MoMA LAB

NDSS

Recurrent Private Set Intersection for Unbalanced Databases with Cuckoo Hashing and Leveled FHE

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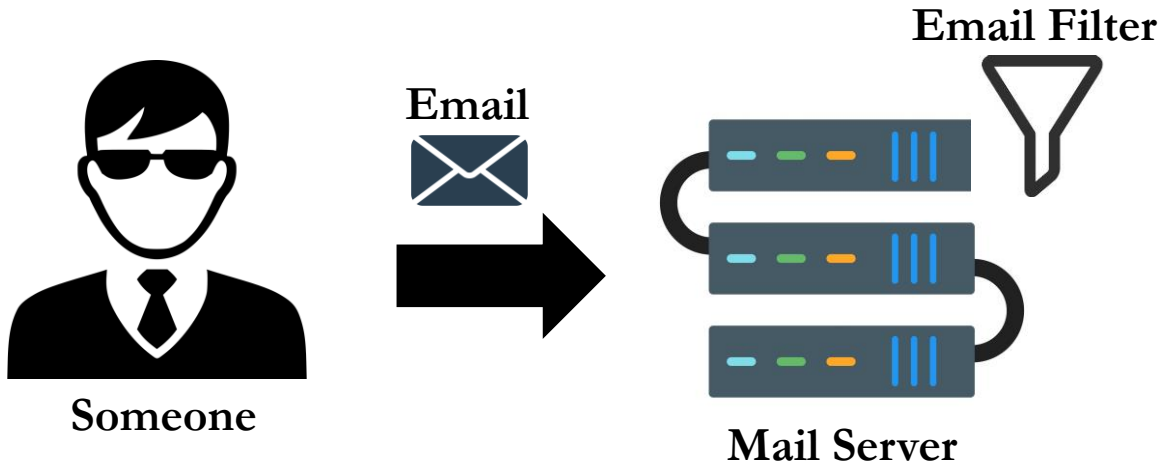
URL Denylisting / Email Filtering



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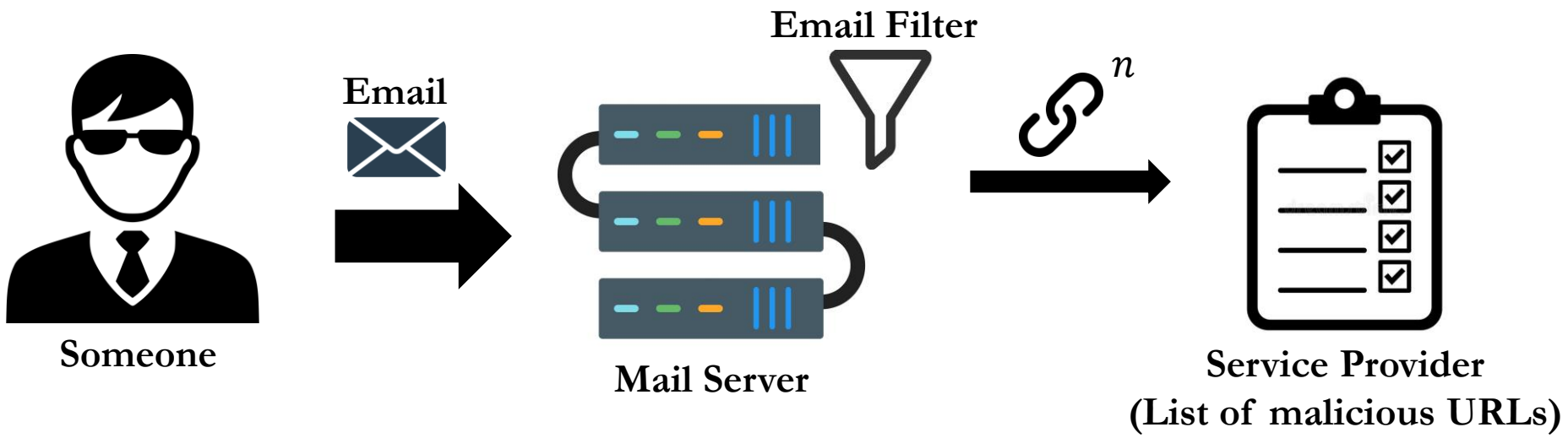

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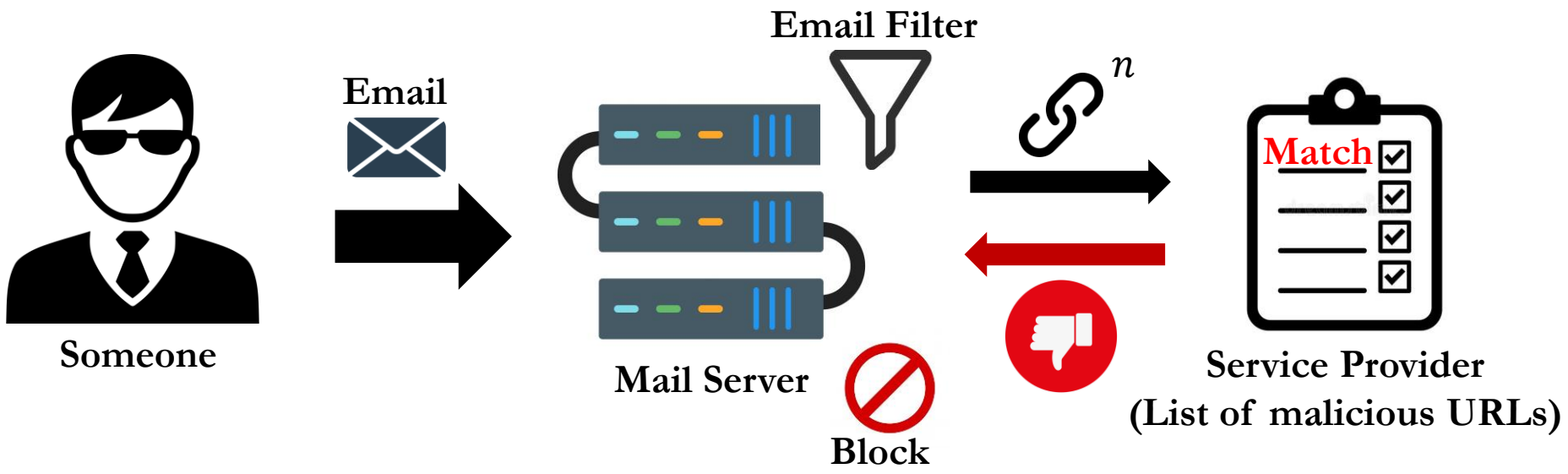

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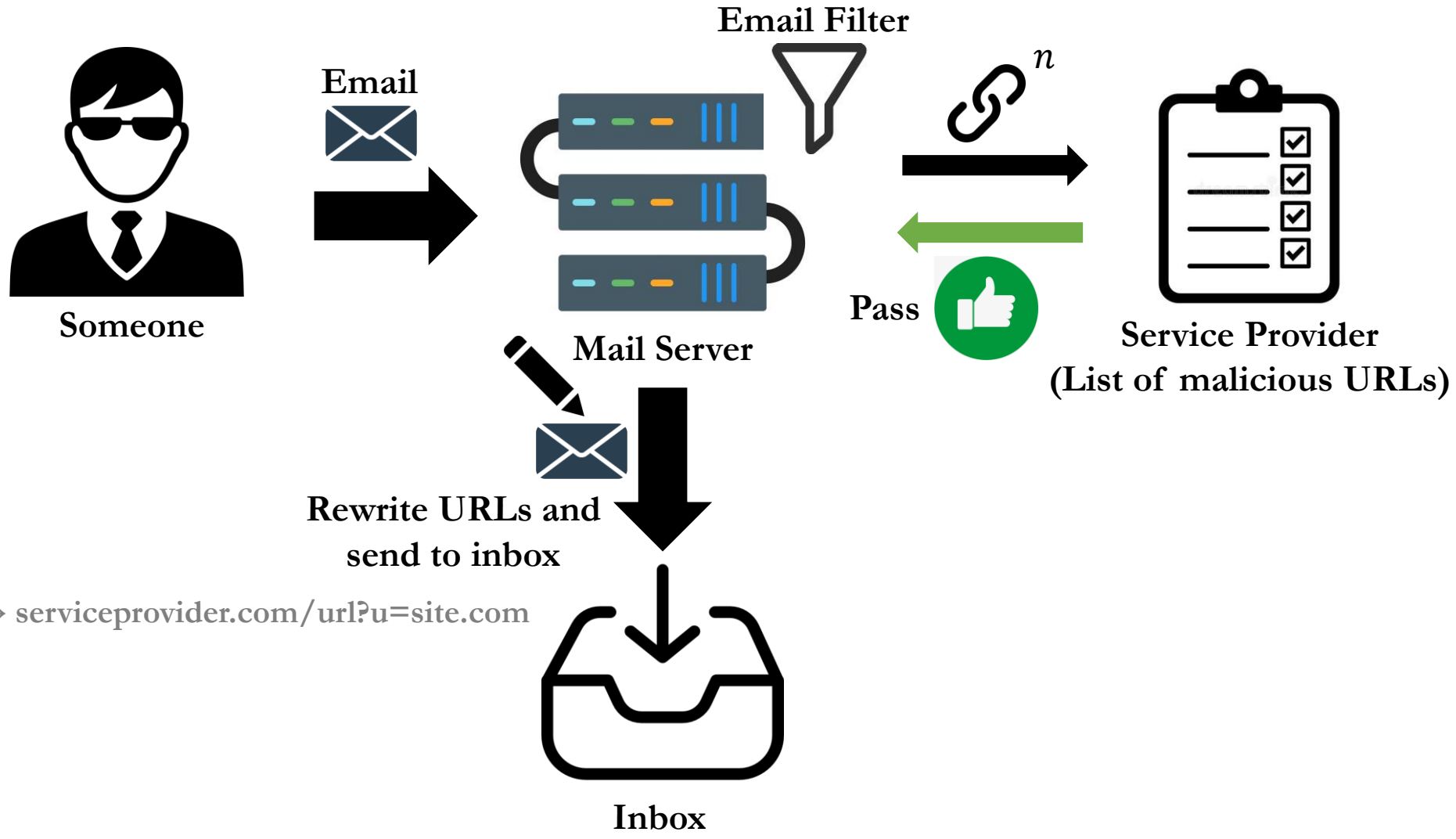

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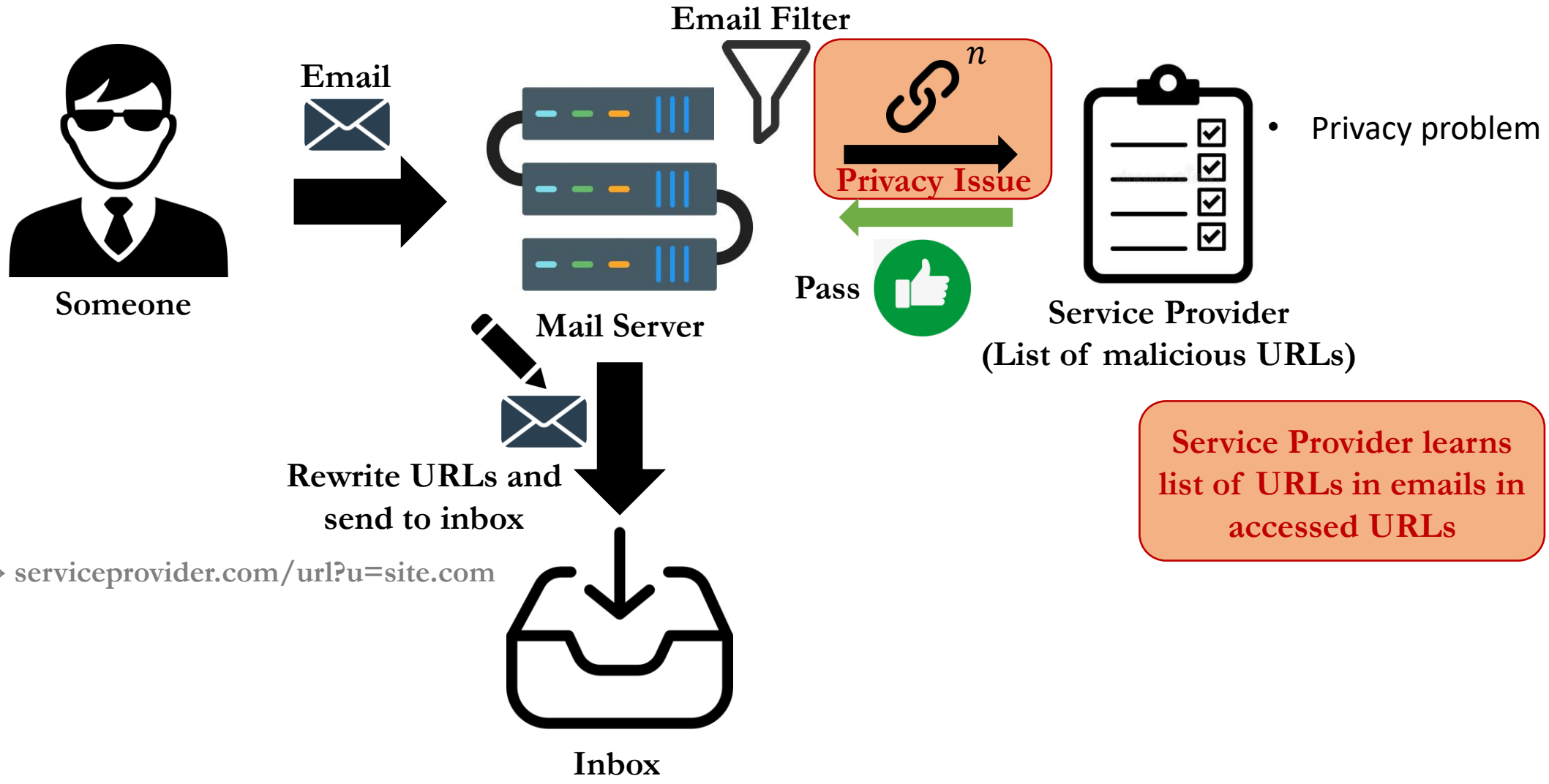

- Privacy problem

Service Provider learns list of URLs in emails in accessed URLs

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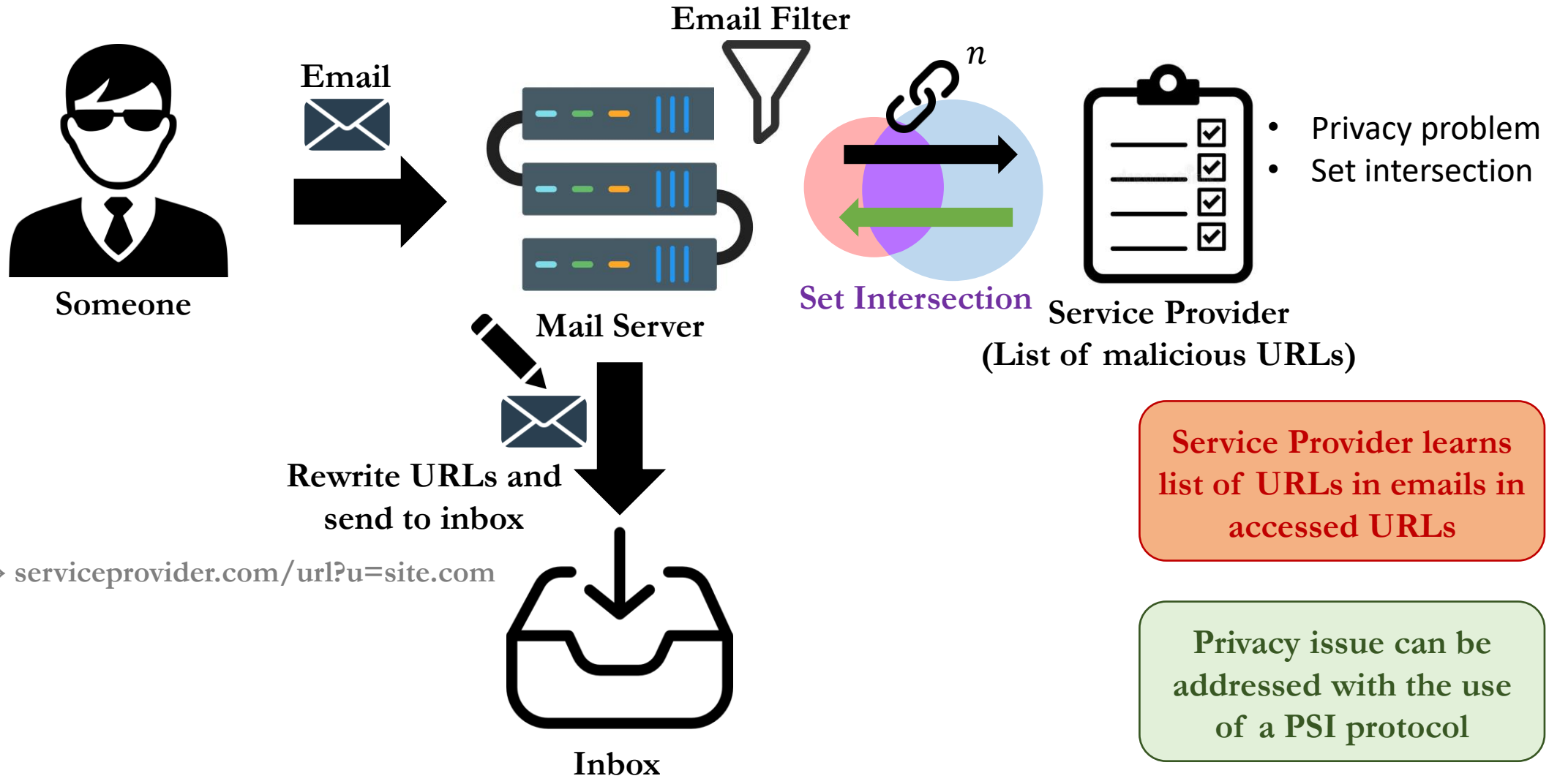

- Privacy problem
- Set intersection

site.com → serviceprovider.com/url?u=site.com

Service Provider learns list of URLs in emails in accessed URLs

Privacy issue can be addressed with the use of a PSI protocol

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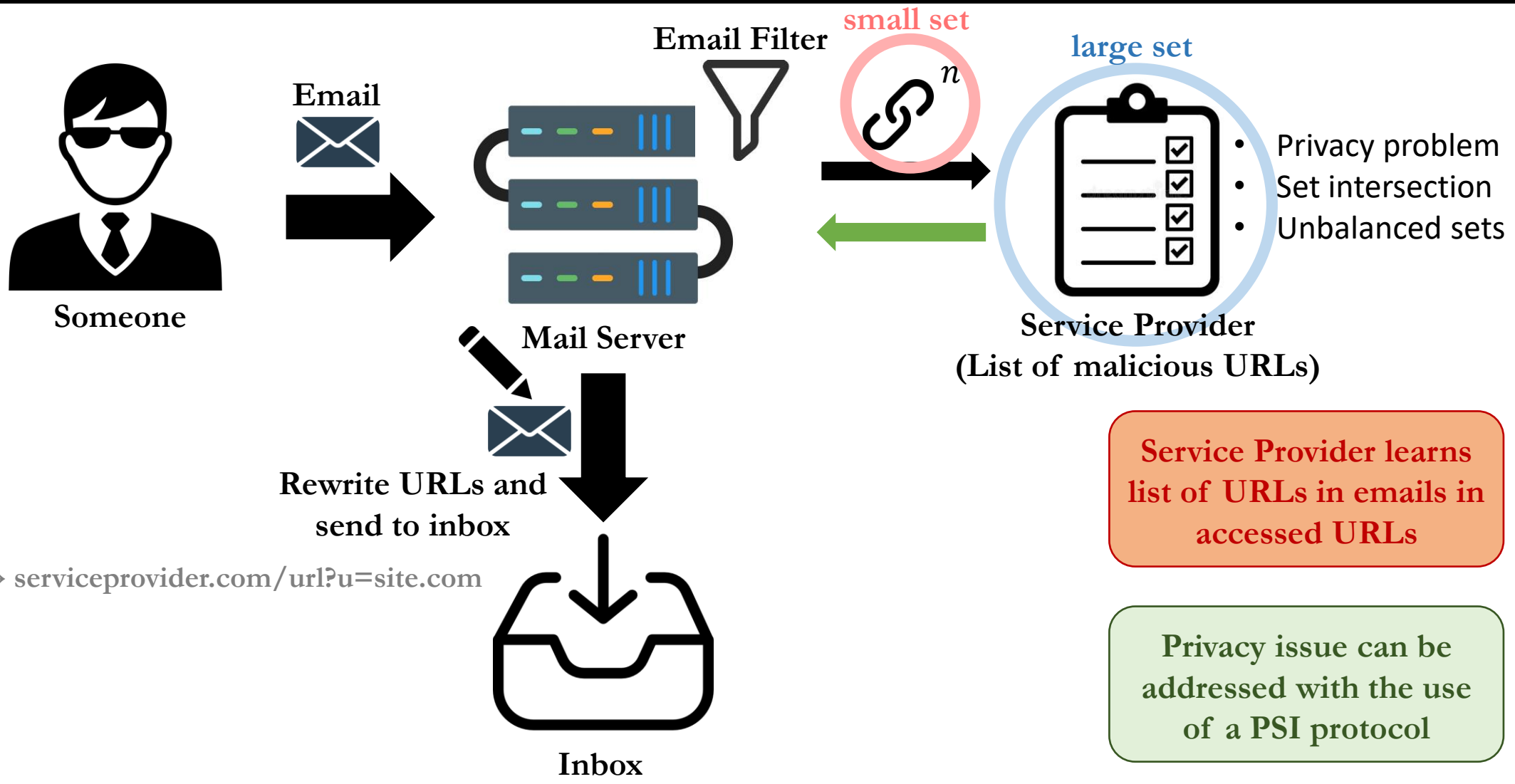

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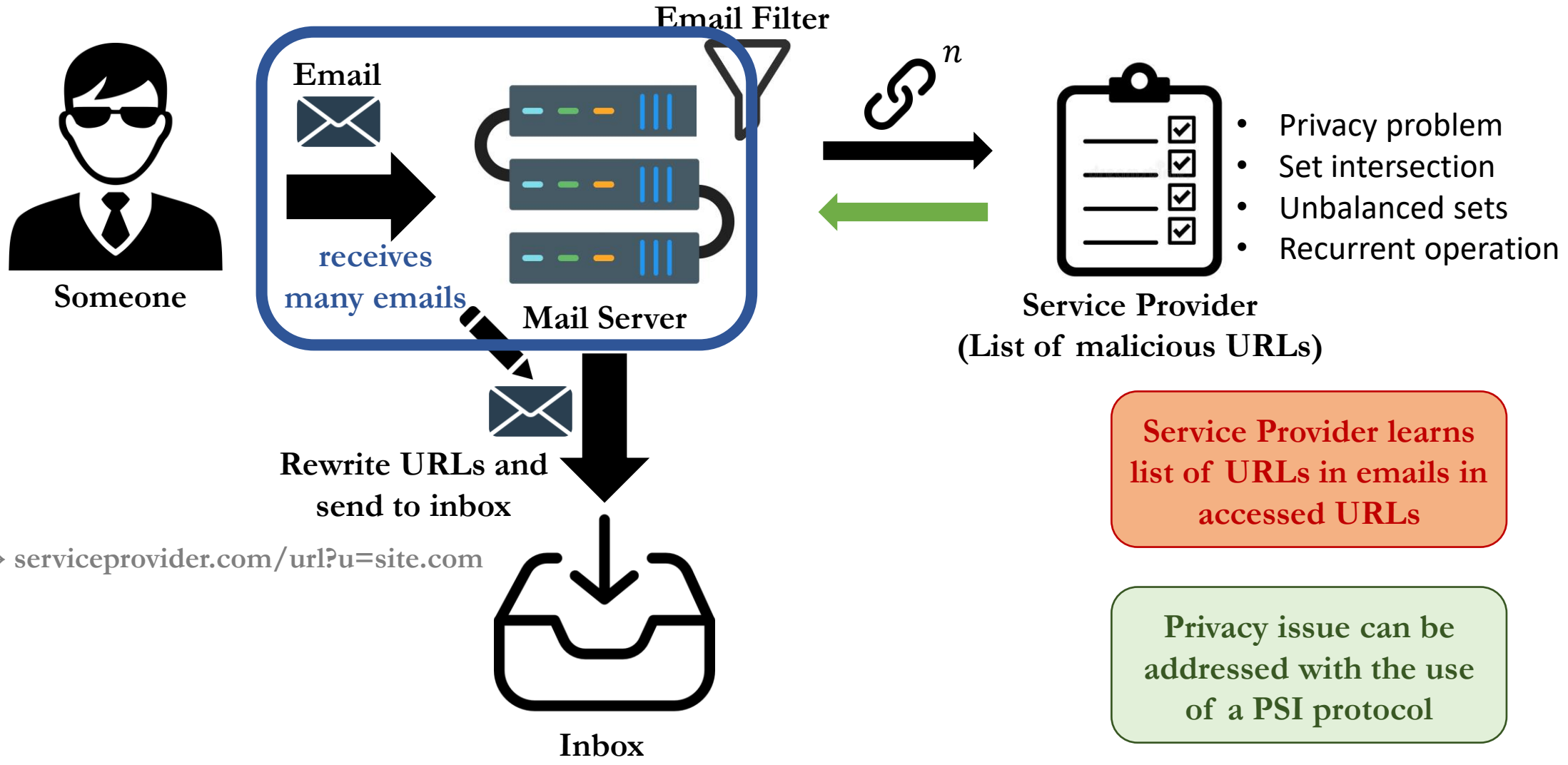

Contributions

- **Developed a PSI protocol for recurrent set intersection**

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- **One-time cost on the large set and linear recurrent cost on the smaller set**
- **Proposed optimizations to reduce computation time and communication**
- **Reduce intersection time by one/two OOM compared to SOTA on slow/fast networks**

Recurrent time (s) for $|X| \approx 2^{20}, |Y| = 4$

Protocol	10 Gbps	100 Mbps
This work	0.03	0.24
CLR [1]	2.21	2.81
KKRT [2]	1.67	6.46
PSSZ [3]	0.88	2.94

[1] Hao Chen, Kim Laine, and Peter Rindal. "Fast private set intersection from homomorphic encryption." *CCS*, 2017.
[2] Vladimir Kolesnikov, Ranjit Kumaresan, Mike Rosulek, and Ni Trieu. "Efficient batched oblivious PRF with applications to private set intersection." CCS, 2016.
[3] Benny Pinkas, Thomas Schneider, Gil Segev, and Michael Zohner. "Phasing: Private set intersection using permutation-based hashing." *USENIX Security, 2015.*

Proposed PSI Protocol

(Blueprint) Basic Protocol

Protocol 1 Basic Protocol

Input: $\mathcal{S}$ inputs set X and $\mathcal{R}$ inputs set Y. Both sets consist of bit strings of length σ. Sizes $|X|$, $|Y|$, and σ are public.
Output: $\mathcal{S}$ outputs $\perp$; $\mathcal{R}$ outputs $X \cap Y$.

1) **Setup**: Parties agree on a Fully Homomorphic Encryption scheme and encryption parameters (n, q, t).
2) **Set encryption**: $\mathcal{S}$ encrypts each element $x_i \in X$ under its own key, and sends the $|X|$ ciphertexts $\overline{X} = (\overline{x_1}, ..., \overline{x_{|X|}})$ to $\mathcal{R}$.
3) **Computing intersection**: For each $y_j \in Y$, $\mathcal{R}$:
   a) samples a random plaintext $r_j \in \mathbb{Z}_t$ from a uniform distribution;
   b) homomorphically computes
   $$\overline{d_j} = r_j + \prod_{i=1}^{|X|} (\overline{x_i} - y_j)$$
   c) encrypts $r_j \mapsto \widehat{r_j}$ under its own key;
   d) sends $\overline{d_j}$ and $\widehat{r_j}$ to $\mathcal{S}$.
4) **Decryption**: For each $(\overline{d_j}, \widehat{r_j})$, $\mathcal{S}$:
   a) decrypts $\overline{d_j} \mapsto d_j$;
   b) samples a non-zero random plaintext value $\rho_j \in \mathbb{Z}_t \backslash \{0\}$ from a uniform distribution;
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   $$\widehat{e_j} = (\widehat{r_j} - d_j) \cdot \rho_j$$
   d) sends $\widehat{e_j}$ to $\mathcal{R}$.
5) **Result**: $\mathcal{R}$ decrypts $\widehat{e_j} \mapsto e_j$ and outputs
   $$X \cap Y = \cup_{j=1}^{|Y|} \{y_j : e_j = 0\}$$

Receiver **Sender**

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encrypts set with Sender's key

sends encrypted set

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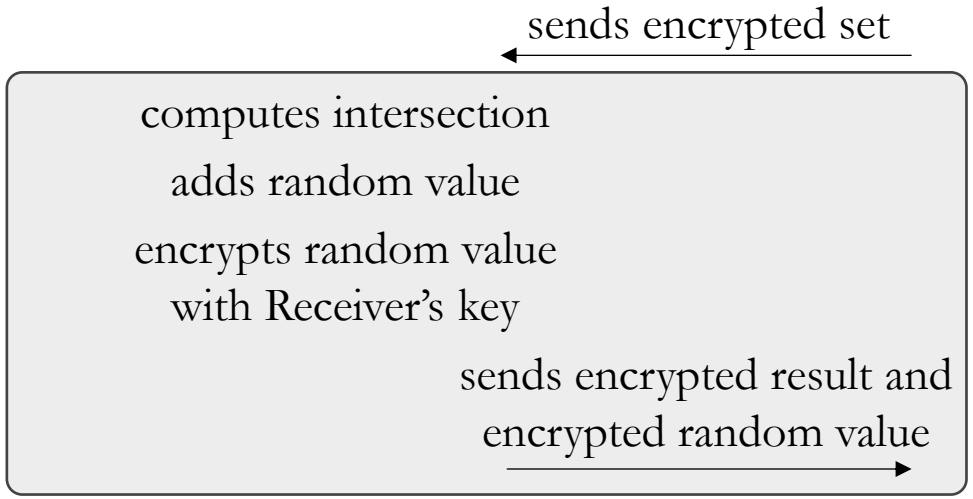

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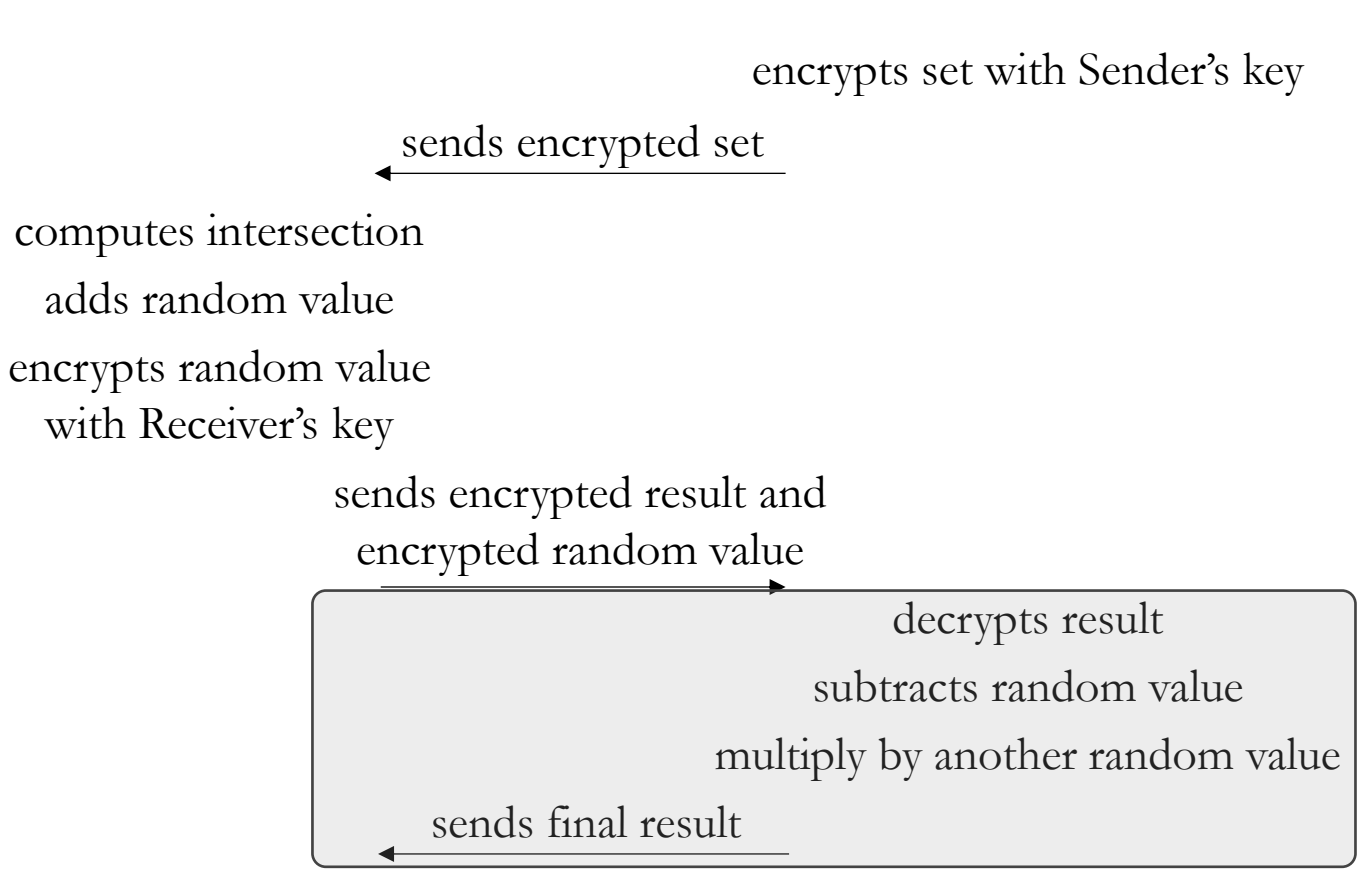

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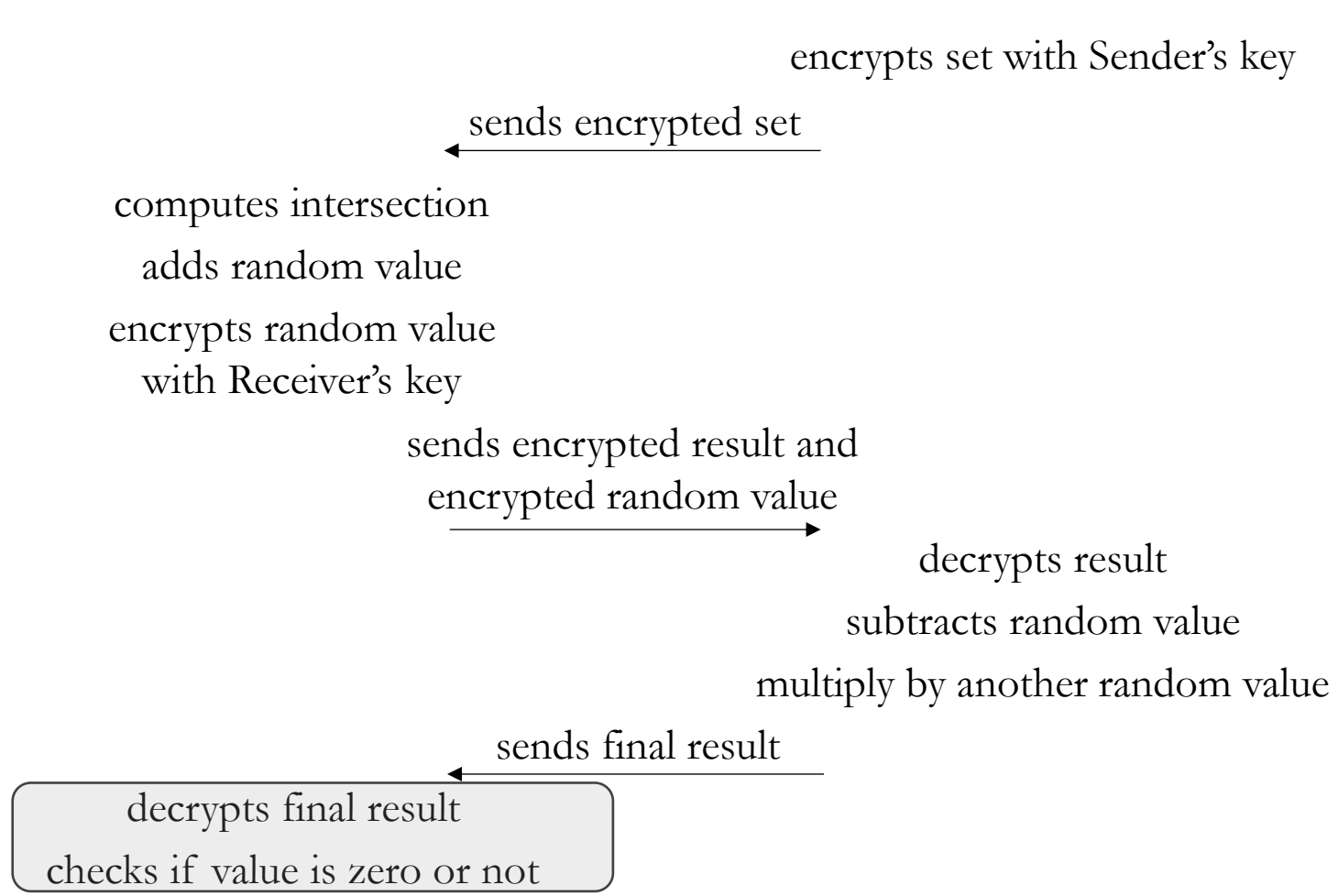

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Receiver | **Sender**

One-time

encrypts set with Sender's key

sends encrypted set ←

computes intersection

adds random value

encrypts random value with Receiver's key

Recurrent

sends encrypted result and encrypted random value →

decrypts result

subtracts random value

multiply by another random value

← sends final result

decrypts final result

checks if value is zero or not

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Assuming a Sender's set with one million entries

	Receiver	Sender
One-time		encrypts set with Sender's key
	sends encrypted set ≈ 7 Terabytes →	
Recurrent	computes intersection	Linear search (≈ 1 million multiplications)
	adds random value	
	encrypts random value with Receiver's key	
	sends encrypted result and encrypted random value →	
		decrypts result
		subtracts random value
		multiply by another random value
	← sends final result	
	decrypts final result	
	checks if value is zero or not	

Solving The Linear Search Problem

Sender hashes set *X* before sending it to Receiver.

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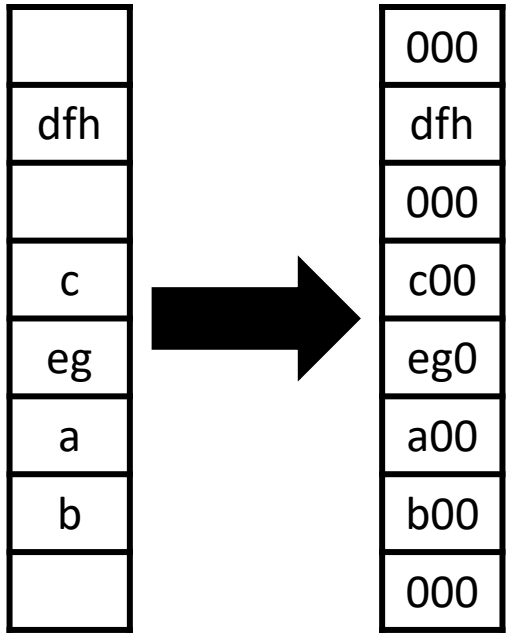
Constraint: All bins must have the same number of items.

Simple hashing



Hash functions: h

Maximum load

$$O\left(\frac{\log n}{\log \log n}\right)$$

Number of entries

$$O\left(\frac{n \log n}{\log \log n}\right)$$

Multiplicative depth

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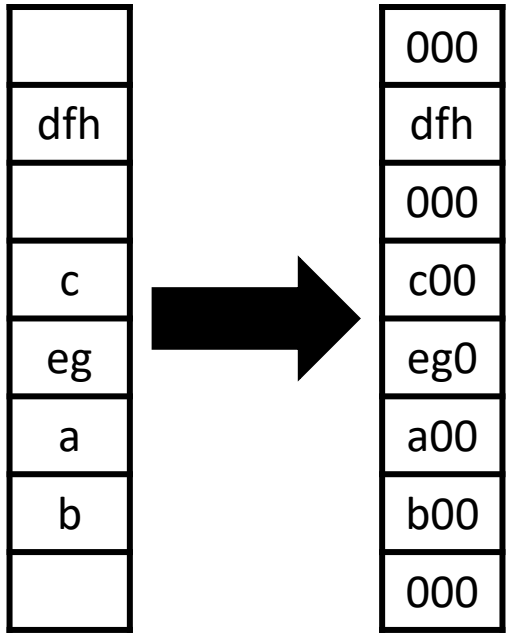

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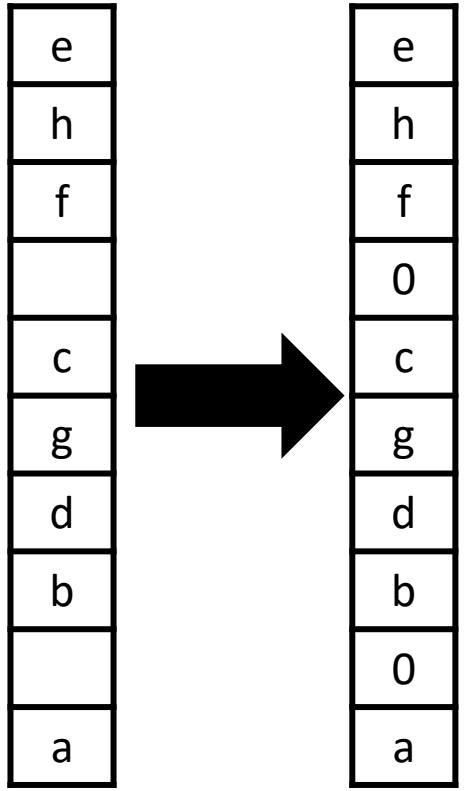

Hash functions: $h_1, \cdots, h_{|H|}$

Maximum load

1

Number of entries

$$\leq 2n(1+\epsilon)$$

Multiplicative depth

$$O(\log |H|)$$

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   d) sends $\overline{d_j}$ and $\widehat{r_j}$ to $\mathcal{S}$.
4) **Decryption**: For each $(\overline{d_j}, \widehat{r_j})$, $\mathcal{S}$:
   a) decrypts $\overline{d_j} \mapsto d_j$;
   b) samples a non-zero random plaintext value $\rho_j \in \mathbb{Z}_t \backslash \{0\}$ from a uniform distribution;
   c) homomorphically computes
   $$\widehat{e_j} = (\widehat{r_j} - d_j) \cdot \rho_j$$
   d) sends $\widehat{e_j}$ to $\mathcal{R}$.
5) **Result**: $\mathcal{R}$ decrypts $\widehat{e_j} \mapsto e_j$ and outputs
   $$X \cap Y = \cup_{j=1}^{|Y|} \{y_j : e_j = 0\}$$

Assuming a Sender's set with one million entries

Receiver		Sender
		encrypts set with Sender's key
One-time	sends encrypted set ≈ **100 Gigabytes** ←	
computes intersection		**Constant-time search (3 multiplications)**
adds random value		
encrypts random value with Receiver's key		
	sends encrypted result and encrypted random value →	
Recurrent		decrypts result
		subtracts random value
		multiply by another random value
	sends final result ←	
decrypts final result		
checks if value is zero or not		

Reducing Communication on Sender's Set

Pack many entries into one ciphertext.

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FHE encrypts plaintext polynomials into ciphertext polynomials.

Message space: $\boldsymbol{M = \mathbb{Z}_t}$ **Plaintext space:** $\boldsymbol{P = \mathbb{Z}_t[x]/(x^n + 1)}$ **Ciphertext space:** $\boldsymbol{C = \mathbb{Z}_q[x]/(x^n + 1)}$

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$p = \varepsilon(m) : M \mapsto P$

$c = E(p) : P \mapsto C^2$

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$$p = \varepsilon(m) : M \mapsto P$$
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Batching [4]

$$p = \varepsilon(m_1, m_2, \cdots, m_n) : M^n \mapsto P$$
$$c = E(p): P \mapsto C^2$$

[4] Nigel P. Smart and Frederik Vercauteren. "Fully homomorphic SIMD operations." *Designs, codes and cryptography*, 2014.

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Batching + Packing

$$p = \varepsilon(m_1, m_2, \cdots, m_{kn}) : M^{kn} \mapsto P$$
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Integer	Batching [4]	Batching + Packing
$p = \varepsilon(m) : M \mapsto P$	$p = \varepsilon(m_1, m_2, \cdots, m_n) : M^n \mapsto P$	$p = \varepsilon(m_1, m_2, \cdots, m_{kn}) : M^{kn} \mapsto P$
$c = E(p) : P \mapsto C^2$	$c = E(p) : P \mapsto C^2$	$c = E(p) : P \mapsto C^2$

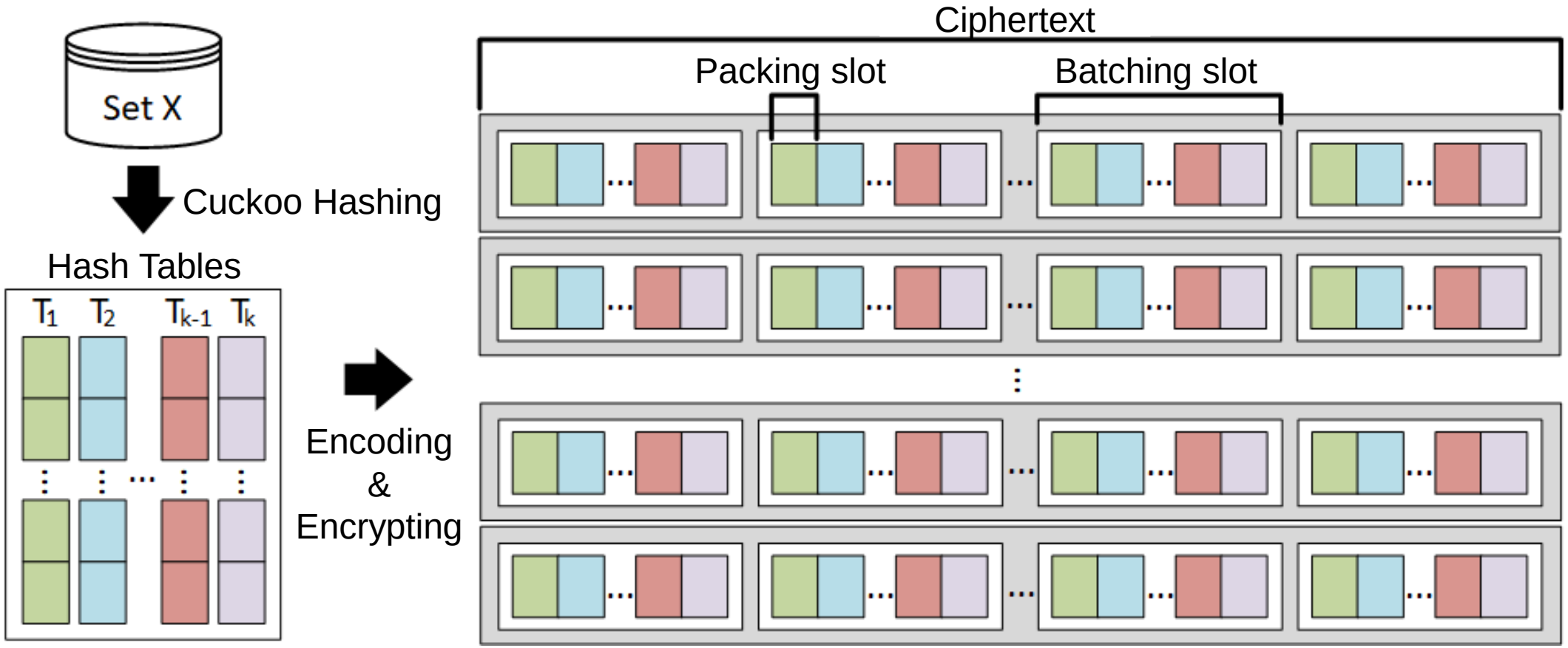
We encode Cuckoo hash table T with proposed "Batching + Packing" method.

≈ 12.5 Megabytes

(Unencrypted is 4 MB)

[4] Nigel P. Smart and Frederik Vercauteren. "Fully homomorphic SIMD operations." *Designs, codes and cryptography*, 2014.

Reducing Communication on Sender's Set



(Blueprint) Basic Protocol

Protocol 1 Basic Protocol

Input: $\mathcal{S}$ inputs set X and $\mathcal{R}$ inputs set Y. Both sets consist of bit strings of length σ. Sizes $|X|$, $|Y|$, and σ are public.
Output: $\mathcal{S}$ outputs $\perp$; $\mathcal{R}$ outputs $X \cap Y$.

1) **Setup**: Parties agree on a Fully Homomorphic Encryption scheme and encryption parameters (n, q, t).
2) **Set encryption**: $\mathcal{S}$ encrypts each element $x_i \in X$ under its own key, and sends the $|X|$ ciphertexts $\overline{X} = (\overline{x_1}, ..., \overline{x_{|X|}})$ to $\mathcal{R}$.
3) **Computing intersection**: For each $y_j \in Y$, $\mathcal{R}$:
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Assuming a Sender's set with one million entries

Receiver | **Sender**

One-time

encrypts set with Sender's key

sends encrypted set ≈ **12.5 Megabytes** ←

Recurrent

computes intersection — **Constant-time search (3 multiplications)**

adds random value

encrypts random value with Receiver's key

sends encrypted result and encrypted random value →

decrypts result

subtracts random value

multiply by another random value

← sends final result

decrypts final result

checks if value is zero or not

Results

$|X| \approx 2^{20}, |Y| = \{4, 16, 64\}$

			$\|X\| = \mathscr{L} \cdot 2^{20}$
One-time	Computation	Fast Setup	0.09
		Fast Intersection	0.30
	Communication	Fast Setup	12.63
		Fast Intersection	25.25
	Total time (10 Gbps)	Fast Setup	**0.10**
		Fast Intersection	0.32
	Total time (100 Mbps)	Fast Setup	1.26
		Fast Intersection	2.48

			$\|Y\|$ = 4	16	64
Recurrent	Computation	Fast Setup	0.02	0.11	0.43
		Fast Intersection	0.03	0.10	0.37
	Communication	Fast Setup	1.85	7.39	29.55
		Fast Intersection	0.66	2.65	10.59
	Total time (10 Gbps)	Fast Setup	**0.02**	0.12	0.45
		Fast Intersection	0.03	**0.10**	**0.38**
	Total time (100 Mbps)	Fast Setup	0.33	0.86	2.95
		Fast Intersection	**0.24**	**0.47**	**1.38**

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One-time	Computation	Fast Setup	0.09
		Fast Intersection	0.30
		CLR [8]	1.21
		KKRT [31]	NA
		PSSZ [38]	NA
	Communication	Fast Setup	12.63
		Fast Intersection	25.25
		CLR [8]	0.00
		KKRT [31]	NA
		PSSZ [38]	NA
	Total time (10 Gbps)	Fast Setup	**0.10**
		Fast Intersection	0.32
		CLR [8]	1.21
		KKRT [31]	NA
		PSSZ [38]	NA
	Total time (100 Mbps)	Fast Setup	1.26
		Fast Intersection	2.48
		CLR [8]	**1.21**
		KKRT [31]	NA
		PSSZ [38]	NA

			$\lvert Y\rvert$ = 4	16	64
Recurrent	Computation	Fast Setup	0.02	0.11	0.43
		Fast Intersection	0.03	0.10	0.37
	Communication	Fast Setup	1.85	7.39	29.55
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	Total time (10 Gbps)	Fast Setup	**0.02**	0.12	0.45
		Fast Intersection	0.03	**0.10**	**0.38**
	Total time (100 Mbps)	Fast Setup	0.33	0.86	2.95
		Fast Intersection	**0.24**	**0.47**	**1.38**

[8] Hao Chen, Kim Laine, and Peter Rindal. "Fast private set intersection from homomorphic encryption." *CCS*, 2017.

[31] Vladimir Kolesnikov, Ranjit Kumaresan, Mike Rosulek, and Ni Trieu. "Efficient batched oblivious PRF with applications to private set intersection." CCS, 2016.

[38] Benny Pinkas, Thomas Schneider, Gil Segev, and Michael Zohner. "Phasing: Private set intersection using permutation-based hashing." *USENIX Security, 2015.*

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		KKRT [31]	NA
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		KKRT [31]	NA
		PSSZ [38]	NA
	Total time (10 Gbps)	Fast Setup	**0.10**
		Fast Intersection	0.32
		CLR [8]	1.21
		KKRT [31]	NA
		PSSZ [38]	NA
	Total time (100 Mbps)	Fast Setup	1.26
		Fast Intersection	2.48
		CLR [8]	**1.21**
		KKRT [31]	NA
		PSSZ [38]	NA

			$\|Y\|$ = 4	16	64
Recurrent	Computation	Fast Setup	0.02	0.11	0.43
		Fast Intersection	0.03	0.10	0.37
		CLR [8]	2.21	2.21	2.21
		KKRT[31]	1.62	1.62	1.62
		PSSZ [38]	0.86	0.86	0.71
	Communication	Fast Setup	1.85	7.39	29.55
		Fast Intersection	0.66	2.65	10.59
		CLR [8]	5.60	5.60	5.60
		KKRT [31]	57.17	57.17	57.17
		PSSZ [38]	24.05	24.05	27.11
	Total time (10 Gbps)	Fast Setup	**0.02**	0.12	0.45
		Fast Intersection	0.03	**0.10**	**0.38**
		CLR [8]	2.21	2.21	2.21
		KKRT [31]	1.67	1.67	1.67
		PSSZ [38]	0.88	0.88	0.73
	Total time (100 Mbps)	Fast Setup	0.33	0.86	2.95
		Fast Intersection	**0.24**	**0.47**	**1.38**
		CLR [8]	2.81	2.81	2.81
		KKRT [31]	6.46	6.46	6.46
		PSSZ [38]	2.94	2.94	3.05

[8] Hao Chen, Kim Laine, and Peter Rindal. "Fast private set intersection from homomorphic encryption." *CCS*, 2017.

[31] Vladimir Kolesnikov, Ranjit Kumaresan, Mike Rosulek, and Ni Trieu. "Efficient batched oblivious PRF with applications to private set intersection." CCS, 2016.

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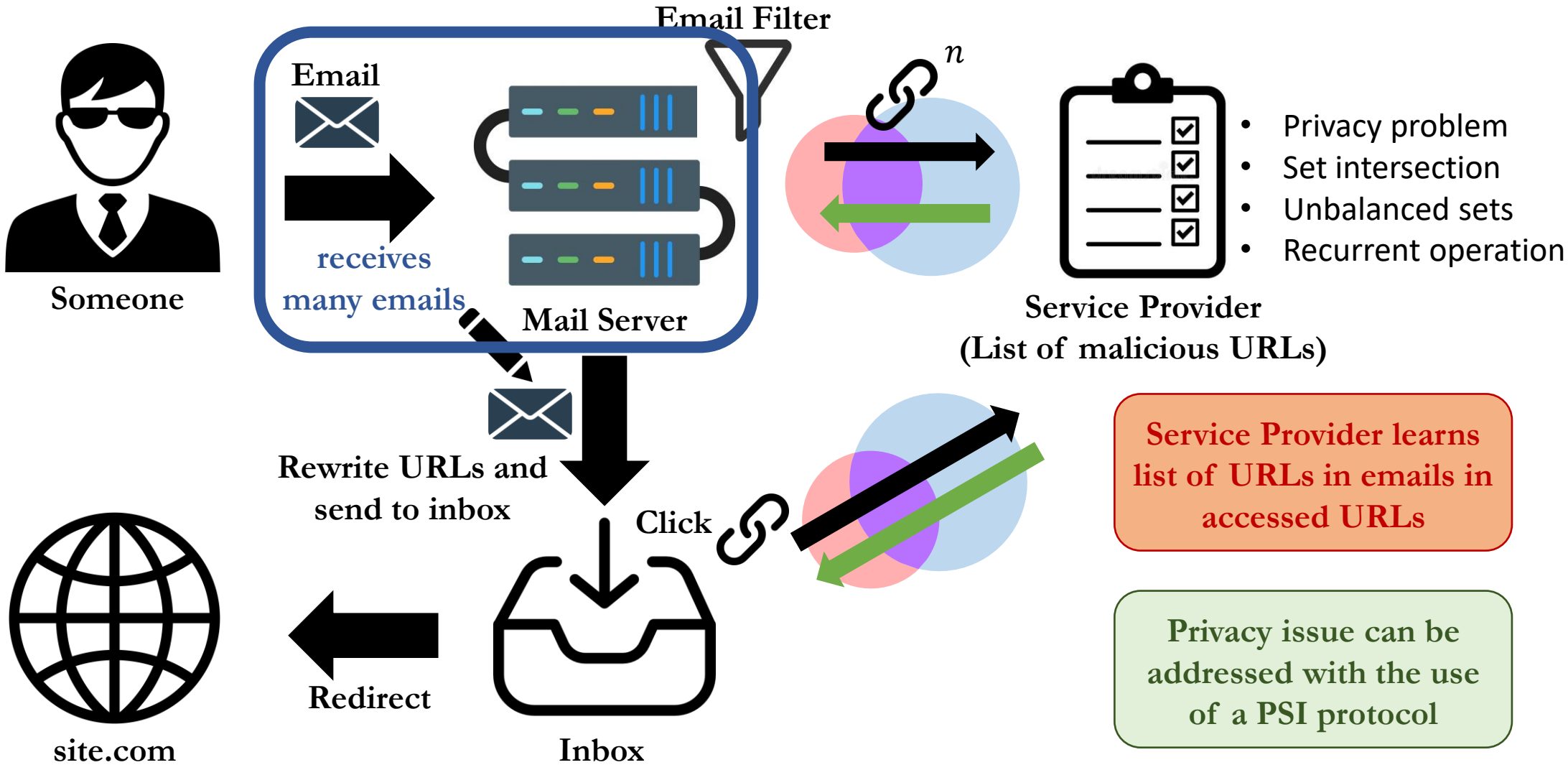
Thank You

GitHub

github.com/momalab/psi-ndss2025

URL Denylisting / Email Filtering



Full Protocol

Protocol 2 Full Protocol

Input: $\mathcal{S}$ inputs set X of size $|X|$. $\mathcal{R}$ inputs set Y of size $|Y|$. Both sets consist of bit strings of length σ_d. $|X|$, $|Y|$, and σ_d are public.

Output: $\mathcal{S}$ outputs $\perp$; $\mathcal{R}$ outputs $X \cap Y$.

1) **Setup**: In this step, parties select all parameters to be used in the protocol.
   a) **Security parameters**: Parties agree on computational and statistical security parameters (κ and λ, respectively).
   b) **Data compression**: From Eqs. 4 and 5 (§IV-A5), we have that $\sigma = \min(\sigma_d, \sigma_h)$. Therefore, if $\sigma_h < \sigma_d$, parties agree on a hash function $\mathcal{Z}(\cdot) : \mathbb{Z}_{2^{\sigma_d}} \mapsto \mathbb{Z}_{2^{\sigma_h}}$ for data compression. Otherwise, $\mathcal{Z}(x) = x$.
   c) **Cuckoo hashing and Permutation-based hashing**:
      i) Parties agree on the number of hash functions h and insertion depth limit d for Cuckoo hashing.
      ii) They select the number of Cuckoo hash tables k ($\equiv$ number of packing slots), and a function $g(\cdot)$ that maps a σ-bit entry x to Cuckoo hash table $T^{(g(x))}$ (§IV-B5).
      iii) Following §IV-A3 and §VI-A, $\mathcal{S}$ chooses the Cuckoo hash table size $|T^{(i)}|$ for a failure rate $\leq 2^{-\lambda}$.
      iv) By knowing $|T^{(i)}|$, one can calculate the left $\sigma_L = \lfloor \log_2 |T^{(i)}| \rfloor$ and right $\sigma_R = \sigma - \sigma_L$ sizes for Permutation-based hashing (§IV-A4).
      v) $\mathcal{S}$ selects the h different hash functions $H : \mathbb{Z}_{2^\sigma} \mapsto \mathbb{Z}_{|T^{(i)}|}$, where $H_j(z_L, z_R) = z_L \oplus f_j(z_R)$ and $f_j(z_R) : \mathbb{Z}_{2^{\sigma_R}} \mapsto \mathbb{Z}_{|T^{(i)}|}$ (§IV-A4).
   d) **Encryption parameters**:
      i) Parties agree on partitioning parameters η_s and η_r (§IV-C1) and plaintext modulus $t = \prod_{i=1}^{k} t_i : t_i \geq 2^{\sigma_R} + 2$ (§IV-B4 and §IV-B7).
      ii) Parties select encryption parameters $(n_s, q_s, t), (n_r, q_r, t) : n_s \geq n_r$ following Eq. 3 and §IV-B7. Encryption parameters are public.
      iii) Each party generates decryption and encryption keys, which are kept private.
2) **Cuckoo hashing**: For each entry $x \in X$, $\mathcal{S}$ performs $z = z_L | z_R = \mathcal{Z}(x) : |z_L| = \lfloor \log_2 |T^{(i)}| \rfloor$ and inserts z_R at $T^{(g(z))}_{H_j(z_L, z_R)} : 1 \leq j \leq h$. A dummy value is assigned to empty bins after inserting entries $\in X$ into tables $T^{(i)}$ (§IV-A2).
3) **Set encryption**: $\mathcal{S}$ encodes all Cuckoo hash tables and bins into polynomials following Eq. 8 (§IV-B5), encrypts them into ciphertexts under its own key, and sends the $\lceil \frac{|T^{(i)}|}{n} \rceil$ ciphertexts $\overline{C}$ to $\mathcal{R}$.
4) **Computing intersection**: For each $y \in Y$, $\mathcal{R}$:
   a) Computes $z = z_L | z_R = \mathcal{Z}(y) : |z_L| = \lfloor \log_2 |T^{(i)}| \rfloor$, and for each Cuckoo hash function $H_j(\cdot)$ $\forall j \in \mathbb{Z} : 1 \leq j \leq h$, $\mathcal{R}$:
      i) Creates a polynomial $P \in Z_t[x]/(x^{n_s} + 1)$ s.t. $P_{u,v} = z_R$ for $(u, v) = (H_j(z_L, z_R) \bmod n_s,\ g(z) - 1)$ and a dummy value otherwise.
      ii) Homomorphically computes the difference $\overline{S}^{(j)} = \overline{C}^{\left(\lfloor \frac{H_j(z_L, z_R)}{n_s} \rfloor\right)} - P$.
   b) Performs $h - \eta_s - 1 : \eta_s \in \mathbb{Z}_h$ homomorphic multiplications between $\overline{S}^{(j)} : j \in \mathbb{Z}_{h+1} \backslash \{0\}$, resulting in $\eta_s + 1$ ciphertexts $\overline{M}^{(i)}$ $\forall i \in \mathbb{Z}_{\eta_s+1}$.
   c) Samples $\eta_s + 1$ tuples of random values $(r_1, ..., r_{n_s} \in \mathbb{Z}_t)$ from a uniform distribution, where each tuple is encoded as a polynomial $R^{(i)} \in \mathbb{Z}_t[x]/(x^{n_s} + 1)$.
   d) Computes $\overline{D}^{(i)} = \overline{M}^{(i)} + R^{(i)}$ $\forall i \in \mathbb{Z}_{\eta_s+1}$, modulus switches it, encrypts $R^{(i)} \mapsto \widehat{R}^{(i)}$ under its key, and sends the $(\overline{D}^{(i)}, \widehat{R}^{(i)})$ pairs to $\mathcal{S}$. Note that each $\widehat{R}^{(i)}$ will be several ciphertexts if $n_s > n_r$.
5) **Decryption**: For all pairs $(\overline{D}^{(i)}, \widehat{R}^{(i)})$ $\forall i \in \mathbb{Z}_{\eta_s+1}$, $\mathcal{S}$:
   a) Decrypts each $\overline{D}^{(i)} \mapsto D^{(i)}$, and homomorphically computes $\widehat{M}^{(i)} = \widehat{R}^{(i)} - D^{(i)}$ $\forall i \in \mathbb{Z}_{\eta_s+1}$.
   b) Performs $h - \eta_s - 1 - \eta_r : \eta_r \in \mathbb{Z}_{\eta_s+1}$ homomorphic multiplications between $\widehat{M}^{(i)} : i \in \mathbb{Z}_{\eta_s+1}$, resulting in $\eta_r + 1$ ciphertexts $\widehat{N}^{(j)}$ $\forall j \in \mathbb{Z}_{\eta_r+1}$.
   c) Samples $\eta_r + 1$ tuples of random values $(\rho_1, ..., \rho_{n_r} \in \mathbb{Z}_t \backslash \{\alpha \cdot t_i\}$ $\forall \alpha, i \in \mathbb{Z} : 1 \leq i \leq k)$ such that no random value is a multiple of any packing modulus t_i, and encode each tuple as a polynomial $P^{(j)} \in \mathbb{Z}_t/(x^{n_r} + 1)$.
   d) Homomorphically computes $\widehat{E}^{(j)} = rotate(\widehat{N}^{(j)} \cdot P^{(j)}, \omega_j)$ $\forall j \in \mathbb{Z}_{\eta_r+1}$, where the function $rotate(\cdot)$, rotates the batching slots by a random number of positions $\omega_j \in \mathbb{Z}_{n_r}$, modulus switches and sends each $\widehat{E}^{(j)}$ to $\mathcal{R}$.
6) **Result**: $\mathcal{R}$ decrypts each $\widehat{E}^{(j)} \mapsto E^{(j)}$ and outputs $X \cap Y = \cup_{j=1}^{|Y|} \{y_j \iff 0 \in \cup_{j=0}^{\eta_r} E^{(j)}\}$.

$|X| \approx 2^{24}, |Y| = \{4, 16, 64\}$

			$\|X\| = \mathscr{L} \cdot 2^{24}$
One-time	Computation	Fast Setup	1.79
		Fast Intersection	7.74
		CLR [8]	21.54
		KKRT [31]	NA
		PSSZ [38]	NA
	Communication	Fast Setup	202.04
		Fast Intersection	404.08
		CLR [8]	0.00
		KKRT [31]	NA
		PSSZ [38]	NA
	Total time (10 Gbps)	Fast Setup	1.96
		Fast Intersection	8.08
		CLR [8]	21.54
		KKRT [31]	NA
		PSSZ [38]	NA
	Total time (100 Mbps)	Fast Setup	18.68
		Fast Intersection	41.44
		CLR [8]	21.54
		KKRT [31]	NA
		PSSZ [38]	NA

			$\|Y\|$ = 4	16	64
Recurrent	Computation	Fast Setup	0.02	0.11	0.43
		Fast Intersection	0.03	0.10	0.37
		CLR [8]	23.22	23.22	23.22
		KKRT[31]	30.42	40.42	30.42
		PSSZ [38]	11.11	11.11	8.54
	Communication	Fast Setup	1.85	7.39	29.55
		Fast Intersection	0.66	2.65	10.59
		CLR [8]	11.00	11.00	11.00
		KKRT [31]	946.75	946.75	946.75
		PSSZ [38]	432.05	432.05	432.11
	Total time (10 Gbps)	Fast Setup	0.02	0.12	0.45
		Fast Intersection	0.03	0.10	0.38
		CLR [8]	23.22	23.22	23.22
		KKRT [31]	31.21	31.21	31.21
		PSSZ [38]	11.47	11.47	8.90
	Total time (100 Mbps)	Fast Setup	0.33	0.86	2.95
		Fast Intersection	0.24	0.47	1.38
		CLR [8]	23.59	23.59	23.59
		KKRT [31]	109.27	109.27	109.27
		PSSZ [38]	47.14	47.14	44.57

TABLE VI: Total time (in seconds) for two configurations of our PSI protocol, *Fast Setup* and *Fast Intersection*, and related work, considering a $\mathcal{S}$'s set size $|X| = \mathscr{L} \cdot 2^{24}$ and several sizes of $\mathcal{R}$'s set $|Y|$, where we evaluate the one-time costs and recurrent costs of performing set intersections. KKRT and PSSZ do not have one-time costs.