Practical Anonymous Subscriptions

Alan Dunn, Jonathan Katz, Sangman Kim, Michael Lee, Lara Schmidt, Brent Waters, Emmett Witchel
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Anonymous subscriptions

Provide registered/paid users with the ability to log in and access a service…

…while remaining anonymous…

…yet still allowing the server to enforce admission control

I.e., users cannot share their login with friends
System model

Time broken into a series of well-defined *epochs*
Anonymity/unlinkability

- Cannot link a user login to a user registration
- Cannot link logins by the same user (in different epochs) to each other
Anonymity/unlinkability
Each registered user can only have one active login per epoch

- I.e., a user cannot freely share their login information with their friends
- (Formal definition later)
Soundness
How long is an epoch?

Shorter epochs $\Rightarrow$ better anonymity

Longer epochs $\Rightarrow$ less computation
How long is an epoch?

- Here: **conditional linkability**
  - Logged in user can choose to “re-up” his login for the next epoch
    - Re-up is cheaper than a login
  - Allows server to link user across epochs
    - User decides when this is acceptable
    - User can do a full login if unlinkability is desired
Related (but different)

- Anonymous credentials, DAA, group signatures
  - Anonymity, but no admission control

- Anonymous blacklisting systems
  - Anonymity, revocation, but no notion of per-epoch admission control

- E-cash
  - Anonymity, double spending detected, but no notion of unlimited re-use
Related work

- Unclonable authentication
  [Damgård, Dupont, Østergaard]

- n-time anonymous authentication
  [Camenisch et al.]
    - Uses prior ideas from e-cash
      [Camenisch, Hohenberger, Lysyanskaya]
    - Different model – multiple verifiers, traceability after the fact
Our contributions

- **More efficient, simpler** construction
  - “Weaker” cryptographic assumptions
  - Cleaner definitions

- **Conditional linkability** for improved efficiency

- **Implementation** and system evaluation
What we do *not* prevent

- Users sharing login information to use at *different* times

- **Other ways** of breaking anonymity
  - Traffic analysis, IP addresses
  - User behavior
  - History of accessed content

- Address using complementary techniques
Functional definition I

- **Setup** – server generates public/private keys; initializes state including *cur/next*

- **Registration** – user/server interact; user obtains secret key sk (or error)
Functional definition II

- **Login** – Using sk and the current epoch number, user logs in to server
  - Server increments `cur`

- **Link** (“re-up”) – User currently logged in during epoch $t$ can log in for epoch $t+1$
  - Server increments `next`
Functional definition III

- **EndEpoch** – server refreshes state; updates `cur/next`
  - `cur = next; next = 0`
Security definitions

- (Honest) user is **logged in** at some point in time if (1) that user previously ran Login in that epoch, or (2) at some point in previous epoch, user was logged in and ran Link

- (Honest) user $i$ is **linked** at some point in time if at some previous point during that epoch, user was logged and ran Link
Soundness (informal)

- Attacker registers any number $N$ of users; honest users also register
- Attacker interacts with server arbitrarily
- Honest users login/link (so affect server state), but attacker cannot observe
- Attacker controls when epochs end

Attacker \textbf{succeeds} if, at any point in time, $\text{cur} > N + \#\text{honest users logged in}$
Anonymity (informal)

- **Phase 0**
  - Attacker outputs arbitrary public key
  - Two honest users register (and get secret keys)
- **Phase I**
  - Attacker induces honest users to Login/Link
- **Phase II – neither user logged in**
  - Users either permuted or not
  - Attacker induces honest users to Login/Link

**Attacker succeeds** if it can guess whether users were permuted in Phase II (with significantly better than \( \frac{1}{2} \) probability)
Construction (intuition)

- **Registration**: user gets “anonymous credential” $C$ (i.e., a re-randomizable blind signature) on PRF key $k$

- **Login** in epoch $t$: user sends $C' + F_k(t) + \text{ZK proof of correctness}$
  - Server verifies signature and proof; checks that $F_k(t)$ not in table; stores $F_k(t)$ in table

- **Link** in epoch $t$: user sends $F_k(t) + F_k(t+1) + \text{ZK proof of correctness}$
  - Look up $F_k(t)$ in table; verify proof; add $F_k(t+1)$
Construction (further detail)

- Anonymous credential is based on variant of Camenisch-Lysyanskaya signatures
  - Public key = \((g^x, g^y, g^z)\)
  - Signature on \((d, r)\) is \((g^a, g^{ay}, g^{azy}, g^{ax}(g^dZ^r)^{axy})\)
  - Re-randomizable, blindable, efficient ZK proofs

- Dodis-Yampolskiy PRF
  - \(F_k(t) = g^{1/(k+t)}\)
  - Compatible with various efficient ZK proofs
Construction (further detail)

- Registration

User:
\[ d, r \leftarrow \mathbb{Z}_q \]

\[ M = g^d Z^r \]

Server:
\[ a \leftarrow \mathbb{Z}_q \]

PoK \((d, r)\)

\[ g^a, g^{ay}, g^{ayz}, g^{ax}M^{axy} \]

Verify…
**Construction (further detail)**

- **Login** (epoch t)

User:
- sk = (A, B, Z_B, C, d, r)
- \( r, s \leftarrow Z_q \)

Server:
- \( A^r, B^r, Z_B^r, C^{rs} \)
- \( Y = g^{1/(d+t)} \)

**PoK**
- (d in signature matches d in Y)

Verify:
- Y not in table
Construction (further detail)

- **Link** (epoch t)

User

\[ Y = g^{1/(d+t)}, \quad Y' = g^{1/(d+t+1)} \]

Server

\[ \text{sk} = (A, B, Z_B, C, d, r) \]

Y in table?

PoK

(Y and Y’ have correct form, and d in Y matches d in Y’)

Construction (further detail)

- ZK proofs (of knowledge) fairly standard
  - Made non-interactive using Fiat-Shamir
Security guarantees

- Soundness holds under **LRSW assumption** (essentially, unforgeability of CL signatures)

- Anonymity holds under **DDHI assumption**
  - $g^{1/x}$ “looks random” even given $g^x, \ldots, g^{xn}$

- Note: in our security proofs, we assume extraction from all ZKPoKs is possible
  - Can be enforced if interactive proofs are used and sequentiality is enforced
  - Heuristic security if Fiat-Shamir proofs are used
System architecture
Only loose synchronization needed
- Server sends timestamp when connection is established
- User caches previous timestamp to prevent rollback attacks on anonymity

Login + (multiple) link(s) are done more efficiently than running Login, Link, …
Implementation

- Using PBC library [Lynn] and PolarSSL
  - Symmetric pairing; 160-bit elliptic-curve group over 512-bit field
- 1400 loc
- Pre-processing used when possible
### Raw performance

<table>
<thead>
<tr>
<th></th>
<th>User</th>
<th>Server</th>
</tr>
</thead>
<tbody>
<tr>
<td>Login</td>
<td>13.5 ms</td>
<td>7.9 ms</td>
</tr>
<tr>
<td>Link</td>
<td>1.3 ms</td>
<td>0.72 ms</td>
</tr>
</tbody>
</table>

(quad-core 2.66 GHz Intel Core 2 CPU, 8GB RAM)
Evaluation I

- Integrated our system into a streaming-music service
  - 7500 users
  - Epoch length = 15 seconds
  - Acceptable performance in terms of playback delay/latency; details in paper
Evaluation II

- Anonymous public-transit passes
  - Epoch length = 5 minutes
  - Estimate <10 servers could handle BART peak-traffic volumes

- Implemented user agent as Android app
  - Login message displayed as QR code for physical scanner to read
  - No network connectivity required
  - Login time: 220 ms (HTC Evo 3D)
Conclusions

- Design, implementation, and evaluation of a system providing **anonymous subscriptions**

- Formal definitions, cryptographic proofs

- Performance acceptable for practical applications