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Cheetah: Lean and Fast Secure 2PC DNN Inference

Part 1 Background

About Secure NN Inference

Resnet50: one of the most popular DNN models

However, secure 2PC Resnet50 inference takes lots of time:

- Prior best work: CryptFLOW2
- 10 mins for 1 image(224*224 rbg) inference (LAN, 3Gbps)

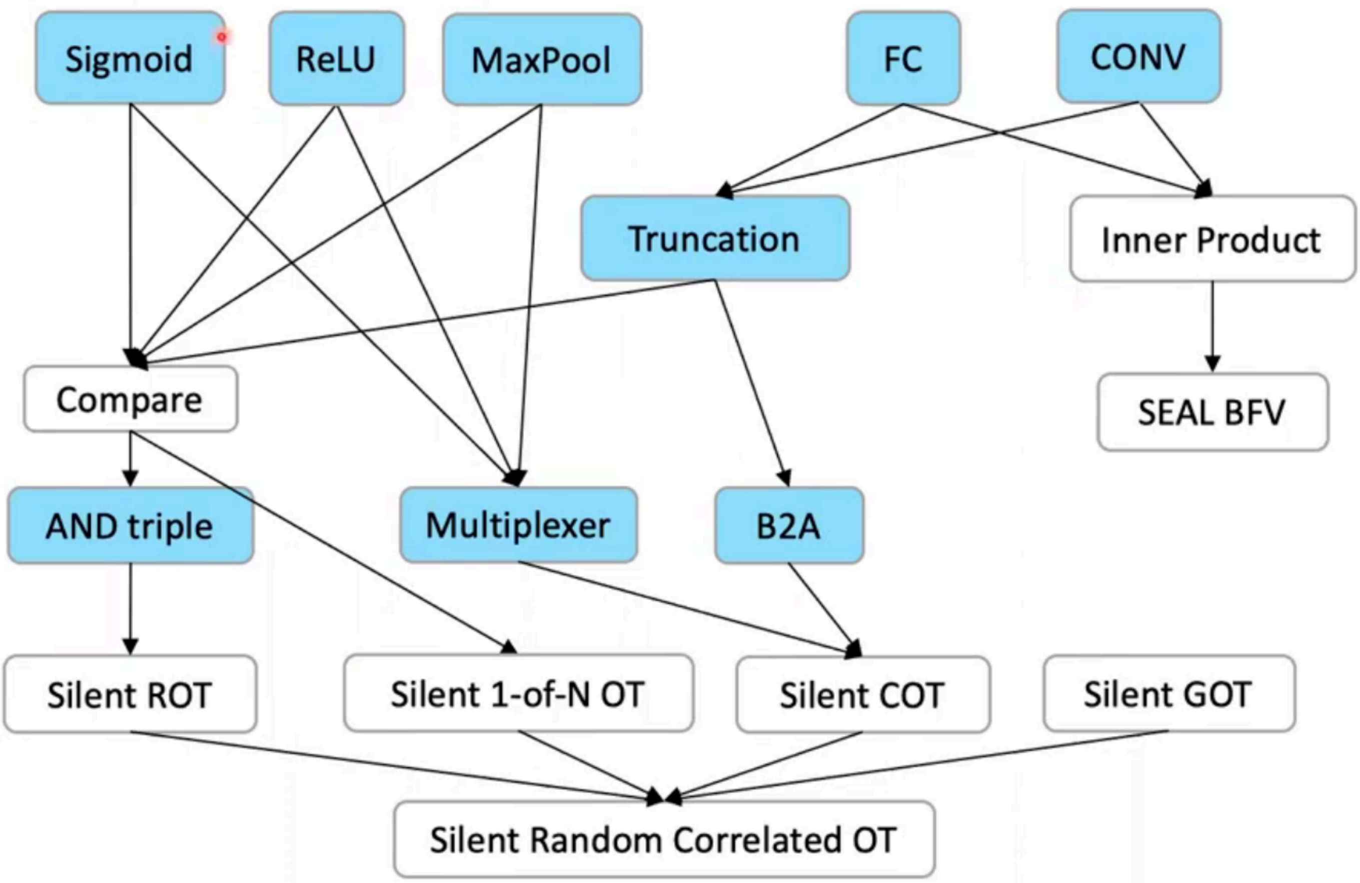
- 20 mins for 1 image(224*224 rbg) inference (WAN, 300Mbps)

Design Chanllenges in 2PC Frameworks

- Optimize trade-offs among different primitives
- Adapt to concrete application

Framework Type	Computation Cost	Communication Amount	Communication Round	Existing Works
GC（Y）	☆	☆☆☆	☆	EMP
SS（A、B）	☆	☆☆	☆☆☆	SPDZ、CryptFlow2
FHE	☆☆☆	☆	☆	Pegasus
A + B + Y	☆	☆☆☆	☆☆	ABY、SecureML
SS（A、B）	☆	☆	☆☆	Cheetah

Cheetah Protocol Architecture



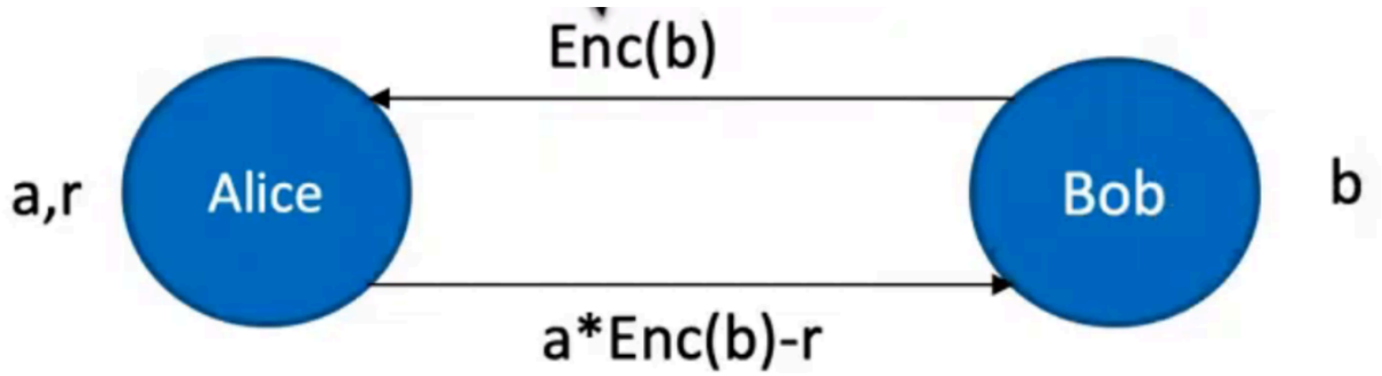
Additive Secret Sharing Recap

- Integer $a \in [0, P)$ is split into shares a_1, a_2
  - Computation party P_i has share a_i
  - Satisfy $a_1 + a_2 \ mod \ P = a$
- Local Add/Sub computation
- 2 types of sharings depending on modulus P
  - P=2: Boolean share
  - P>2: Arithmetic share, typically, P is a prime or a power of 2

Part 2 Linear Primitives

Linear Layers: CONV, FC

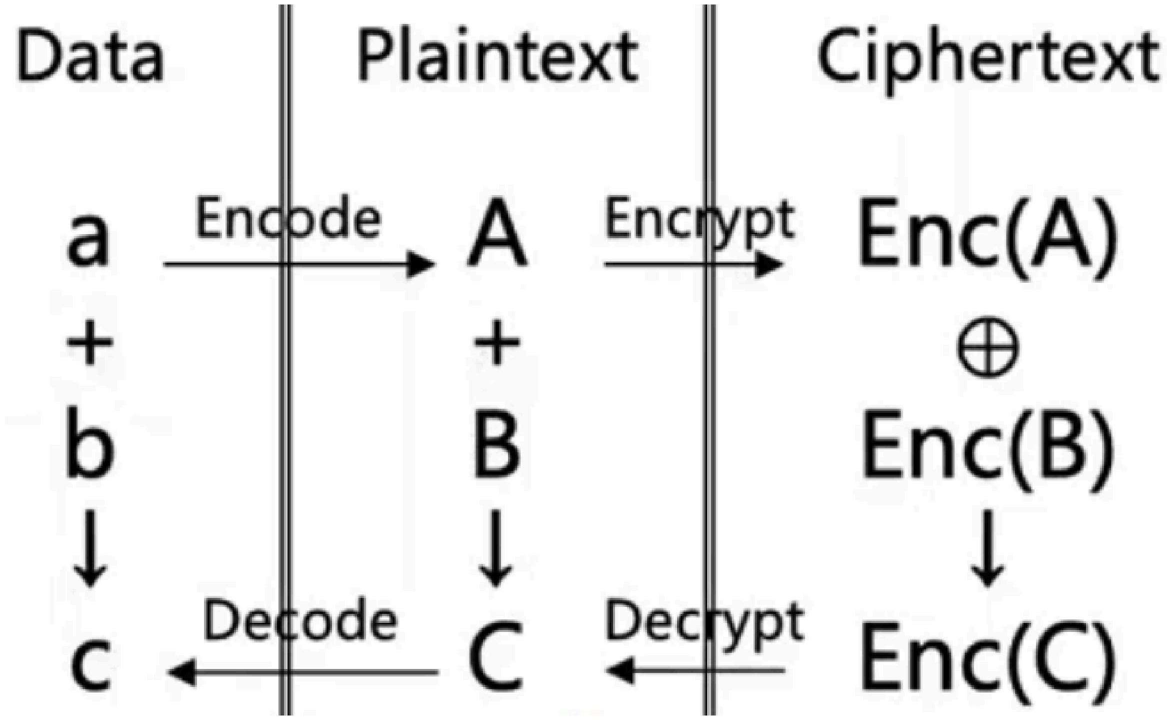
- CONV/FC: Matrix Mult $\rightarrow$ Inner Product
- Input:
  - Alice(model owner): vector $\vec{a}$
  - Bob(data owner): vector $\vec{b}$
- Output:
  - Alice: r
  - Bob: $\vec{a} \cdot \vec{b} - r \ mod \ k$



Here, the encryption is HE

Computation based on Polynomials

- Plaintext space for BFV: Polynomial Ring
  - Polynomial $Z_t(x)/(X^N + 1)$
  - Degree of N-1. Each integer coeff in $[0, t-1]$
  - Ciphertext add/mul $\leftrightarrow$ Polynomial add/ mul

- 

Packing: CRT Batching

- Encode data into polynomials:
  - $x^n + 1$ can be broken into the product of n polynomials: $x^n + 1 = (x + a_1)(x + a_2)\ldots(x + a_n)$
    - E.g.: t=17, n=2 → $x^2 + 1 = (x - 4)(x - 13)$ // $x^2 - 17 + 25 \ mod \ 17$
  - $f(x) \ mod \ (x^n + 1)$ can be represent n integers: $x_i = f(x) \ mod \ (x + a_i)$
    - E.g.: $x \ mod \ (x^2 + 1) \rightarrow x \ mod \ (x - 4) \ \& \ x \ mod \ (x - 13)$: $x \ mod \ (x^2 + 1)$ packs 4 and 13
- Given n integers, find corresponding $f(x)$ to encode them by CRT
  - E.g.: $2x - 7$ packs 1 and 2 // 2x-7 mod (x-4) = 1, 2x-7 mod (x-13) = 19 mod 17 = 2
- Packing keeps homomorphism modulo t
  - Add: $x + (2x - 7)$ packs 5 and 15 // 3x-7 mod (x-4) = 5, 3x-7 mod (x-13) = 32 mod 17 = 15
  - Mul: x*(2x-7) packs 4 and 9 // $2x^2 - 7x \ mod \ (x^2 + 1) = -7x - 2$, -7x-2 mod (x-4) = 4, -7x-2 mod (x-13) = -93 mod 17 = 9
- SIMD: 1 polynomial calculation completes n integer calculations

Precondition of SIMD Packing in BFV

- Almost all efficient BFV applications use SIMD Packing

- 1 poly mult → 1000+ plain integer mults

- SIMD requires plain modulus t to be a prime

  - Secret sharing has to work in prime field in a mixed protocol
  - Performance degrades significantly (60% more overhead in CryptFlow2)

Inner Product 1st Try: SIMD Packing + Ciphertest Rotation

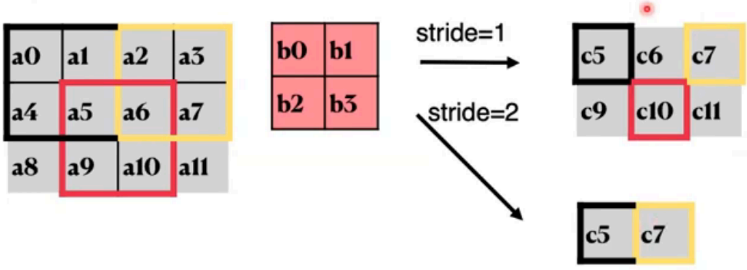
- A has a vector $a = (a_0, a_1, ..., a_n)$, B has a vector $b = (b_0, b_1, ..., b_n)$
- A SIMD packs a as a poly $A(x)/X^N + 1$; B SIMD packs b as a poly $B(x)/X^N + 1$;
- B uses its public key to encrypt $B(x)$, and send to A
- A performs homomorhic mult on Enc(B(x)) and A(x) → Obtains $Enc(C(x))/X^N + 1$
  - C(x) packs $(a_0 b_0, ..., a_n, b_n)$
  - Innerproduct needs to sum those up
- A rotates the ciphertext Enc(C(x)), obtaing
  - $$(a_1b_1, \dots a_{n-1}b_{n-1}, a_nb_n, a_0b_0)$$
    $$(a_2b_2, \dots a_nb_n, \quad a_0b_0, a_1b_1)$$
    $$\dots$$
    $$(a_nb_n, a_0b_0, a_1b_1, \dots a_{n-1}b_{n-1})$$
  - then perform homomorphic add to get (ab,...,ab), sends to B, and B decrypts to get ab
- Needs log(n) rotates and n adds

2D Convolution

Multiplication between a long poly an d a shart poly → Convolution

$$a(X) = a_0 + a_1X + a_2X^2 + a_3X^3 + a_4X^4 + a_5X^5 + a_6X^6 + a_7X^7 + a_8X^8 + a_9X^9 + a_{10}X^{10} + a_{11}X^{11}$$

$$b(X) = b_3 + b_2X + 0X^2 + 0X^3 + b_1X^4 + b_0X^5$$



$$a(X) \cdot b(X) = \sum_{i=0}^{15} c_i X^i$$

$$c_5 = a_0b_0 + a_1b_1 + a_4b_2 + a_5b_3 \qquad c_6 = a_1b_0 + a_2b_1 + a_5b_2 + a_6b_3$$

$$c_7 = a_2b_0 + a_3b_1 + a_6b_2 + a_7b_3 \qquad c_9 = a_4b_0 + a_5b_1 + a_8b_2 + a_9b_3$$

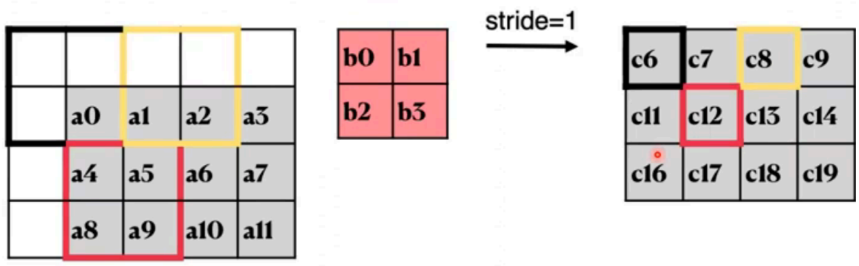
$$c_{10} = a_5b_0 + a_6b_1 + a_9b_2 + a_{10}b_3 \qquad c_{11} = a_6b_0 + a_7b_1 + a_9b_2 + a_{11}b_3$$

Valid Padding

$$a(X) = a_0X^6 + a_1X^7 + \cdots + a_{11}X^{19}$$

$$b(X) = b_3 + b_2X + 0X^2 + 0X^3 + 0X^4 + b_1X^5 + b_0X^6$$

$$a(X) \cdot b(X) = \sum_{i=0}^{25} c_i X^i$$



The whole tensor needs to be encoded into a poly of degree N

- HWC ≤ N (valid padding)
- (H-h+1)(W-h+1)C ≤ N (valid still)
- (rare case) when stride s >= h, we can skip some computation

Big tensor (HWC>N) can be split into small tensors

- Along Channels: just a simple addition in the ends
- Along Height/Width: Might contain overlaps

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Part 3 Non-Linear Primitives

OT (Primitive)

this section is discribed in "OT.md"

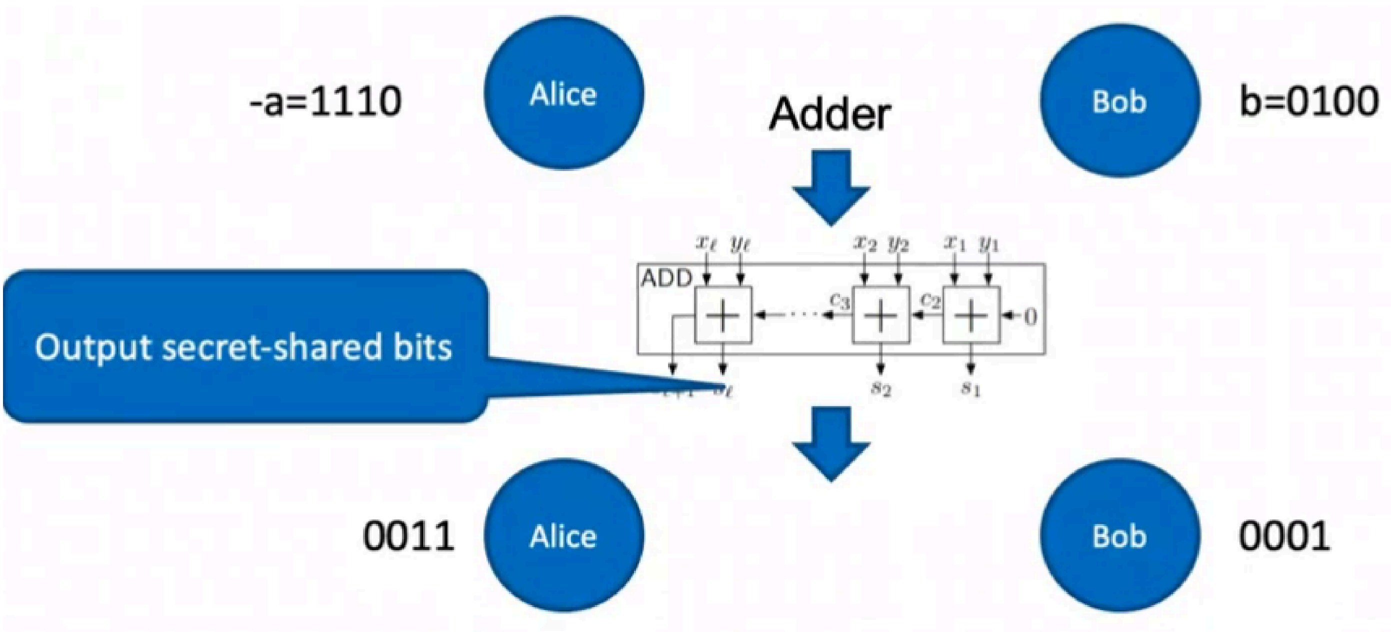
Non-Linear Layer (ReLU, MaxPool)

ReLU = max(x,0)

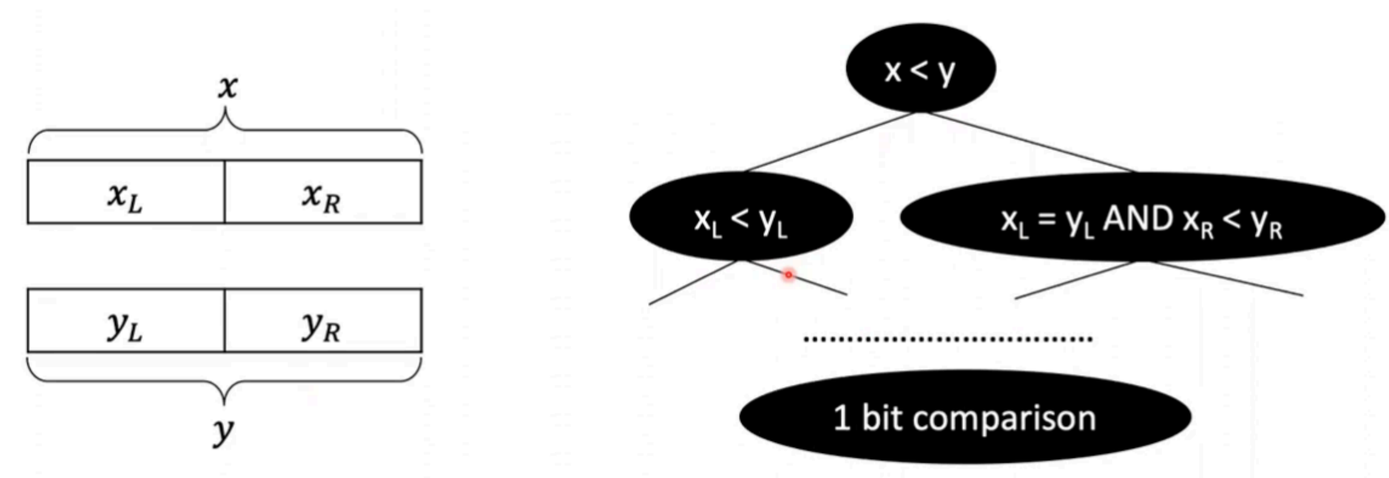
- Input: Alice, Bob: Secret-shared x
- Output: Alice, Bob: Secret-shared DReLU(x)*x
- DReLU(x) = 0(if x<0), 1(otherwise)

Millionaire problem

Solution 1: Boolean addition -a and b, then examine MSB

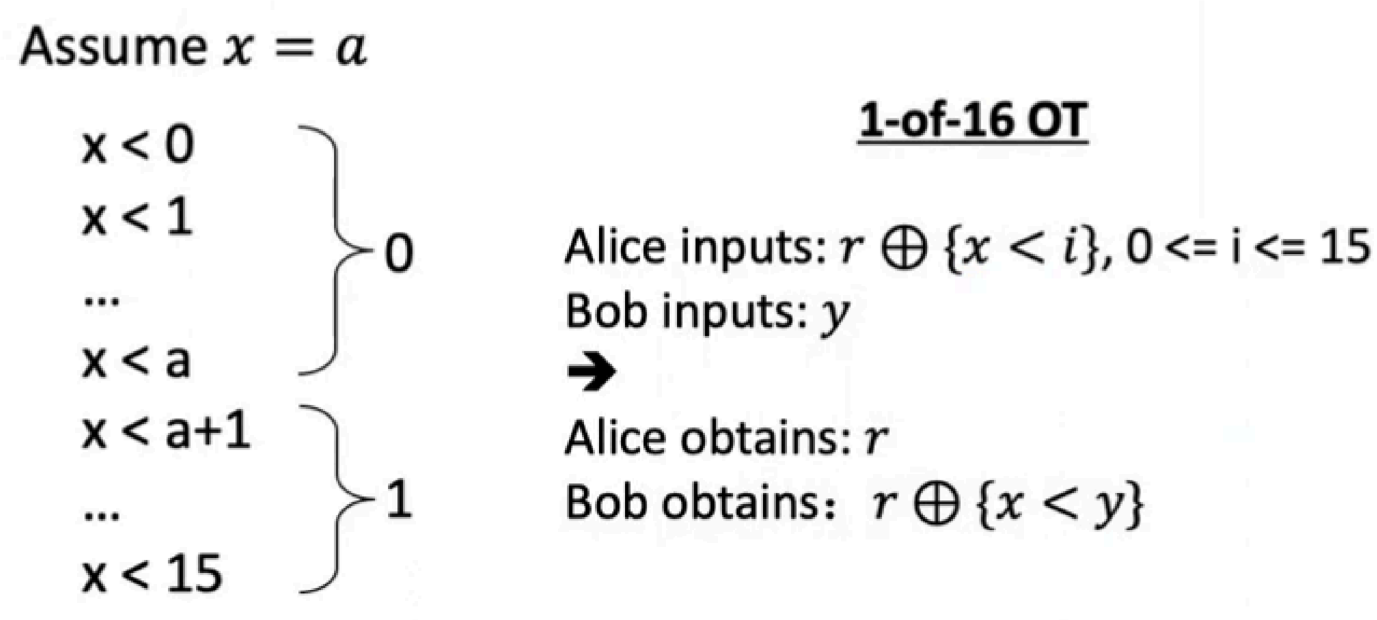


Solution 2: Comparison Tree (CryptFlow2)



Optimization: CTree down to 4 bit block comparison instead of 1 bit

This can Minimize comm. rounds and AND gates

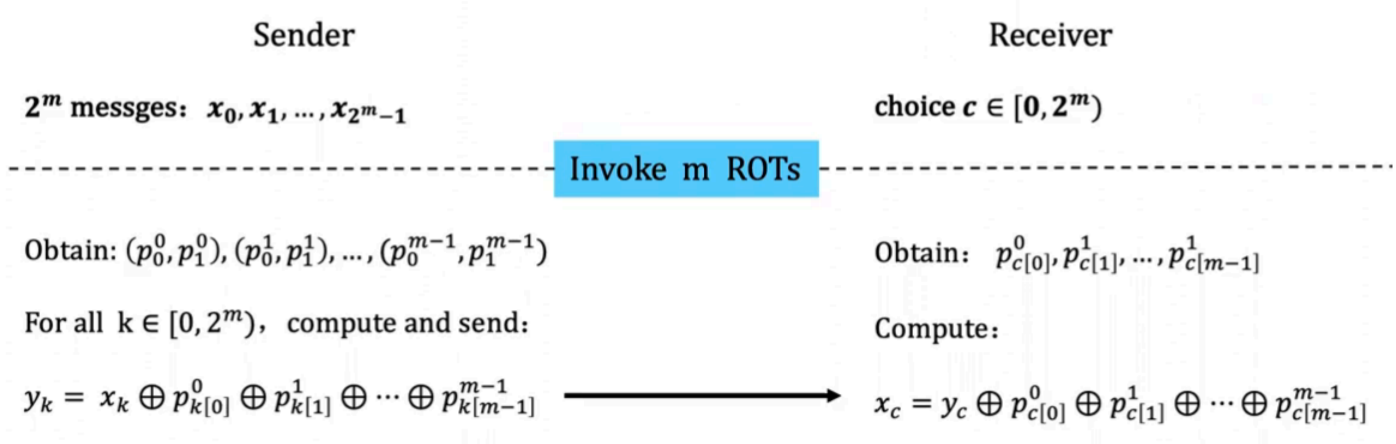


Notice that CryptFlow2 uses classic IKNP-OT

In Cheetah, they use Silent OT based on VOLE (Ferret)

This approach can generate massive amount of RCOT with little comm.

We then use RCOT to generate other OT varient



Primitives in Compare:

Primitives	Communication (bits)	
	IKNP (CF2)	Silent (Cheetah)
$\binom{2}{1} - \mathrm{ROT}_\ell$	λ	0 or 1
$\binom{2}{1} - \mathrm{COT}_\ell$	$\ell + \lambda$	$\ell + 1$
$\binom{2}{1} - \mathrm{OT}_\ell$	$2\ell + \lambda$	$2\ell + 1$
$\binom{n}{1} - \mathrm{OT}_\ell$ (n $\geq$ 3)	$n\ell + 2\lambda$	$n\ell + \log_2 n$

E.g.: $\ell = 64,\ \lambda = 128$

Truncation

Motivation:

- Fixed point numbers for MPC
  - value is 0.5, scale is 2^{15} $\rightarrow$ FP representation: $0.5 \times 2^{15} = 16384$
- Problem: multiplication increases the scale
  - $0.5 \times 0.5 \rightarrow 16384 \times 16384 = 268435456 = 0.25 \times 2^{30}$
  - several mults would leads to an overflow
- Need a method to truncate secret-shared values to maintain the scale
  - plain truncation: x>>15
  - we cannot do it locally:
    - x=x1+x2 mod 2^k, therefore (x>>15) != (x1>>15) + (x2>>15)

Cheetah: Efficient silient OT-based truncation protocol

(1/2 probability with tiny one-bit LSB error)

Part 4 Performance and Summary

Performance

Benchmark	System	End2End Time		Commu.
		LAN	WAN	
SqNet	SCI_{HE} [50]	41.1s	147.2s	5.9GB
	SecureQ8 [16]	4.4s	134.1s	0.8GB
	Cheetah	16.0s	39.1s	0.5GB
RN50	SCI_{HE} [50]	295.7s	759.1s	29.2GB
	SecureQ8 [16]	32.6s	379.2s	3.8GB
	Cheetah	80.3s	134.7s	2.3GB
DNet	SCI_{HE} [50]	296.2s	929.0s	35.4GB
	SecureQ8 [16]	22.5s	342.6s	4.6GB
	Cheetah	79.3s	177.7s	2.4GB

SqNet = SqueezeNet; RN50 = ResNet50; DNet = DenseNet121

SqNet=SqueezeNet; RN50=ResNet50; DNet=DenseNet121

SCI_{HE}: CryptFlow

SecureQ8: State-of-art 3PC framework