Information:

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- Presentation 25 minutes + 5 minutes for questions.

- Presentation is on Wednesday, 11:30-12:00 in B05-B06

- Presentation is after: Abhi Shelat
(fast two-party secure computation with minimal assumptions)

- Presentation is before: Nigel Smart
(An architecture for practical actively secure MPC with dishonest majority)

- BF Private Set-Intersection protocol is 2 sessions after us

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More Efficient Oblivious Transfer and Extensions for Faster Secure Computation

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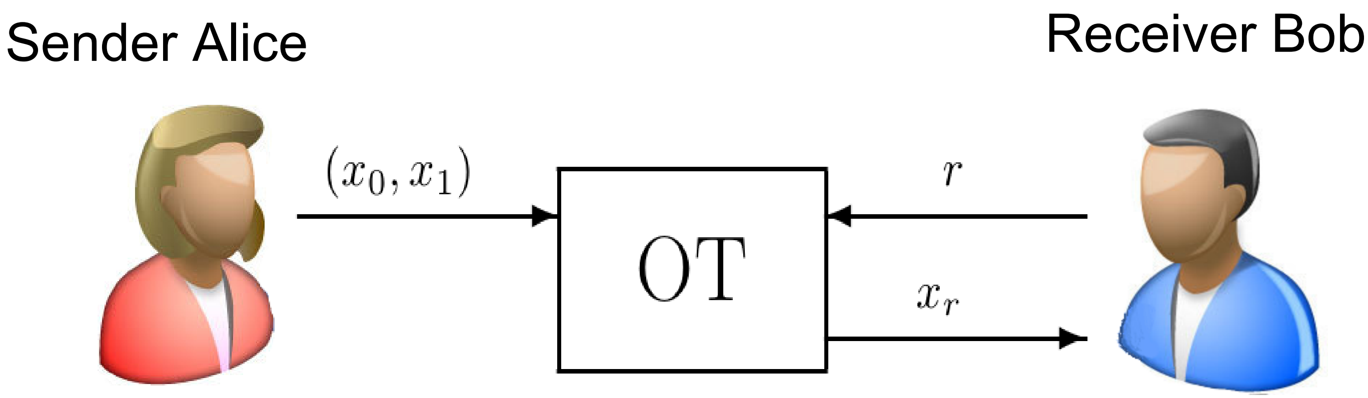
1-out-of-2 Oblivious Transfer (OT)



- Input: Alice holds two strings (x_0, x_1), Bob holds a choice bit r

- Output: Bob receives x_r but learns nothing about x_{1-r} , Alice learns nothing about r

Motivation

- OT is basis of many generic secure computation protocols
    - Yao's garbled circuits protocol [Yao86]: one OT per input
    - Goldreich-Micali-Wigderson [GMW87]: one OT per AND gate

- Several special purpose protocols directly use OT:
    - Set-Intersection [DCW13]
    - Biometric identification [BCP13]

- We focus on semi-honest (passive) adversaries
    - Enables highly efficient protocols

OT via Public-Key Cryptography

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- Several protocols for OT exist that use public-key cryptography
    - e.g., by [NP01] in random-oracle and standard model
    - Other protocols exist that require weaker security assumptions

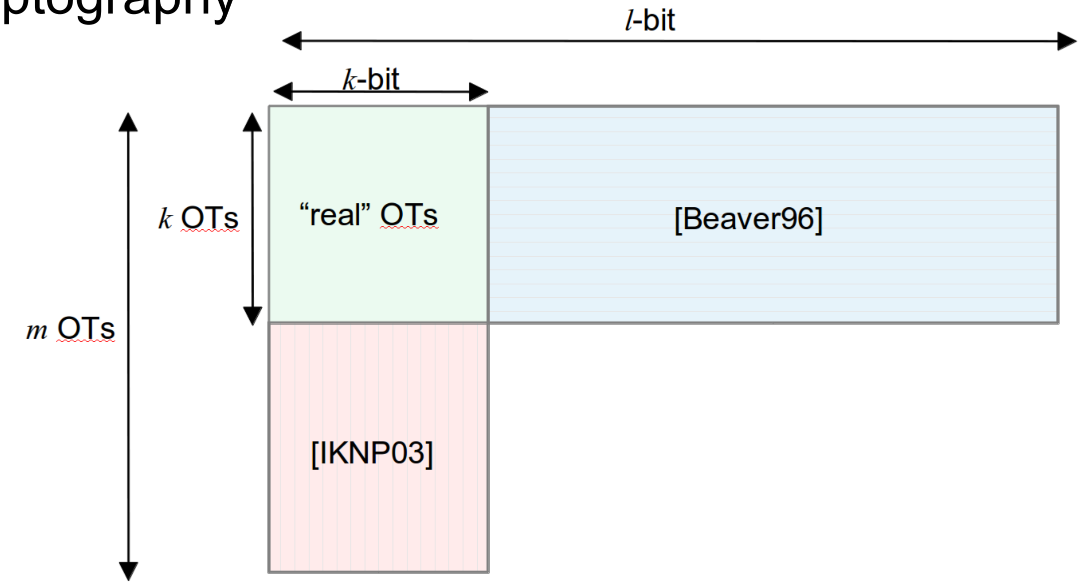
- Impagliazzo and Rudich [IR86] proved that OT requires public-key cryptography

- Since public-key cryptography is expensive, OT was believed inefficient

OT Extensions

- OT extensions use secret-key cryptography to efficiently extend OT
    - OT on long strings by exchanging short seeds [Beaver96]
    - Many OTs extended from few "real" OTs [IKNP03]

- Similar to hybrid encryption, where symmetric key is encrypted using public-key cryptography



Our Contributions

- Optimizations for the OT extension protocol of [IKNP03]
    - Algorithmic optimizations => less computation
    - Protocol optimizations => less communication

- Specific OT functionalities for more efficient secure computation

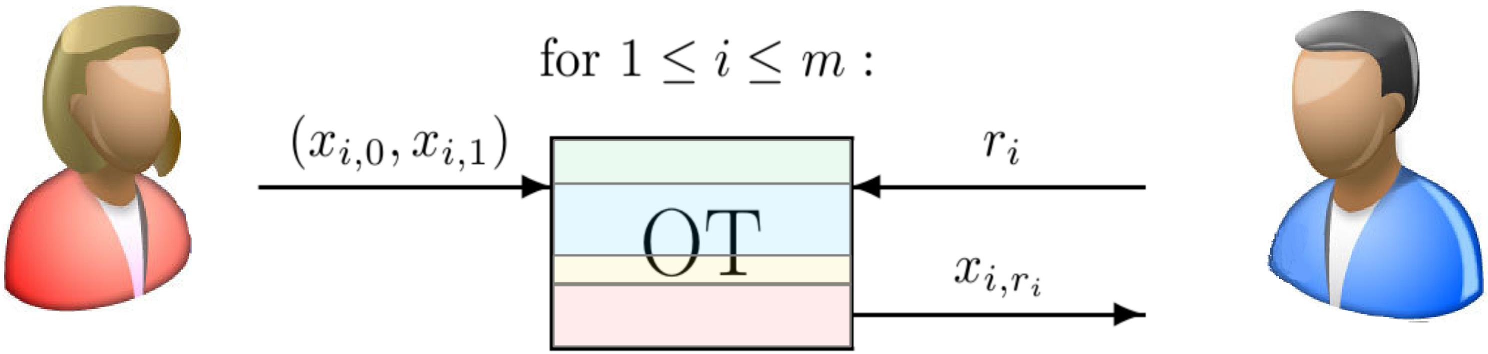
- An open source OT extension implementation

OT Extension of [IKNP03] (1)

For each OT i :

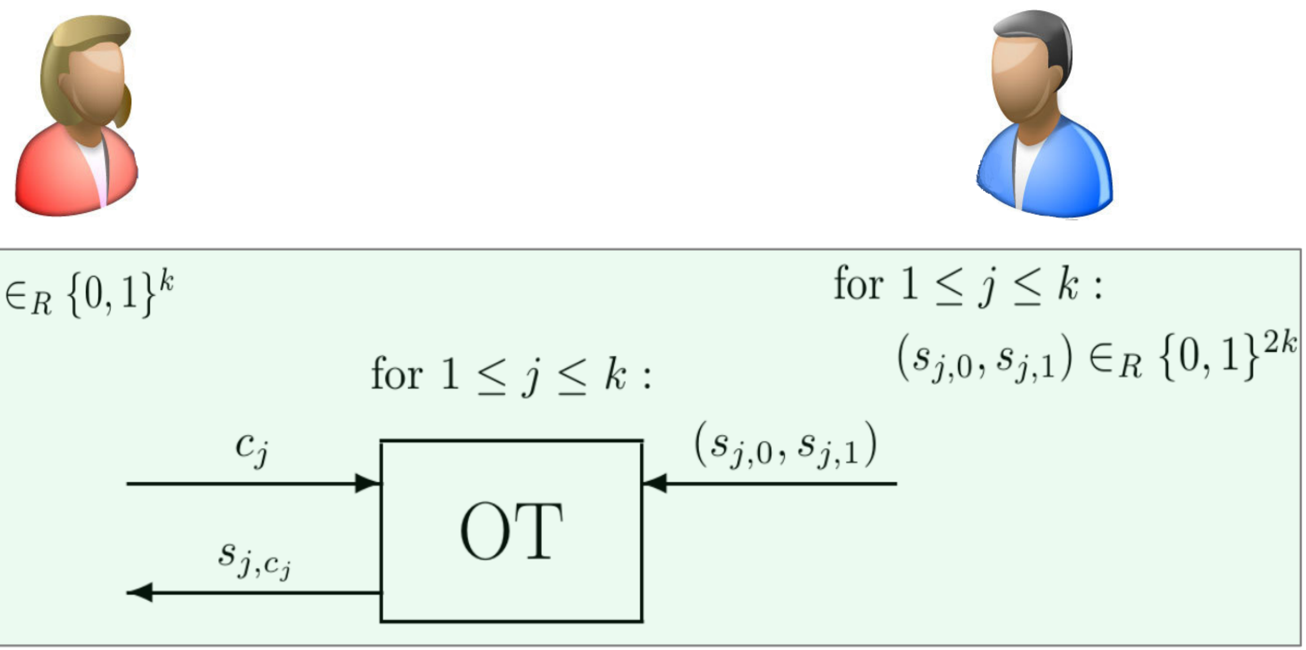
- Alice holds m pairs of l-bit messages $(x_{i,0}, x_{i,1})$

- Bob holds m-bit string r and obtains $x_{i,ri}$



OT Extension of [IKNP03] (2)

- Alice and Bob perform k “real” OTs on random seeds with reverse roles (k is symmetric security parameter)



OT Extension of [IKNP03] (3)

- Bob obliviously transfers a random $m \times k$ bit matrix $\mathbf{T}$

- The matrix is masked with the seeds of the "real" OTs

$$\mathbf{T} \in_R \{0,1\}^{m \times k}$$

$$\text{for } 1 \leq j \leq k:$$

$$u_{j,0} = PRG(s_{j,0}) \oplus \mathbf{T}[\mathrm{j}]$$

$$u_{j,1} = PRG(s_{j,1}) \oplus \mathbf{T}[\mathrm{j}] \oplus \mathbf{r}$$

$$\xleftarrow{(u_{j,0}, u_{j,1}),\ 1 \leq i \leq k}$$

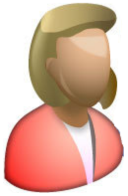
$$\text{for } 1 \leq j \leq k:$$

$$\mathbf{V}[\mathrm{j}] = u_{j,c_j} \oplus PRG(s_{j,c_j})$$

OT Extension of [IKNP03] (4)

- The $\mathbf{V}$ and $\mathbf{T}$ matrices are transposed

- Alice masks her inputs and obliviously sends them to Bob
  - H is a correlation robust function (instantiated with a hash function)



Alice	Bob
$\mathbf{V'} = \mathbf{V}^T$	$\mathbf{T'} = \mathbf{T}^T$
for $1 \leq i \leq m$:	
$y_{i,0} = x_{i,0} \oplus H(i, \mathbf{V'}[\mathrm{i}])$	
$y_{i,1} = x_{i,1} \oplus H(i, \mathbf{V'}[\mathrm{i}] \oplus c)$	
$\xrightarrow{(y_{i,0}, y_{i,1}), 1 \leq i \leq m}$	for $1 \leq i \leq m$:
	$x_{i,r_i} = y_{i,r_i} \oplus H(i, \mathbf{T'}[\mathrm{i}])$

Computation Complexity of OT Extension

m pairs $(x_{i,0}, x_{i,1}) \in \{0,1\}^{2\ell}$ | $\mathbf{r} = (r_1, ..., r_m) \in \{0,1\}^m$

for $1 \le j \le k$:

$c_j \in_R \{0,1\}$ → **OT** ← $(s_{j,0}, s_{j,1}) \in_R \{0,1\}^{2k}$

s_{j,c_j} ← **OT**

$\mathbf{T} \in_R \{0,1\}^{m \times k}$

for $1 \le j \le k$:

$u_{j,0} = PRG(s_{j,0}) \oplus \mathbf{T}[j]$

$u_{j,1} = PRG(s_{j,1}) \oplus \mathbf{T}[j] \oplus \mathbf{r}$

← $(u_{j,0}, u_{j,1}),\ 1 \le i \le k$

for $1 \le j \le k$:

$\mathbf{V}[j] = u_{j,c_j} \oplus PRG(s_{j,c_j})$

$\mathbf{V'} = \mathbf{V}^T$ | $\mathbf{T'} = \mathbf{T}^T$

for $1 \le i \le m$:

$y_{i,0} = x_{i,0} \oplus H(i, \mathbf{V'}[i])$

$y_{i,1} = x_{i,1} \oplus H(i, \mathbf{V'}[i] \oplus c)$

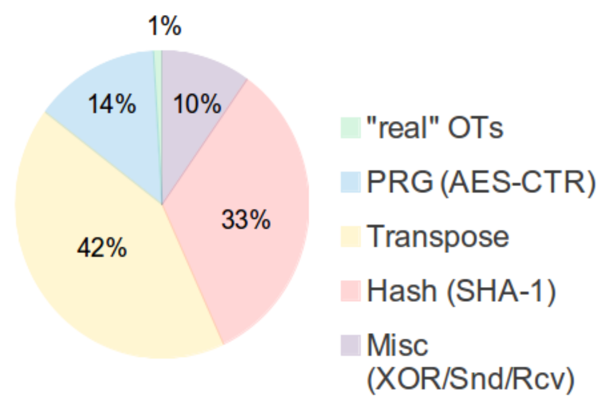
$(y_{i,0}, y_{i,1}), 1 \le i \le m$ →

for $1 \le i \le m$:

$x_{i,r_i} = y_{i,r_i} \oplus H(i, \mathbf{T'}[i])$

	Per OT:	
1	# PRG evaluations	2
2	# H evaluations	1

Time distribution for 10 Mio. OTs (in 21s):



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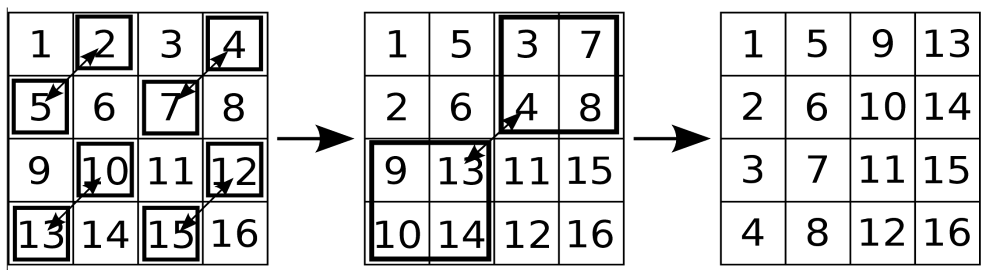
Algorithmic Optimization
Efficient Bit-Matrix Transposition

- Naive matrix transposition performs mk load/process/store operations

- Eklundh's algorithm reduces number of operations to O(m $\log_2 k$) swaps



- Use CPU register to swap multiple bit-values in parallel
  - O(m/r $\log_2 k$) for register size r (e.g, r = 64)

- Time for transposing the $m \times k$ bit matrix is reduced by factor 9

Algorithmic Optimization
Parallelized OT Extension

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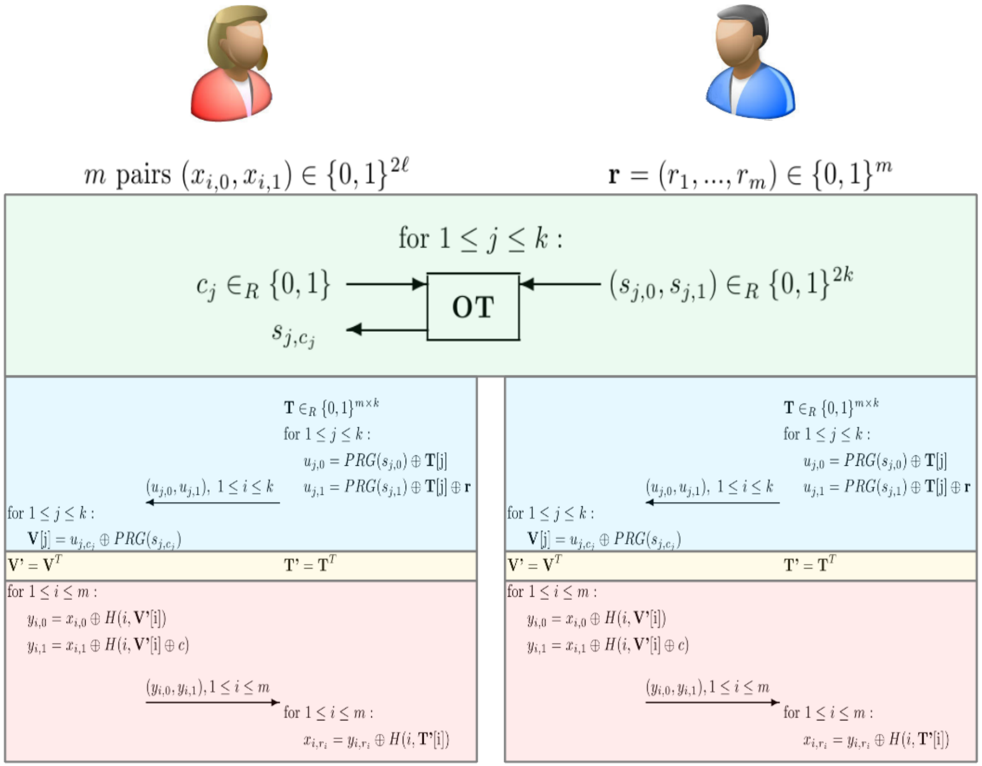
- OT extension can easily be parallelized by splitting the $\mathbf{T}$ matrix into sub-matrices

- Since each column is independent of the next, OT is highly parallelizable



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Communication Complexity of OT Extension

m pairs $(x_{i,0}, x_{i,1}) \in \{0,1\}^{2\ell}$ $\quad$ $\mathbf{r} = (r_1, ..., r_m) \in \{0,1\}^m$

for $1 \le j \le k$:

$c_j \in_R \{0,1\}$ → **OT** ← $(s_{j,0}, s_{j,1}) \in_R \{0,1\}^{2k}$

s_{j,c_j} ← **OT**

$\mathbf{T} \in_R \{0,1\}^{m \times k}$

for $1 \le j \le k$:

$u_{j,0} = PRG(s_{j,0}) \oplus \mathbf{T}[j]$

$u_{j,1} = PRG(s_{j,1}) \oplus \mathbf{T}[j] \oplus \mathbf{r}$

← $(u_{j,0}, u_{j,1}),\ 1 \le i \le k$

for $1 \le j \le k$:

$\mathbf{V}[j] = u_{j,c_j} \oplus PRG(s_{j,c_j})$

$\mathbf{V'} = \mathbf{V}^T$ $\quad$ $\mathbf{T'} = \mathbf{T}^T$

for $1 \le i \le m$:

$y_{i,0} = x_{i,0} \oplus H(i, \mathbf{V'}[i])$

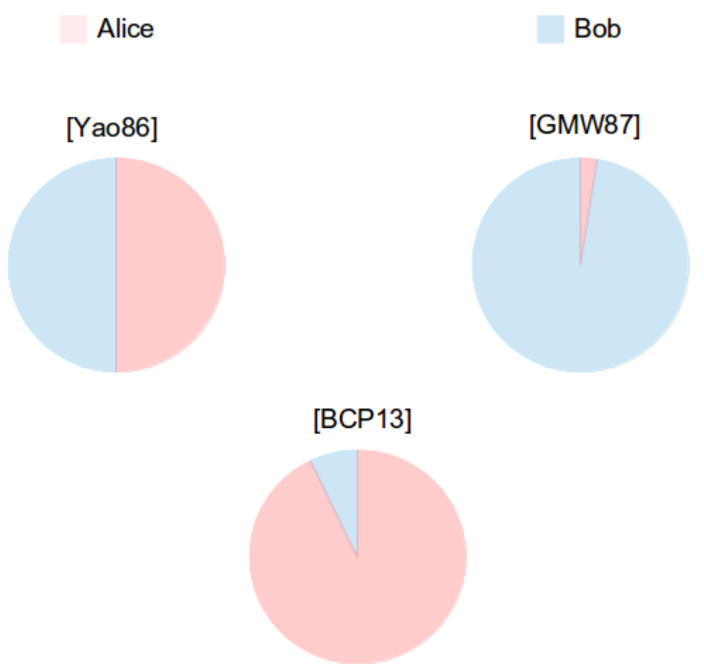
$y_{i,1} = x_{i,1} \oplus H(i, \mathbf{V'}[i] \oplus c)$

→ $(y_{i,0}, y_{i,1}), 1 \le i \le m$

for $1 \le i \le m$:

$x_{i,r_i} = y_{i,r_i} \oplus H(i, \mathbf{T'}[i])$

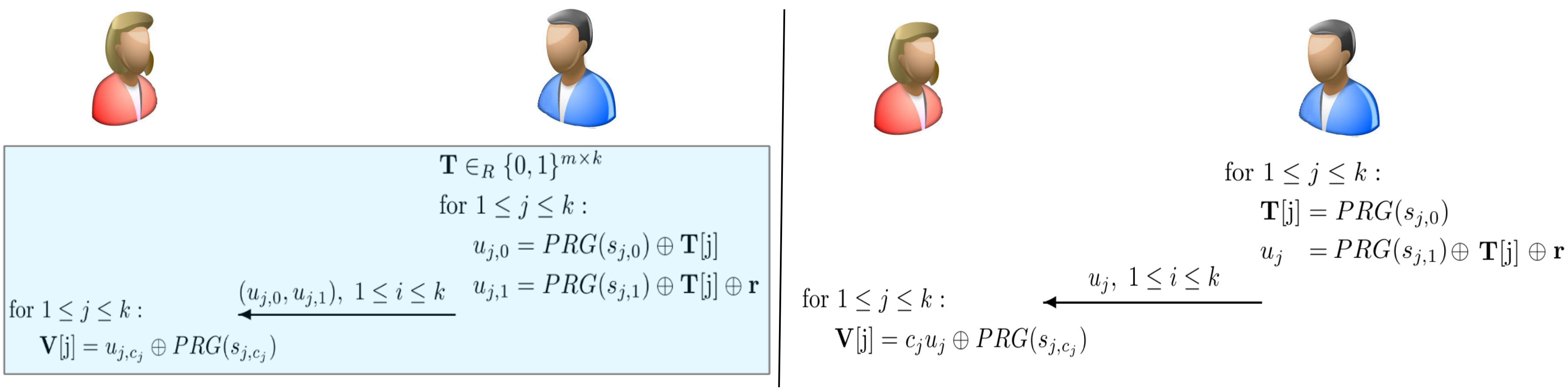
$2l$	Per OT: Bits sent by	$2k$



Protocol Optimization
General OT Extension (G-OT)

- Instead of using a random T matrix, we derice it from $s_{j,0}$:

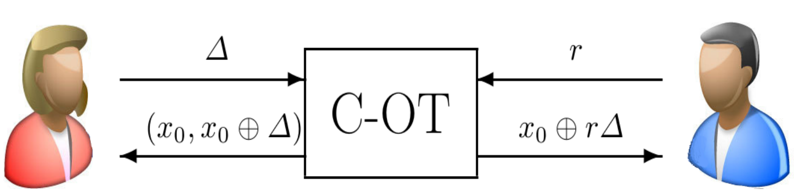
- Reduces data Bob sends by factor 2



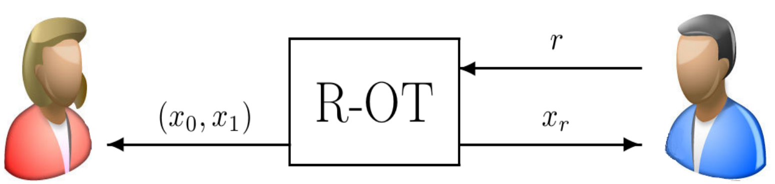
Specific OT Functionalities

- Secure computation protocols often require a **specific OT functionality**
  - Yao's garbled circuits with free XOR [KS08] requires **correlated** inputs
  - GMW with multiplication triples can use **random** inputs

- We introduce two OT functionalities for secure computation protocols:
  - Correlated OT: **random** x_0 and $x_1 = x_0 \oplus \Delta$
  - Random OT: **random** x_0 **and** x_1



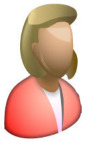
Correlated OT



Random OT

Specific OT Functionalities
Correlated OT Extension (C-OT)

- Choose $x_{i,0}$ as random output of H
- Compute $x_{i,1}$ as $x_{i,0} \oplus \Delta_i$ to obliviously transfer correlated values
- Reduces data Alice sends by factor 2



$\mathbf{V'} = \mathbf{V}^T$ $\qquad$ $\mathbf{T'} = \mathbf{T}^T$

for $1 \leq i \leq m$:

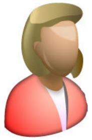
$y_{i,0} = x_{i,0} \oplus H(i, \mathbf{V'}[\mathrm{i}])$

$y_{i,1} = x_{i,1} \oplus H(i, \mathbf{V'}[\mathrm{i}] \oplus c)$

$\xrightarrow{(y_{i,0}, y_{i,1}), 1 \leq i \leq m}$

for $1 \leq i \leq m$:

$x_{i,r_i} = y_{i,r_i} \oplus H(i, \mathbf{T'}[\mathrm{i}])$



$\mathbf{V'} = \mathbf{V}^T$ $\qquad$ $\mathbf{T'} = \mathbf{T}^T$

for $1 \leq i \leq m$:

$x_{i,0} = H(i, \mathbf{V'}[\mathrm{i}])$

$x_{i,1} = x_{i,0} \oplus \Delta_i$

$y_i \quad = x_{i,1} \oplus H(i, \mathbf{V'}[\mathrm{i}] \oplus c)$

$\xrightarrow{y_i\ , 1 \leq i \leq m}$

for $1 \leq i \leq m$:

$x_{i,r_i} = r_i y_i \oplus H(i, \mathbf{T'}[\mathrm{i}])$

Specific OT Functionalities
Random OT Extension (R-OT)

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- Choose $x_{i,0}$ and $x_{i,1}$ as random outputs of H

- Removes last communication step

$\mathbf{V'} = \mathbf{V}^T$ $\qquad\qquad$ $\mathbf{T'} = \mathbf{T}^T$

for $1 \leq i \leq m$:

$y_{i,0} = x_{i,0} \oplus H(i, \mathbf{V'}[\mathrm{i}])$

$y_{i,1} = x_{i,1} \oplus H(i, \mathbf{V'}[\mathrm{i}] \oplus c)$

$\xrightarrow{(y_{i,0}, y_{i,1}), 1 \leq i \leq m}$

for $1 \leq i \leq m$:

$x_{i,r_i} = y_{i,r_i} \oplus H(i, \mathbf{T'}[\mathrm{i}])$

$\mathbf{V'} = \mathbf{V}^T$

for $1 \leq i \leq m$:

$x_{i,0} = H(i, \mathbf{V'}[\mathrm{i}])$

$x_{i,1} = H(i, \mathbf{V'}[\mathrm{i}] \oplus c)$

$\mathbf{T'} = \mathbf{T}^T$

for $1 \leq i \leq m$:

$x_{i,r_i} = H(i, \mathbf{T'}[\mathrm{i}])$

Empirical Performance Evaluation

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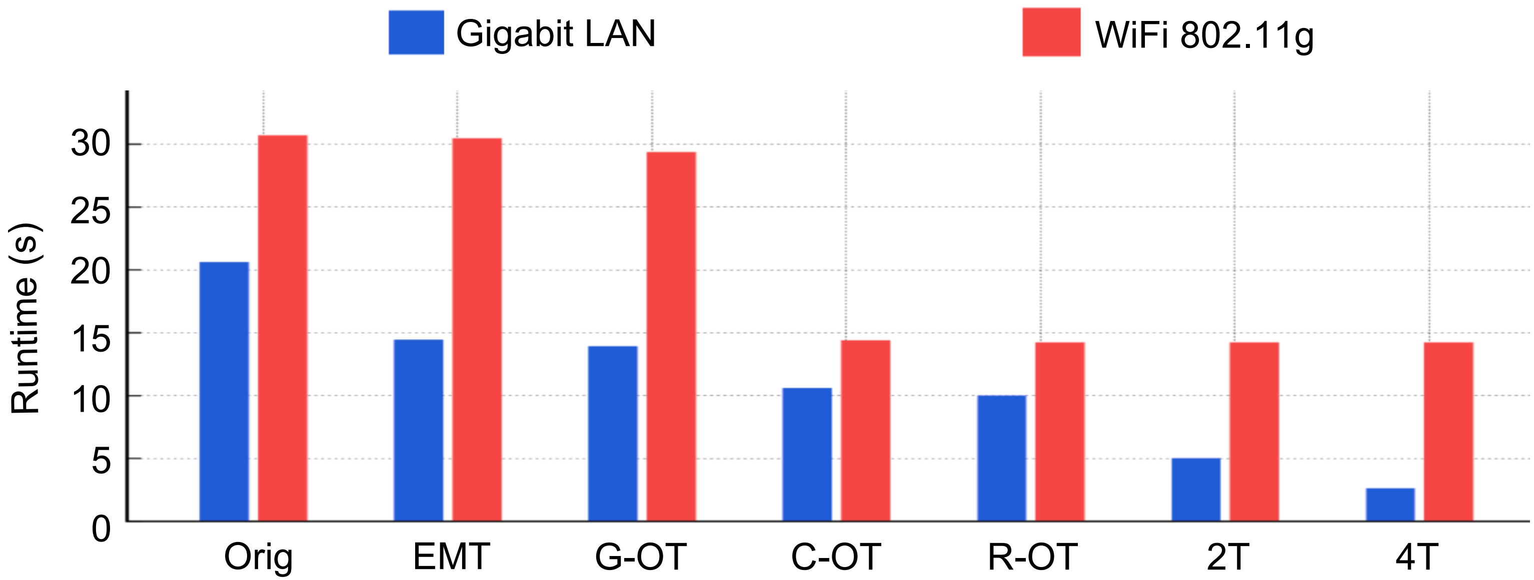
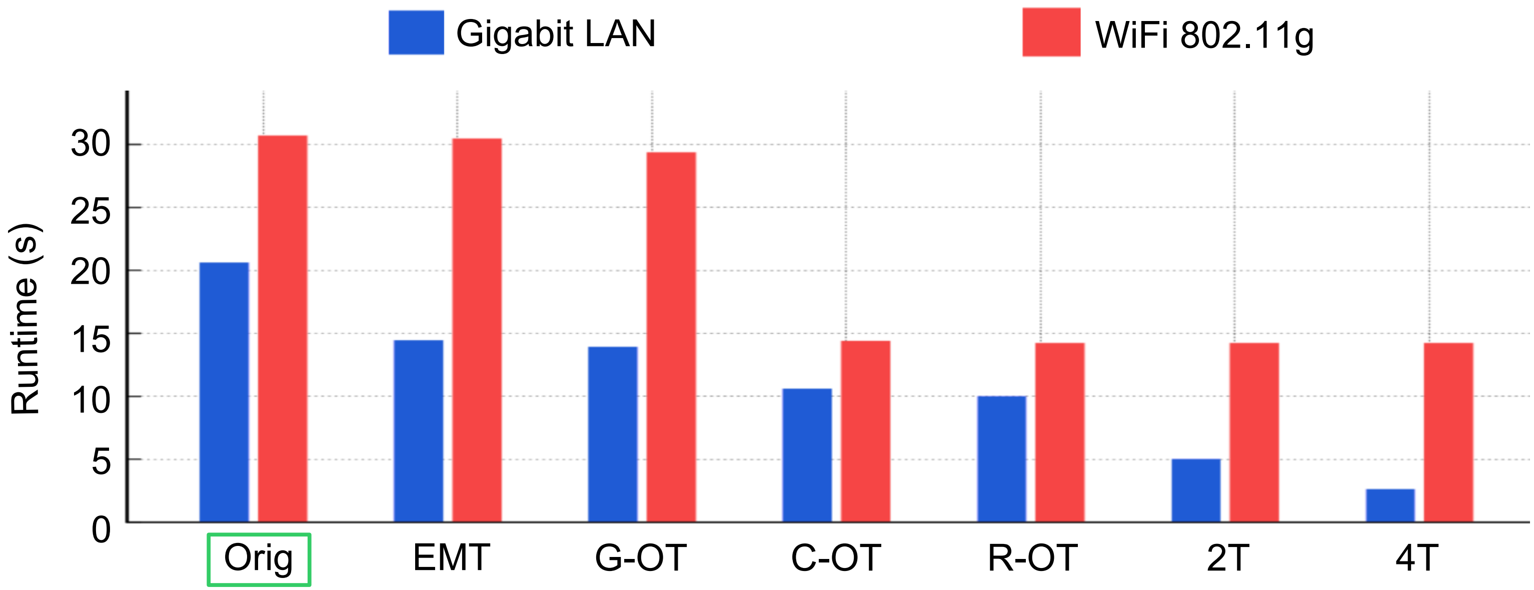


- Performance evaluation of 10 million OT extensions on 80-bit strings

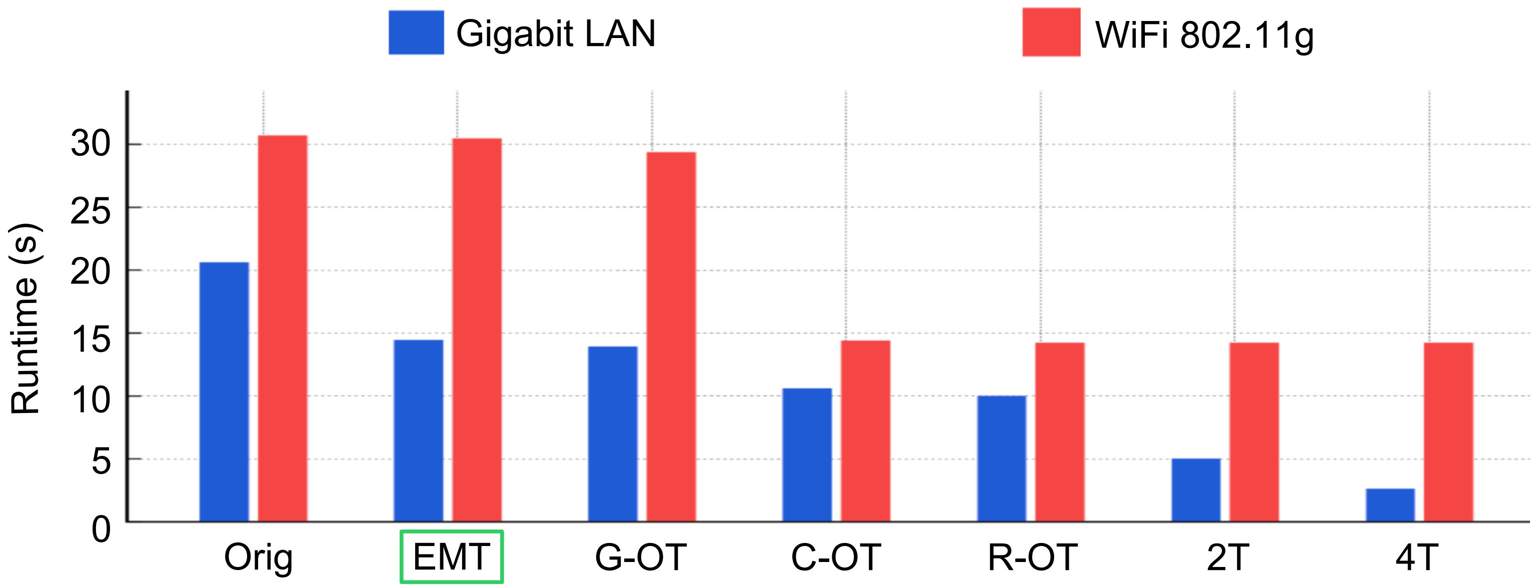
- Two network types: Gigabit LAN and WiFi 802.11g

Empirical Performance Evaluation
Original Implementation



- C++ code of [SZ13] implementing OT extension of [IKNP03]

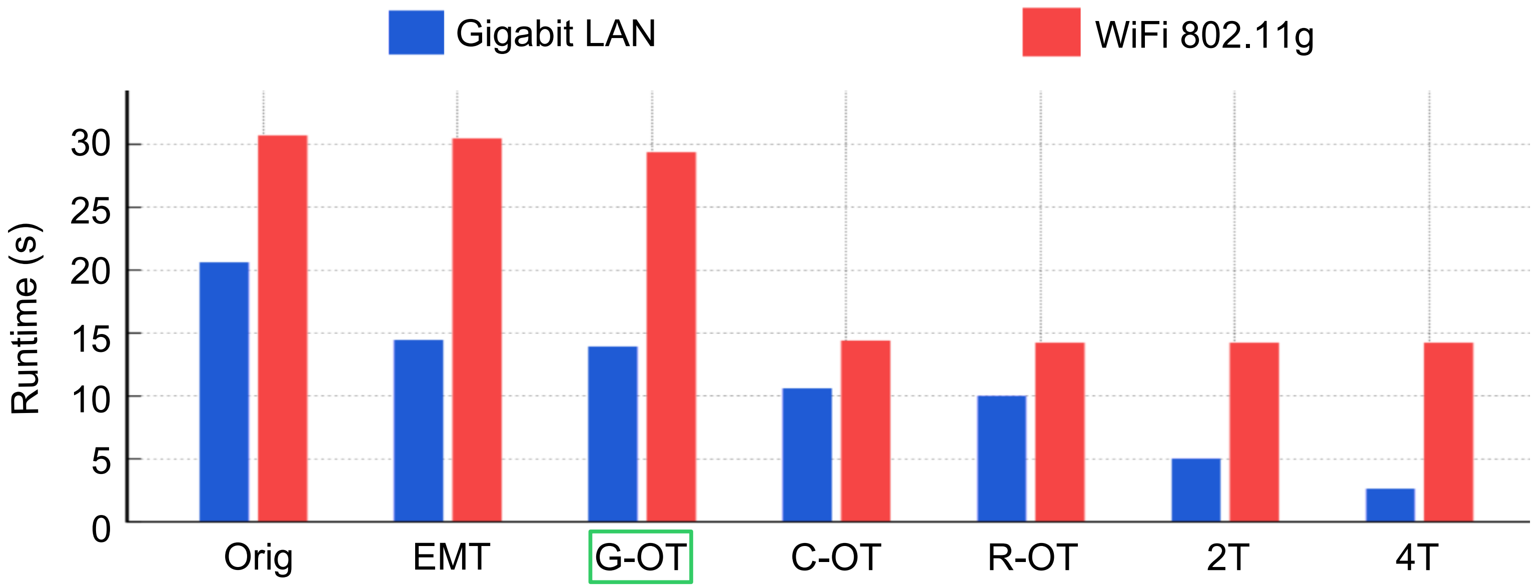
Empirical Performance Evaluation
Efficient Matrix Transposition



- Efficient matrix transposition => improved computation

- Only decreases runtime in LAN where computation is the bottleneck

Empirical Performance Evaluation
General Oblivious Transfer



- Generate **T** from seeds => improved communication (Bob → Alice)

- WiFi runtime decreases only slightly, since communication Alice → Bob becomes the bottleneck

Empirical Performance Evaluation
Correlated Oblivious Transfer

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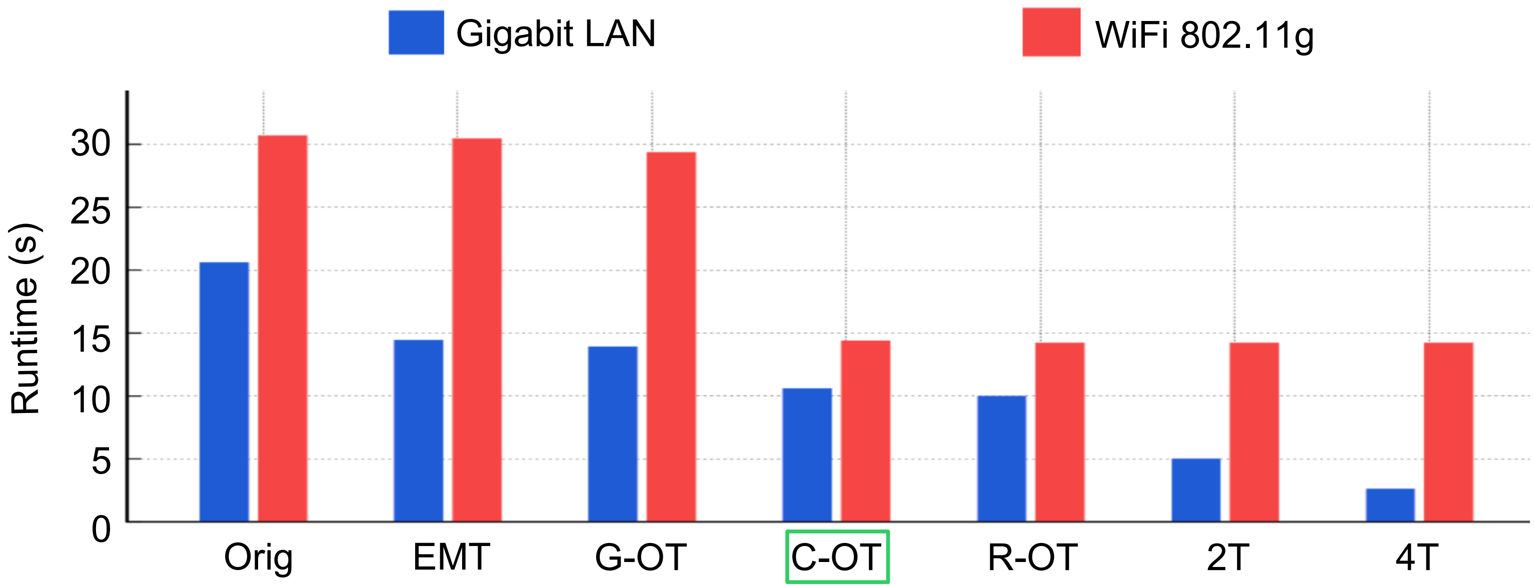

- Correlated OT => improved communication (Alice → Bob)

- WiFi runtime decreases by factor 2

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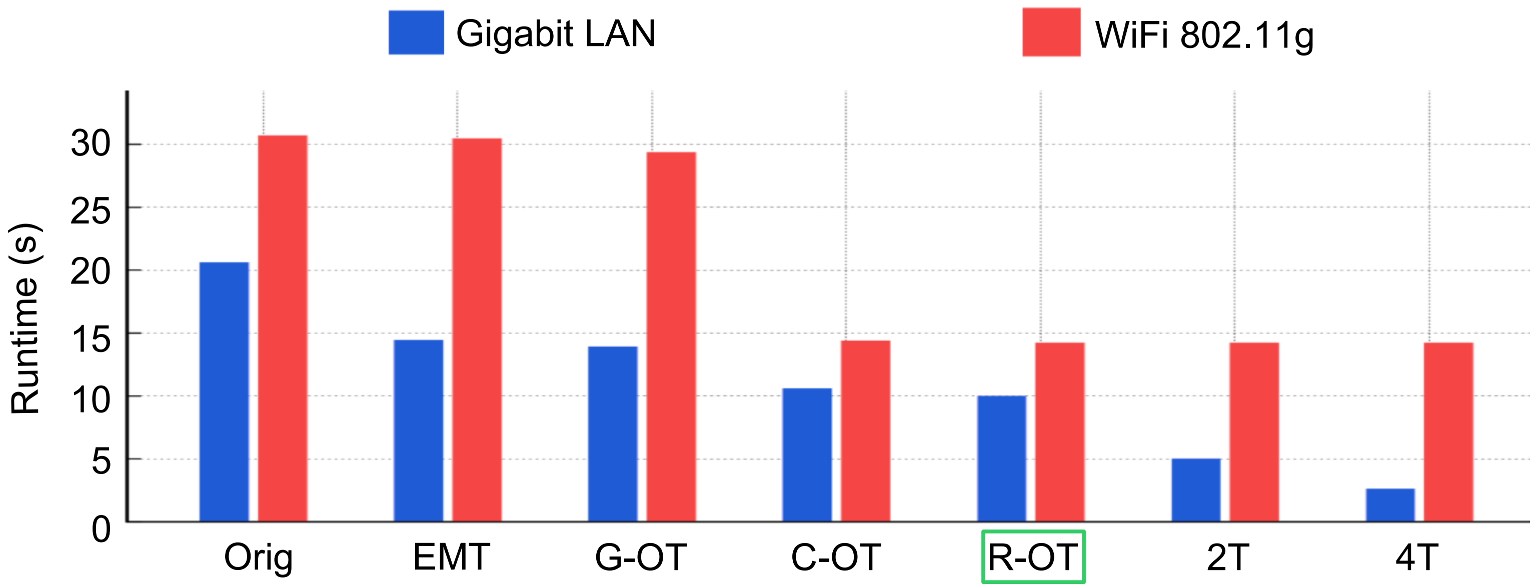
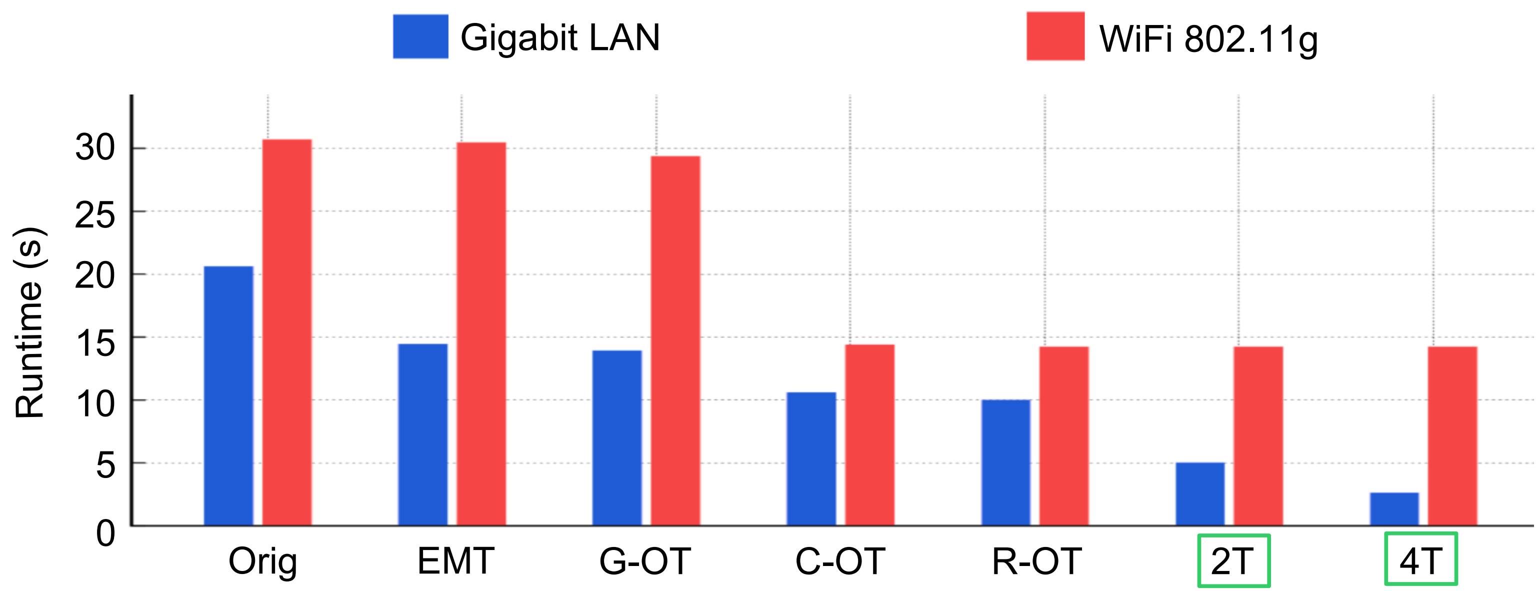
Empirical Performance Evaluation
Random Oblivious Transfer



- Random OT => improved communication (Alice → Bob)

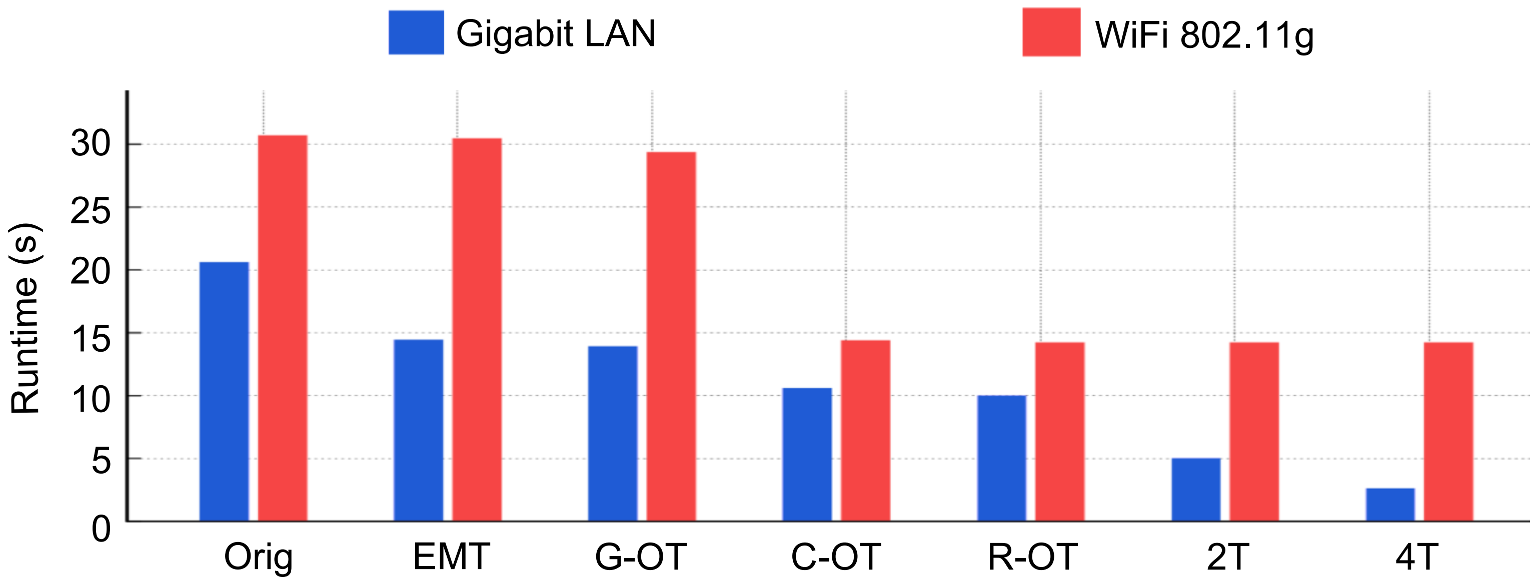
- WiFi runtime does not decrease since communication Bob → Alice becomes the bottleneck

Empirical Performance Evaluation
Parallelized Oblivious Transfer



- Parallel OT extension with 2 and 4 threads => improved computation
- LAN runtime decreases linear in # of threads
- WiFi runtime remains the same (communication is the bottleneck)

Empirical Performance Evaluation
Conclusion



- LAN profits mostly from improved computation

- WiFi profits from improved communication

- Communication has become the bottleneck for OT extension

Summary

- **Communication** has become the **bottleneck** for OT

- New OT functionalities for more efficient secure computation
    - **Correlated OT** for correlated values
    - **Random OT** for random values

- Our OT implementation is available at http://encrypto.de/code/OTExtension
    - A Java wrapper will be available in SCAPI

More Efficient Oblivious Transfer and Extensions for Faster Secure Computation

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Thanks for your attention.

Questions?

Contact: http://encrypto.de

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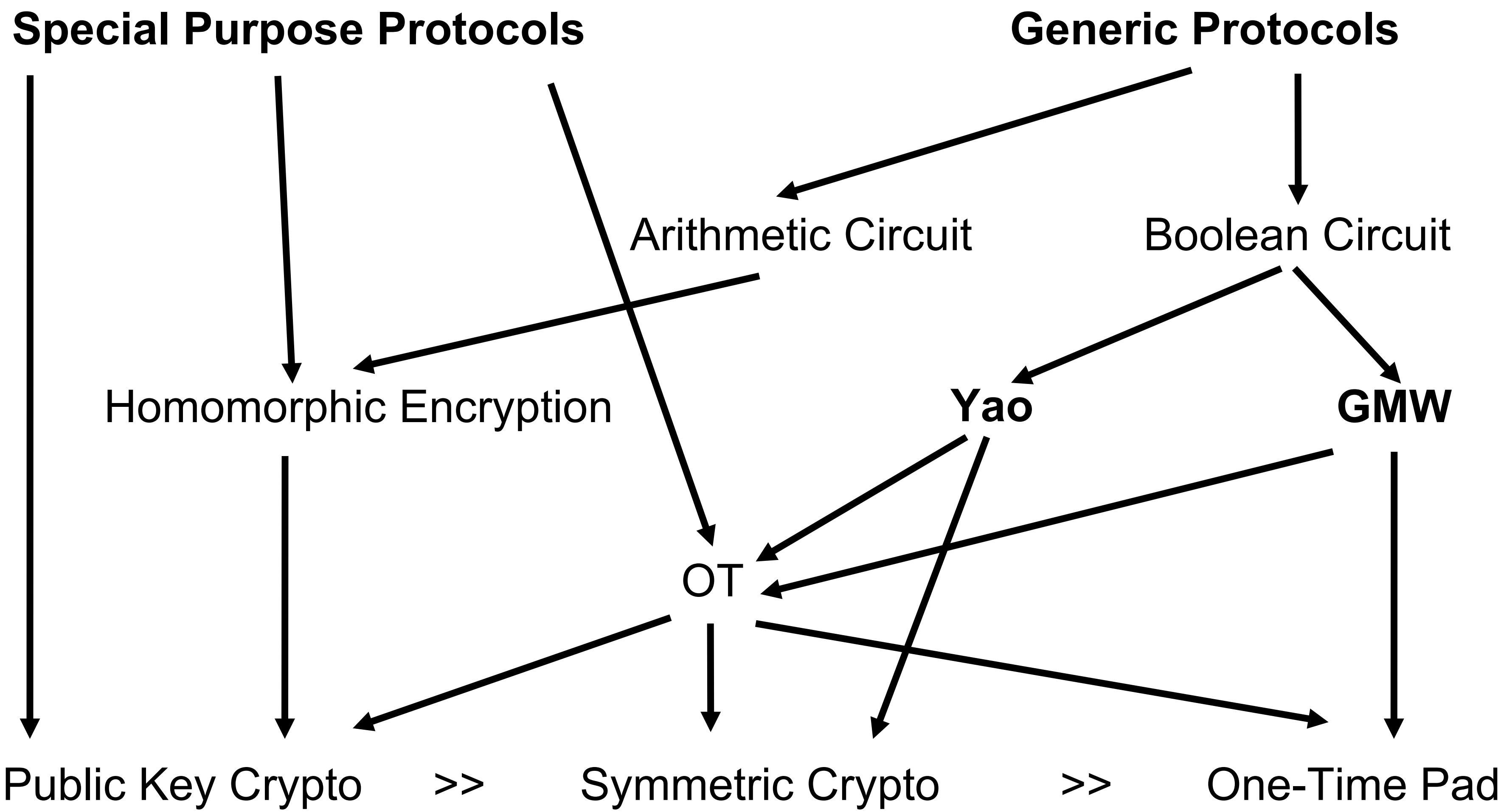
Protocol Overview



Generating Multiplication Triples via R-OT

- A multiplication triple has the form $(a_1 \oplus a_2)(b_1 \oplus b_2) = c_1 \oplus c_2 = (a_1 b_1) \oplus (a_1 b_2) \oplus (a_2 b_1) \oplus (a_2 b_2)$

- P_1 and P_2 generate a multiplication using two R-OTs as follows:

1) P_2 chooses $a_2 \in_R \{0,1\}$
2) P_1 and P_2 perform a random OT, where P_1 gets (x_1,x_2) and P_2 gets x_{a_2}
3) P_1 computes $b_1 = x_1 \oplus x_2$
4) P_1 and P_2 repeat steps 1-3 with reverse roles to get a_1 and b_2
5) P_i computes $c_i = (a_i b_i) \oplus x_1 \oplus x_{a_i}$

Efficient OT without Random Oracles

TODO:
Outline the protocol steps for the proposed base-OT