(\cdot), V(\cdot), S(\cdot)$ ) :
1  V: query DNS for  $d$  and obtain an IP address  $Saddr$ 
2  send SMTP query to  $Saddr$  to check if it supports STARTTLS
3  if yes: establish a TCP connection with  $S$  and notify  $P$ 
4  else: abort
5  P: perform TLS handshake with  $S$  via proxy  $V$  and establish key  $k$ 
output:  $P(k), V(\cdot), S(k)$ 

GenToken( $P(k, cred), V(\cdot), S(k)$ ) :
1  P: send header AUTH containing  $cred$  to  $S$  via  $V$ 
2  send header MAIL containing sender email address to  $S$  via  $V$ 
3  send header RCPT containing recipient email address to  $S$  via  $V$ 
4  send header DATA to  $S$  via  $V$  // begin email body
5  prepare email body  $m = ((p_i)_{i=1}^{n_p}, (c_{i0}, c_{i1})_{i=1}^{n_s}, (s_i)_{i=1}^{n_s})$ 
6   $st_p := (c_{i0}, c_{i1})_{i=1}^{n_s}$ 
7  let  $sqn = \text{current TLS sequence number}$ 
8  for  $i \in [n_p + n + n_s]$ :
9    if  $i \leq n_p$ :
10      $ep_i \leftarrow \text{TLS.Enc}(k, p_i, sqn)$  // see Figure 4
11    else if  $i \leq n_p + n$ :
12      $ec_{i0} \leftarrow \text{TLS.Enc}(k, c_{i0}, sqn)$ 
13      $ec_{i1} \leftarrow \text{TLS.Enc}(k, c_{i1}, sqn)$ 
14    else if  $i > n_p + n$ :
15      $es_i \leftarrow \text{TLS.Enc}(k, s_i, sqn)$ 
16      $sqn \leftarrow sqn + 1$ 
17  update the sequence number in TLS to  $sqn$ 
18  send  $((ep_i)_{i=1}^{n_p}, (ec_{i0}, ec_{i1})_{i=1}^{n_s}, (es_i)_{i=1}^{n_s})$  to  $V$ 
19  send header QUIT to  $S$  via  $V$  // end email transaction
20 V: for  $i \in [n]$ :  $b_i \leftarrow \{0, 1\}$ 
21 send  $((ep_i)_{i=1}^{n_p}, (ec_{ib_i})_{i=1}^{n_s}, (es_i)_{i=1}^{n_s})$  to  $S$ 
22  $st_v := (b_1, \dots, b_n)$ 
23 S: decrypt  $m' = ((p_i)_{i=1}^{n_p}, (c_{ib_i})_{i=1}^{n_s}, (s_i)_{i=1}^{n_s})$  from the TLS channel
24 if CVer( $cred$ ) = 1:  $res \leftarrow m'$ 
25 else:  $res \leftarrow \perp$ 
output:  $P(st_p), V(st_v), S(res)$ 

Prove( $P(st_p, m'), V(st_v)$ ) :
1  P: parse  $m'$  as  $m' = ((p'_i)_{i=1}^{n_p}, (c'_{i0}, c'_{i1})_{i=1}^{n_s}, (s'_i)_{i=1}^{n_s})$ 
2  parse  $st_p$  as  $st_p = (c_{i0}, c_{i1})_{i=1}^{n_s}$ 
3  for  $i \in [n]$ :
4     $b'_i = 0$  if  $c'_{i0} = c_{i0}$  else  $b'_i = 1$ 
5  send  $(b'_1, \dots, b'_n)$  to  $V$ 
6  V: parse  $st_v$  as  $st_v = (b_1, \dots, b_n)$ 
7   $res \leftarrow 1$  if  $(b_1, \dots, b_n) = (b'_1, \dots, b'_n)$  else 0
output:  $P(\cdot), V(res)$ 

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Figure 3: The basic YouChoose protocol. TLS.Enc denotes the TLS encryption algorithm that explicitly takes a sequence number as input (see Figure 4).

TLS via authenticated encryption schemes and strict sequence numbering. We circumvent this restriction as follows. P splits the email message body m into multiple fragments such that $m = ((p_i)_{i=1}^{n_p}, (c_{i0}, c_{i1})_{i=1}^{n_s}, (s_i)_{i=1}^{n_s})$, where c_{i0}, c_{i1} for each i denote the fragments corresponding to the challenge message pairs and p_i and s_i respectively denote fragments for the prefix and suffix of the challenge message pairs in the email body. P encrypts each of these fragments individually into a TLS record via an Encrypt-then-MAC or MAC-then-Encrypt authenticated encryption scheme such that for each challenge message pair i , both c_{i0} and c_{i1} are assigned the same sequence number and a strictly monotonic sequence numbering is followed otherwise. V then drops one of the encrypted TLS records corresponding to each challenge message pair, while forwarding all other TLS records as-is. In this way, S obtains a valid email body consisting of a sequence of TLS records with strictly monotonic sequence numbers.

```

TLS.Enc( $k = (k_{hmac}, k_{enc}), m, sqn = \perp$ )
if  $sqn == \perp$ :
  let  $sqn = \text{current TLS sequence number}$ 
  let  $type = \text{TLS data type}, version = \text{TLS version}$ 
   $mac \leftarrow \text{HMAC}(k_{hmac}, sqn \parallel type \parallel version \parallel \text{size}(m) \parallel m)$ 
   $data := m \parallel mac$ 
   $ciphertext \leftarrow \text{AES-CBC}(k_{enc}, data)$ 
   $record := (type \parallel version \parallel \text{size}(ciphertext) \parallel ciphertext)$ 
  return  $record$ 

```

Figure 4: TLS.Enc algorithm for the AES-CBC/HMAC authenticated encryption scheme.

Since the only unpredictable decision made by V is whether to drop or forward a TLS record corresponding to a challenge message pair, the number of challenge message pairs n directly determines the level of security provided by our scheme (i.e., with n such pairs, the probability that P incorrectly proves account ownership to V is bounded by 2^{-n}).

Transcript privacy. Note that in Encrypt-then-MAC or MAC-then-Encrypt schemes, V only obtains a sequence of semantically secure ciphertexts and hence transcript privacy is maintained. This is not the case in nonce-based authenticated encryption schemes such as AES-GCM, where V obtains a sequence of ciphertexts encrypted under the same nonce for each challenge message pair. V can exploit this to learn the session key, thus violating transcript privacy. Thus, we propose an alternative protocol for AES-GCM in Section 4.2.

Preparing email body for server obliviousness. To achieve server obliviousness, we require that the final email body $m' = ((p_i)_{i=1}^{n_p}, (c_{ib_i})_{i=1}^{n_s}, (s_i)_{i=1}^{n_s})$ for some $b_i \in \{0, 1\}$ received by S must be indistinguishable from some distribution \mathcal{D} representing routine email communication among the account owners. Towards this end, we suggest a simple strategy that hides the challenge message pairs into innocuous looking images that users routinely share over emails. Consider such an image I . P splits I into n fragments $I = (I_1, \dots, I_n)$ and creates a noisy version of each fragment I_i by adding a small amount of noise ϵ_i to it, i.e., $I'_i = I_i + \epsilon_i$. P then constructs the email body as before: $m = ((p_i)_{i=1}^{n_p}, (I_i, I'_i)_{i=1}^{n_s}, (s_i)_{i=1}^{n_s})$. The email body finally obtained by S would be $m' = ((p_i)_{i=1}^{n_p}, (I''_i)_{i=1}^{n_s}, (s_i)_{i=1}^{n_s})$ where I'' is a composite image such that its i^{th} fragment I''_i equals either I_i or I'_i . Since the noises ϵ_i are small, I'' is visually indistinguishable from I . Thus, I'' can be assumed to be drawn from the distribution \mathcal{D} which achieves server obliviousness. Note, however, that P on obtaining m' can still reliably extract the challenge bits since it exactly knows both I and I' .

Size of email body. In a standard SMTP-TLS connection, the email body is fragmented into TLS records of size 16KB (if the email body is smaller than 16KB then it is not fragmented). Since our challenge is solely dependent on the ability to drop or forward an entire fragment, we require each challenge message to be in a fragment of its own. Thus, for a realistic security parameter $n = 80$, we would require the email body to be split into 160 fragments. This would require an email body of size at least $160 \times 16\text{KB} \approx 2.5\text{MB}$. This is commensurate to sending a typical image or a pdf file over email.

4.2 Supporting nonce-based authenticated encryption schemes

In our protocol, we encrypt each challenge message pair (c_{i0}, c_{i1}) using the same sequence number sqn so that V can drop one of the messages. However, this poses a problem in nonce-based authenticated encryption schemes such as AES-GCM used in TLS 1.2 and 1.3. When the same sequence number is used to encrypt two messages it results in the same nonce for both the encryptions (see the TLS.Enc algorithm in Figure 5 for AES-GCM based encryption within TLS). This violates the nonce uniqueness requirement [16] that prohibits using the same nonce to encrypt more than one plaintext while using the same key. Violation of this requirement may lead to key recoverability attacks as shown in [17] which in turn leads to violation of transcript privacy.

To prevent V from obtaining both the ciphertexts (ec_{i0}, ec_{i1}) created using the same nonce, we use an oblivious transfer (OT) protocol where V fetches ec_{ib_i} from P without learning the other ciphertext $ec_{i\bar{b}_i}$ and P does not learn the bit b_i chosen by V . V forwards to S the ciphertext ec_{ib_i} thus obtained. That is, instead of V obtaining ec_{ib_i} as per lines 18-22 of the GenToken protocol, it obtains them via the OT protocol as follows: $(P\langle \cdot \rangle, V\langle ec_{ib_i} \rangle) \leftarrow \text{OT}(P\langle ec_{i0}, ec_{i1} \rangle, V\langle b_i \rangle)$. This mechanism ensures that V only learns a single ciphertext for any given nonce, thus respecting the nonce uniqueness requirement mentioned above and hence preserving transcript privacy. Also, P is oblivious to which ciphertext was fetched by V and then forwarded to S . This preserves the soundness of the protocol.

We note that OT is very fast; in fact, it is used as a primitive operation in many MPC protocols. We only need n OTs for the security parameter n , which is a small number in practice. Thus, the overhead of using OT in our protocol is negligible, as we show in Section 6.

```

TLS.Enc( $k, m, sqn = \perp$ )
  if  $sqn == \perp$ :
    let  $sqn$  = current TLS sequence number
  let  $type$  = TLS data type,  $version$  = TLS version,  $taglen$  = TLS tag length
   $data := m \parallel type$ 
   $outlen := \text{size}(data) \parallel taglen$ 
   $authdata := (type \parallel version \parallel outlen)$ 
  calculate  $nonce$  deterministically using  $sqn$ 
   $ciphertext \leftarrow \text{AES-GCM}(k, nonce, data, authdata)$ 
   $record := (type \parallel version \parallel \text{size}(ciphertext) \parallel ciphertext)$ 
  return  $record$ 

```

Figure 5: TLS.Enc algorithm for AES-GCM authenticated encryption scheme.

5 SECURITY ANALYSIS

Theorem 5.1. The protocols presented in Section 4 satisfy soundness as per Definition 3.1.

Proof (Sketch). In the basic YouChoose protocol presented in Section 4.1, P does not learn about which message out of the message pairs were forwarded by V because V sends them directly to S and by the requirements on SMTP (see Section 3.1), S does not echo any message back to P (note that S is honest in the soundness definition). Thus, the probability that P guesses

the challenge bits (b_1, \dots, b_n) correctly and makes V output 1 during the Prove protocol is bounded by 2^{-n} .

In the variant designed for AES-GCM (Section 4.2), P does not learn which message of any message pair was forwarded by V since the ciphertext ec_{b_i} is obtained by V by running the OT protocol with P where P remains oblivious of the bit b_i . The rest of the argument follows similarly as above. \square

Theorem 5.2. The protocols presented in Section 4 satisfy transcript privacy as per Definition 3.2.

Proof (Sketch). In the basic YouChoose protocol presented in Section 4.1, V only obtains ciphertexts $(ec_{i0}, ec_{i1})_{i=1}^n$ under a MAC-then-Encrypt or Encrypt-then-MAC scheme, which leak no information about the underlying messages, session keys, credentials, etc. In the variant designed for AES-GCM (Section 4.2), V only learns one ciphertext out of (ec_{i0}, ec_{i1}) for any i in 1 to n , by the properties of OT. In particular, V never learns two ciphertexts encrypted with the same nonce (corresponding to the same sequence number) for any i . This is indistinguishable to receiving a fresh ciphertext encrypted under AES-GCM for each i , which does not leak any information about the underlying messages or credentials. \square

Theorem 5.3. The protocols presented in Section 4 satisfy transcript integrity with respect to a modification function \mathcal{M} as per Definition 3.3, where \mathcal{M} takes as input a message $m = ((p_i)_{i=1}^{n_p}, (c_{i0}, c_{i1})_{i=1}^n, (s_i)_{i=1}^{n_s})$ and outputs the set $\{((p_i)_{i=1}^{n_p}, (c_{ib_i})_{i=1}^n, (s_i)_{i=1}^{n_s}) \mid b_i \in \{0, 1\}\}$.

Proof (Sketch). As per the GenToken protocol, P authenticates TLS records containing repeated sequence numbers only for challenge message pairs (c_{i0}, c_{i1}) for $i = 1$ to n and otherwise follows strict sequence ordering. This restricts V to drop exactly one ciphertext ec_{ib_i} from each ciphertext pair (ec_{i0}, ec_{i1}) and sequentially forward all other TLS records, otherwise S will abort the connection as per the integrity guarantees of TLS. Thus, if S does not abort, it only obtains a message $m' \in \mathcal{M}(m)$. \square

Theorem 5.4. The protocols presented in Section 4 satisfy server obliviousness with respect to \mathcal{D} as per Definition 3.4, where \mathcal{D} is the distribution defined in Section 4.

Proof (Sketch). If both P and V are honest then by the properties of TLS, S obtains a message $m' = ((p_i)_{i=1}^{n_p}, (c_{ib_i})_{i=1}^n, (s_i)_{i=1}^{n_s})$ for some $b_i \in \{0, 1\}$, where P sent the message $m = ((p_i)_{i=1}^{n_p}, (c_{i0}, c_{i1})_{i=1}^n, (s_i)_{i=1}^{n_s})$ to the TLS channel. If m was chosen by adding small noises to the images, then m' is indistinguishable from a message sampled from \mathcal{D} because of the arguments mentioned in Section 4. Hence, we achieve server obliviousness. \square

6 IMPLEMENTATION AND EVALUATION

We demonstrate the feasibility of YouChoose by implementing a prototype using only open-sourced libraries. We write our codebase in Python using `tlslite-ng` [18] as our TLS library. However, we tailor this library to allow fragmentation of email body as described in Section 4, and to accept sequence numbers as parameters at interfaces like `_encryptthenSeal` (AES-GCM

and ChaCha20/Poly1305) and `_macThenEncrypt` (AES-CBC / HMAC-SHA256). This adaptation enables us to support various TLS ciphersuites effectively. We use `smtplib` within `tlslite-ng` to send emails according to the SMTP specifications. Further, to support oblivious transfer as described in Section 4.2, we use the OTC library [19]. Our implementation is available at this github link.⁶

In our experiments, P runs on a laptop with an AMD Ryzen 5 (4500U) 6-core processor with 8GB of RAM, V runs on an Amazon EC2 t2.micro instance hosted in the ap-south-1 region, and S is a mail server provided by MailTrap [20]. To evaluate the performance of our prototype, we measure the overhead incurred by YouChoose compared to a simple email exchange between P and S where the email body is of size 2.5MB and V acts as a passive proxy that does not modify or drop any messages. We choose such a baseline to prevent network latencies between P , V and S from confounding the overhead incurred by YouChoose. The size of the email body for the baseline was chosen as such because as shown in Section 4, YouChoose requires the email body to be of size at least 2.5MB for maintaining server obliviousness.

Compared to the baseline, we observed that the overhead incurred by both P and V in both the variants of YouChoose (AES-CBC/HMAC and AES-GCM including OT) was negligible (a few milliseconds). This establishes that from a performance point of view anonymous PAO using YouChoose behaves as if a standard email transaction where the email body is of size 2.5MB.

In the case of SCI, Wang et al. report timings only for the AES-CBC/HMAC-SHA256 ciphersuite, and count the overhead of its constituent 2P-HMAC and 2P-CBC sub-protocols. For AES-GCM, although they provide another specialized MPC protocol, they do not provide any performance benchmarks. The total overhead reported for SCI’s 2P-HMAC and 2P-CBC protocols is around 8-10s, in contrast to the negligible overhead introduced by YouChoose. Further, the size of the email forced upon by SCI is also comparable to that forced upon by YouChoose (2.5MB) because the recommended way in SCI to hide challenges in the email body and achieve server obliviousness is to embed them in an image or media file, which are typically in MBs.

7 CONCLUSION AND FUTURE WORK

We formalized the security requirements for anonymous PAO and proposed YouChoose, a lightweight approach to meet these security guarantees. Our approach provides a simple way to achieve anonymous PAO without resorting to specially designed MPC protocols for different proofs of account ownership. We demonstrate our approach for email account ownership using SMTP over TLS. Specifically, we implemented the first anonymous PAO that works with all the ciphersuites of TLS 1.2 and 1.3. The overhead introduced in our anonymous PAO is not more than the time required to send a typical email containing an image file as an attachment.

Anonymous PAOs introduced by Wang et al. [1] are an important primitive to provide the necessary security and privacy guarantees for extremely sensitive uses cases such as whistleblowing.

However, they present interesting opportunities in other use-cases as well. In this regard, we conjecture that the following directions are worth exploring in the future:

1. **Anonymous PAO for other account types.** Although both our work and Wang et al.’s work has focused on email-based anonymous PAO, it appears that anonymous PAO for other account types such as social media accounts may have other interesting use-cases. For example, many Internet based service providers need to verify that the account owners on their website are genuine and for this purpose they trust social-media identity providers such as Google, Facebook and Twitter. However, the current technologies for this purpose (e.g., OAuth [21]) reveal to the identity providers the services availed by the user. Furthermore, tracking users is in the business interest of these identity providers. Anonymous PAOs fit in this setup perfectly as they allow the users to anonymously prove to the service providers that they own a genuine social media account without even requiring any co-operation from the social media account providers. For such a use-case, an MPC-based SCI approach is likely to be expensive and cumbersome to implement. In contrast to the MPC-based SCI protocol in email-based account ownership that exploits the fixed format of the SMTP protocol messages, the format of messages exchanged in these social media account APIs is likely to be more complex and dynamic. The YouChoose approach of selectively forwarding messages does not require any MPC protocol and is thus likely to be a more suitable fit.
2. **Shared email hosting.** We now point out a limitation of YouChoose and SCI’s paradigm of email-based anonymous PAO where V sends a challenge to S and considers a reproduction of this challenge by P as a proof that P owns an email account at the domain of S . For example consider a common case where the organization controlling the domain `domain.com` outsources its email services to third party providers such as Gmail (Google Workspace [22]). In this case, P , an employee at the organization wants to prove to V that it owns an email address of the form `____@domain.com` but the outsourced mail server S provides its services to other organizations too, say `domain2.com`. Now, when V forwards its challenge to S , and this challenge is reproduced by P , V is not convinced that P owns an account at `domain.com` or `domain2.com`. Such use-cases are completely beyond the general paradigm of both YouChoose and SCI. For this, one could leverage a modified version of the “parse-and-extract” protocol from recent research on zero-knowledge middleboxes (ZKMBs [23]). This will prove to V in zero-knowledge that P ’s email address (used in the SMTP AUTH step) ends with `domain.com`. We leave this thread open for future work.

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⁶Link: <https://github.com/aarav22/anon-pao>

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