Bloom Filter Encryption and Applications to Efficient Forward-Secret 0-RTT Key Exchange

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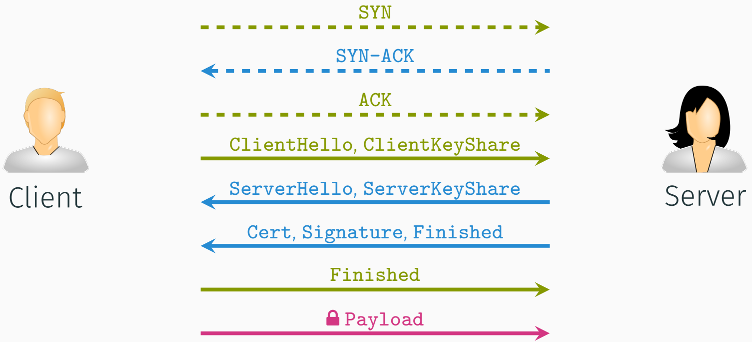
Key Establishment with TLS



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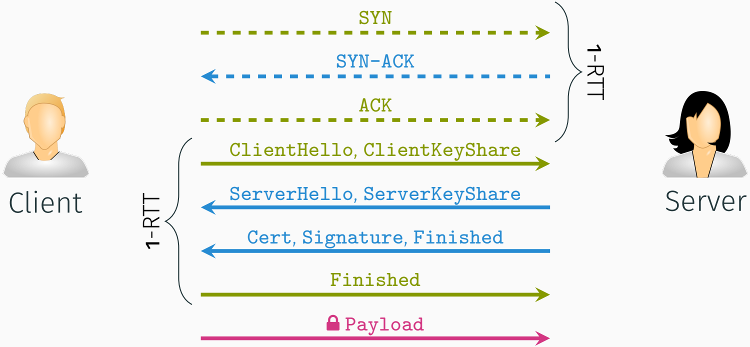

» 2-RTTs before first payload message

? Is this necessary

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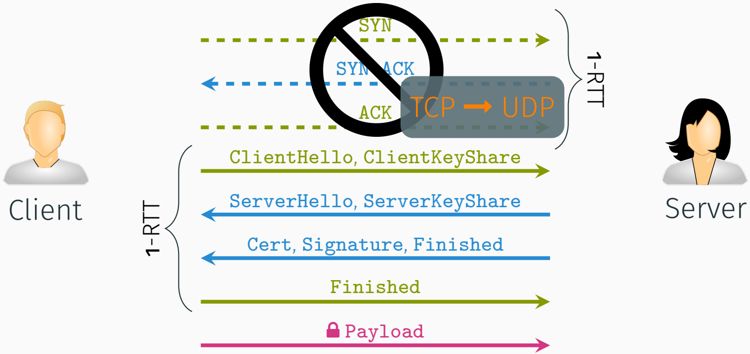

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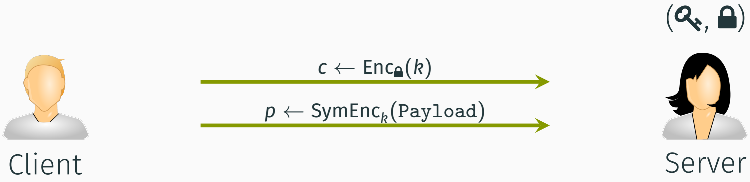
Send cryptographically protected payload in first message (0-RTT KE)?

Trivial Protocol



Major deficiencies:

- No forward secrecy
- Vulnerable to replay attacks

Existing Approaches

0-RTT in TLS1.3/QUIC

- First session 1-RTT, session resumption 0-RTT
- ✔ Replay protection
- ? Forward secrecy for most transmitted data

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Full forward secrecy, replay protection, and 0-RTT?

- A priori not even clear if possible
- Günther, Hale, Jager, and Lauer at EUROCRYPT'17
- » Using puncturable encryption (Green, Miers at S&P 2015)

Puncturable Encryption

Conventional encryption scheme:

- $(\mathsf{KeyGen}, \mathsf{Enc}, \mathsf{Dec})$

+ Additional algorithm 🔑$' \leftarrow \mathsf{Punc}($🔑$, C)$

Properties

- 🔑$'$ no longer useful to decrypt C
- 🔑$'$ still useful to decrypt other ciphertexts
- Repeated puncturing possible

Puncturable Encryption

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fs 0-RTT KE via puncturable encryption

- Client encrypts message under public key 🔒
- Server decrypts using secret key 🔑′
- Server punctures 🔑′ on C

Our Approach

Downsides of existing approaches

- Puncturing and/or decryption expensive

  (experiments by authors of [GHJL17]: 30s - several minutes)

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Observation

- Can accept somewhat larger (secret) keys
- Can accept non-negligible correctness error
- For example, 1 in 1000 sessions fail

» Can fall back to 1-RTT in this case

Bloom Filters

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

1 m

- Initial state $T := 0^m$
- k universal hash functions $(H_j)_{j \in [k]}$
- $H_j : \mathcal{U} \to [m]$
- Throughout this talk, let $k = 3$

Bloom Filters

$\{x, y, z\}$

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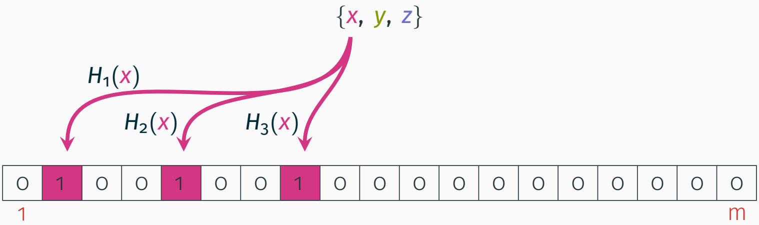

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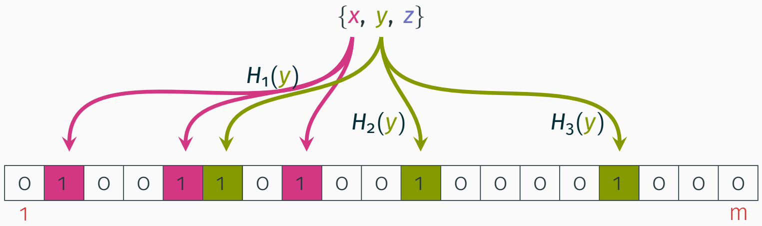

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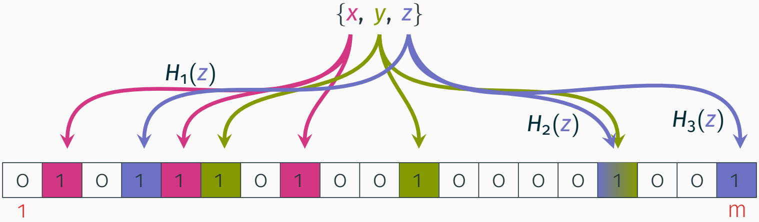
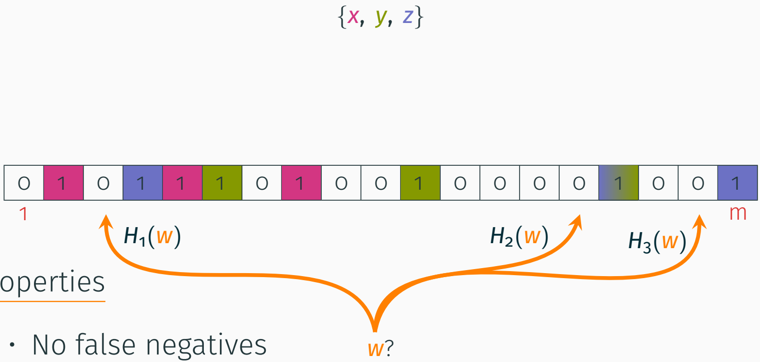


Properties

- No false negatives

Bloom Filters



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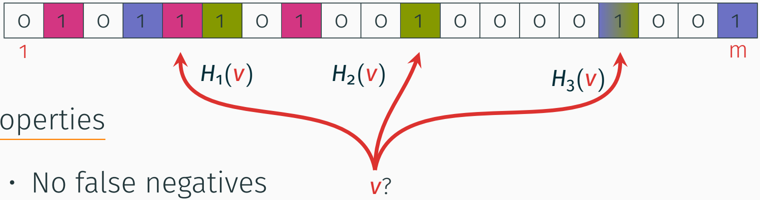

Properties

- No false negatives
- **False positives possible**

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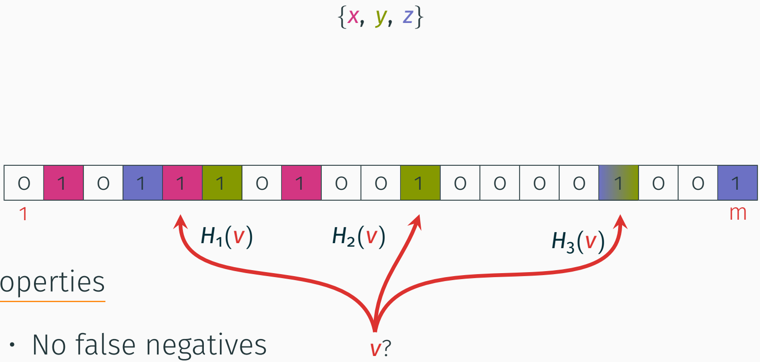


Properties

- No false negatives
- **False positives possible**
- Probability determined by k, m, and # inserted elements

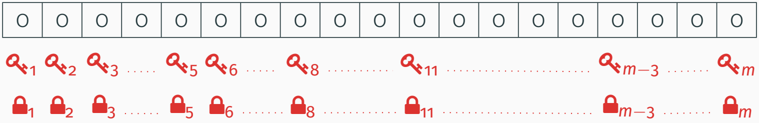
Bloom Filter Encryption

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

KeyGen

- Set up BF

Bloom Filter Encryption



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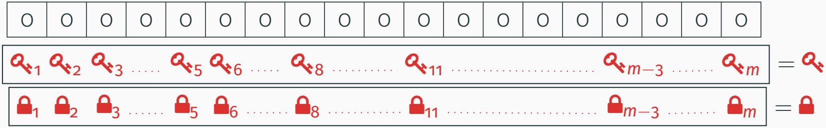
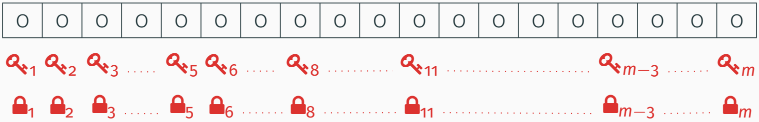


KeyGen

- Set up BF
- Associate key pair to each bit
- Compose BFE key pair (,)

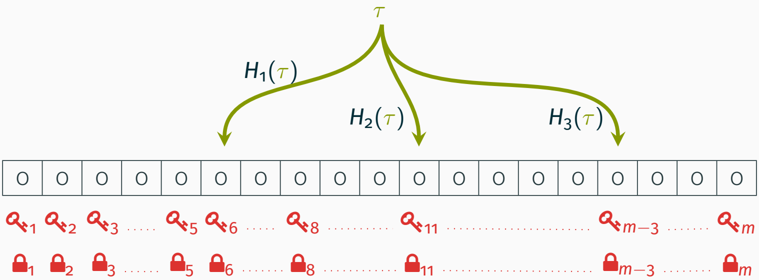
Bloom Filter Encryption



Encrypt message M

- Randomly choose tag τ

Bloom Filter Encryption



Encrypt message M

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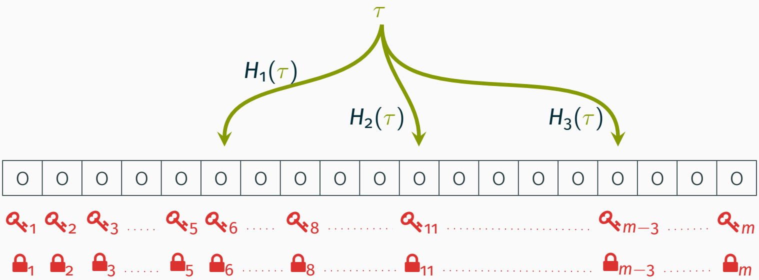

Encrypt message M

- Randomly choose tag τ
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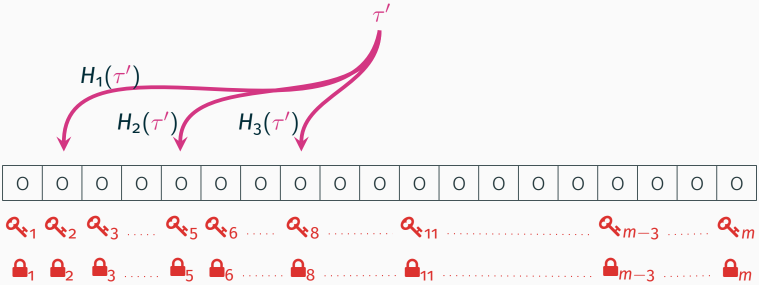
- $C_\tau \leftarrow \mathsf{Enc}_{🔒_6 \vee 🔒_{11} \vee 🔒_{m-3}}(M)$

Bloom Filter Encryption

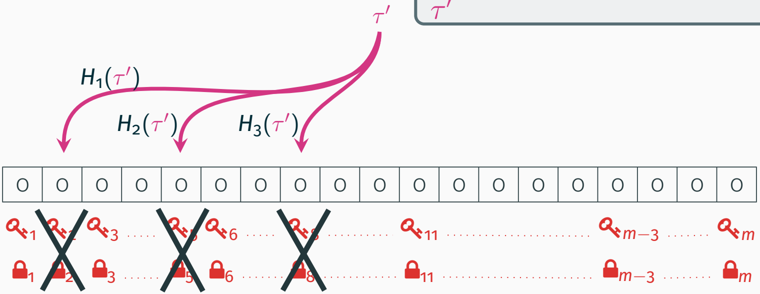


Puncture ciphertext $C_{\tau'}$

- Determine BF indexes from τ'

Bloom Filter Encryption

ℹ Secret key no longer useful to decrypt $C_{\tau'}$ with associated tag τ'



Puncture ciphertext $C_{\tau'}$

- Determine BF indexes from τ'
- Delete associated keys

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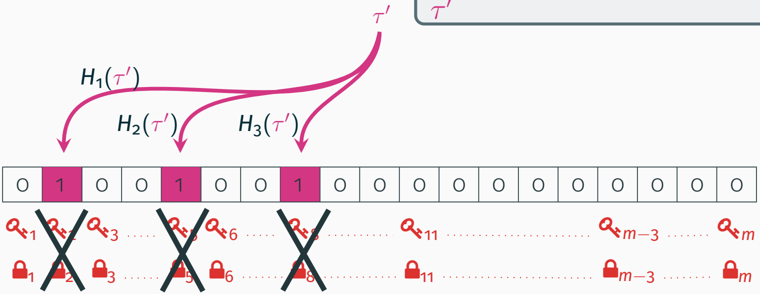
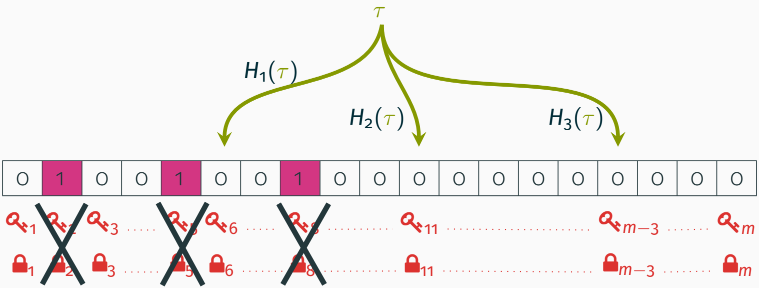


Puncture ciphertext $C_{\tau'}$

- Determine BF indexes from τ'
- Delete associated keys
- Update BF state

Bloom Filter Encryption



Decrypt ciphertext C_τ

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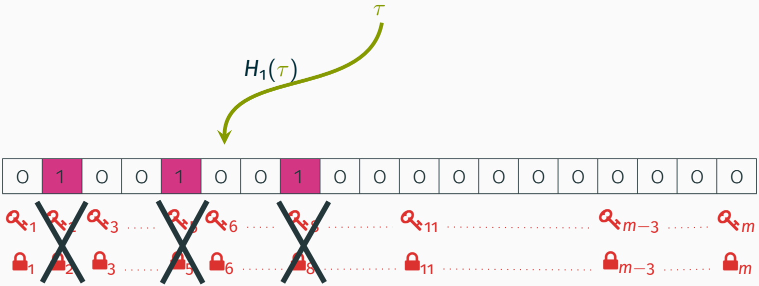

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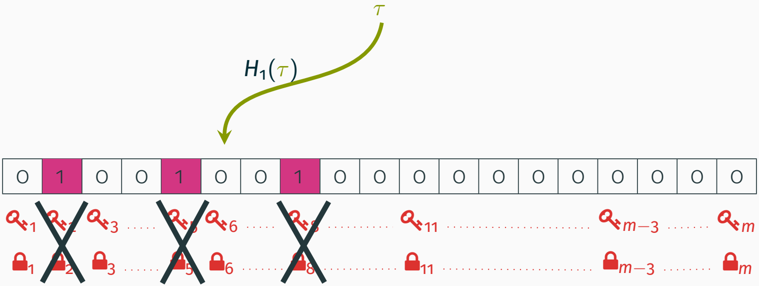

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- $M \leftarrow \mathsf{Dec}_{sk_6}(C_\tau)$

Example BF Parameters

We let

- Maximum # of elements in BF: 2^{20}

$\approx$ 2^{12} puncturings/day for full year

- False positive probability: 10^{-3}

Then we get

- BF size $m = {}^{n \ln p}/_{(\ln 2)^2} \approx 2MB$
- # hash functions $k = \lceil {}^{m}/_{n} \ln 2 \rceil = 10$

Instantiations

Three instantiations with different trade-offs

» Identity-based encryption (IBE)

» Attribute-based encryption (ABE)

NEW Identity-based broadcast encryption (IBBE)[1]

[1]Construction by Kai Gellert in extended version (ePrint 2018/199)

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NEW Identity-based broadcast encryption (IBBE)[1]

Construction	|🔒|	|🔑|	$\lvert C \rvert$	Dec	Punc
IBE [Crypto'01]	$O(1)$	$O(m)$	$O(k)$	$O(k)$	$O(k)$
ABE [CT-RSA'13, AC'15]	$O(m)$	$O(m^2)$	$O(1)$	$O(k)$	$O(k)$
IBBE [AC'07]	$O(k)$	$O(m)$	$O(1)$	$O(k)$	$O(k)$

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Based on Boneh-Franklin (BF) IBE

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  - Original keys have perfect correctness
  - Semi correctness of punctured keys

» Publicly-checkable puncturing

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Works generically for all our approaches!

Instantiations contd’

Extensions

- Time-based BFE (TBBFE)
- Enable multiple time intervals
- Similar approach as [GM S&P’15, GHJL EC’17]

Use hierarchical identity-based encryption (HIBE) scheme

- Tree of identities

» Upper part represent time intervals

» Lower part represent the bits of BF

(as in BFE)

Comparison of TB-BFEs

Scheme	**Dec** (online)	**PuncCtx** (online)	**PuncInt** (offline)
2^w time slots			
GM [S&P'15]	$O(p)$	$O(1)$	$O(w^2)$
GHJL [EC'17]	$O(\lambda^2)$	$O(\lambda^2)$	$O(w^2)$
Ours	$O(k)$	$O(k)$	$O(w^2 + m)$

With m size of BF, k # hash functions (e.g., $k = 10$), $\lambda \geq 120$, p number of puncturings already performed

Conclusions

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Our approach

- ✔ Offload expensive ops to less critical phases (key generation, resp. switch of time interval for TB)
- ✔ Very efficient decryption
- ✔ Only deletions & hash evaluations upon puncture
- ✔ Conjectured dec. & punc. times in order of milliseconds
- ✔ Applications of BFE beyond 0-RTT KE?

Thank you!

Full version: `https://eprint.iacr.org/2018/199`