Symphony: Threshold Evaluation of Symmetric Primitives

A protocol family for threshold AES, SHA2, SHA3 and G-/C-/H-/KMAC evaluation in the three-party, honest majority setting

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joint work with
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AARHUS UNIVERSITY

Overview

Planned Submission

Threshold evaluation of

- AES *(secret-shared key)*
- GMAC and CMAC *(secret-shared key)*
- SHA2 and SHA3 *(secret-shared input)*
- HMAC and KMAC *(secret-shared key)*

Setting

- 3 parties, 1 tolerated corruption
- active security with abort

Techniques

- replicated secret sharing [FLNW17]
- generation of random one-hot vector correlations
- oblivious table lookup
- distributed inner-product checks [BBC+19,MPS+25]

Applications

- threshold symmetric-key (authenticated) encryption
- distributed authentication protocols, private set intersection, secure database joins
- virtual TPM

Outline

- Background
  - Replicated Secret Sharing
  - Oblivious Table Lookup
  - Achieving Active Security
- Module Overview
- Detail Modules
- Experimental Results

Background

Replicated Secret Sharing (1)

secret $x \in \mathrm{GF}(2^k)$

Secret Sharing

- additive sharing, $\langle x \rangle_i = x_i$ where $x_1 + x_2 + x_3 = x$
- replicated sharing $[\![x]\!]_1 = (x_1, x_2)$, $[\![x]\!]_2 = (x_2, x_3)$ and $[\![x]\!]_3 = (x_3, x_1)$.

Linear Computation

- Linear operation L: $[\![L(x)]\!]_i = (L(\langle x \rangle_i), L(\langle x \rangle_{i+1}))$
- Squaring: $[\![x^2]\!] = (\langle x \rangle_i^2, \langle x \rangle_{i+1}^2)$
- Bit decomposition: $[\![x]\!] = ([\![x_0]\!], \ldots, [\![x_{k-1}]\!])$, $x_j \in \{0, 1\}$

$\rightarrow$ no communication

Replicated Secret Sharing (2)

Multiplication $[\![x]\!] \cdot [\![y]\!]$

Given $\langle 0 \rangle$ from preprocessing *(can be derived from correlated PRF keys)*

1. Local multiplication $\langle xy \rangle_i = x_i y_i + (x_i + x_{i+1})(y_i + y_{i+1})$
   $\rightarrow$ obtain additive sharing of xy
2. Send $\langle xy \rangle_i + \langle 0 \rangle_i$ to P_{i-1}, set $[\![xy]\!]_i = (\langle xy \rangle_i + \langle 0 \rangle_i, \langle xy \rangle_{i+1} + \langle 0 \rangle_{i+1})$

Table Lookup LUT $[\![T[x]]\!]$

Table T,given *random one-hot vector* correlation from preprocessing $[\![r]\!], [\![\boldsymbol{e}^{(r)}]\!]$

$$[\![\boldsymbol{e}^{(r)}]\!] = (\underbrace{[\![0]\!], \ldots, [\![0]\!], [\![1]\!]}_{r}, [\![0]\!], \ldots)$$

1. Reveal value $c = r + x$
2. Local computation $[\![T[x]]\!] = \sum_i T[c - i] \cdot [\![e_i^{(r)}]\!]$

Active Security

Linear Operations

- each share of the corrupted party is held by an honest party
- consistency is checked for all revealed values
- before accepting result: parties exchange views (pairwise)
- compress transcript using hash function

Multiplications

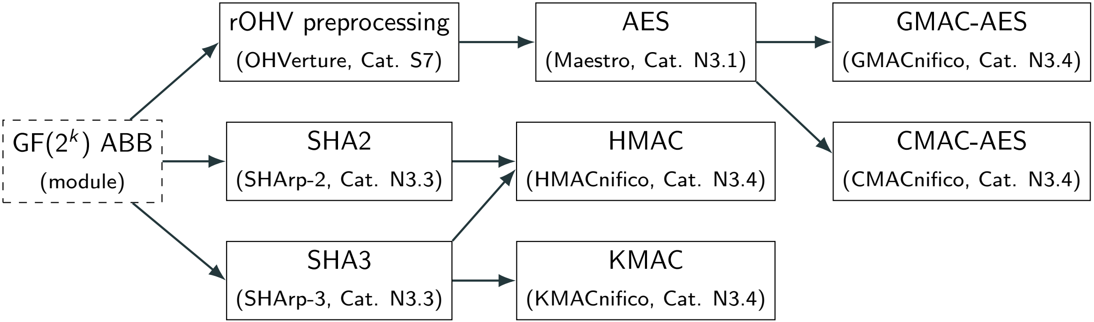
- recursive inner-product check (adapted to our setting from [BBC+19,BGIN20])
- for L inner-product triples $\sum_{i=1}^{m} [\![x_i]\!] \cdot [\![y_i]\!] = [\![z]\!]$; let $N = L \cdot m$

Cost

- $\mathcal{O}(\log N) \cdot (\log |\mathbb{F}|)$ bits of communication (we use $\mathbb{F} = \mathrm{GF}(2^{64})$)
- in $\log N$ rounds of communication

Symphony – Overview

Symphony Modules



GF(2^k) **Arithmetic Black Box (ABB)**

- Input(x, P_i) $\rightarrow [\![x]\!]$: party P_i inputs $x \in$ GF(2^k) into the ABB

- Linop($f, [\![x_1]\!], \dots$) $\rightarrow [\![f(x_1, \dots)]\!]$, for any GF(2)-linear function f
- LocalMul($[\![x]\!], [\![y]\!]$) $\rightarrow \langle x \cdot y \rangle$

- Reshare($\langle x \rangle$) $\rightarrow [\![x]\!]$
- BitMul($[\![x]\!], [\![y]\!]$) $\rightarrow [\![x \cdot y]\!]$ where $x \in$ GF(2) and $y \in$ GF(2^k).
- Reconst($[\![x]\!]$) $\rightarrow x$: unverified opening of the secret-shared $[\![x]\!]$.

- VerifyRecon(): verifies all opened values (via Reconst) so far.
- VerifyMul(): verifies all multiplications (via LocalMul and BitMul) so far.
- Output($[\![x]\!]$) $\rightarrow x/\perp$: verified output

(for $k \in \{1, 4, 8, 64, 128\}$)

OHVerture: Preprocessing for random one-hot vectors

Output

$([\![r]\!], [\![\mathbf{e}^{(r)}]\!])$ or $([\![r]\!], \langle \mathbf{e}^{(r)} \rangle)$
where $\mathbf{e}^{(r)} = (\underbrace{0, \ldots, 0}_{r}, 1, 0, \ldots)$ and r random

Usefulness as Gadget

enable richer MPC gadgets such as table lookup protocols

- secure sampling for common noise distributions [MRS25,FFG+25]
- fast online phase when compiling Boolean circuits into LUT gates [BHS+23]
- ...

- $\mathsf{rOHVrss}(N = 2^k, L) \to ([\![r_j]\!], [\![\mathbf{e}^{(r_j)}]\!])_{j=1}^{L}$ outputs shares of L correlations, where $r_j \leftarrow \$ \mathrm{GF}(2^k)$
- $\mathsf{rOHVadd}(N = 2^k, L) \to ([\![r_j]\!], \langle \mathbf{e}^{(r_j)} \rangle)_{j=1}^{L}$ outputs shares of L correlations, where $r_j \leftarrow \$ \mathrm{GF}(2^k)$

Maestro: AES enciphering & deciphering

Output

distributed key (schedule) generation, enciphering, deciphering for AES-128 and AES-256

- $\mathrm{DistKeyGen}() \to [\![\mathrm{ks}]\!]$: outputs the key schedule ks of a fresh random AES-128/-256 key as shares to the parties
- $\mathrm{InputKey}(k, P_i) \to [\![k]\!]$: inputs the key by party P_i
- $\mathrm{ComputeKS}([\![k]\!]) \to [\![\mathrm{ks}]\!]$: computes the key schedule
- $\mathrm{InputBlock}(m, P_i) \to [\![m]\!]$: inputs a 128-bit block by party P_i
- $\mathrm{OutputBlock}([\![m]\!]) \to m$

- $\mathrm{Encipher}([\![\mathrm{ks}]\!], [\![m]\!]) \to [\![\mathrm{AES}(\mathrm{ks}, m)]\!]$: computes AES enciphering

  with performance mode
  - “online phase throughput”
  - “total throughput”
  - “low latency”

Output

hashing of a secret-shared message for SHA-256, SHA-512, SHA3-256 and SHA3-512

- InputMessage$(m, P_i) \rightarrow [\![m]\!]$: inputs a message by party P_i.
- Hash$([\![m]\!]) \rightarrow [\![\mathcal{H}(m)]\!]$: computes the threshold hash.
- OutputDigest$([\![d]\!]) \rightarrow d$, where $[\![d]\!]$ is obtained from any of the hash computations above.

MACnifico: Threshold GMAC-AES, CMAC-AES, HMAC and KMAC

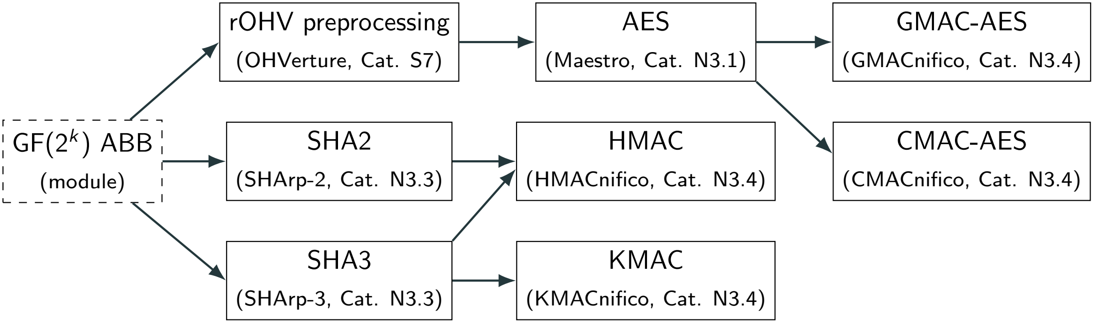
Output

MAC tag computation using secret-shared key:

- GMAC and CMAC (from AES-128 and AES-256)
- HMAC (from SHA-256, SHA-512, SHA3-256 and SHA3-512)
- KMAC-128 and KMAC-256

- InputKey$(k, P_i) \to [\![k]\!]$: inputs the MAC key by party P_i
- InputMessage$(m, P_i) \to [\![m]\!]$: inputs the message by party P_i
- TagGen$([\![k]\!], [\![m]\!]) \to [\![\tau]\!]$: computes the threshold MAC tag generation on the given key and message
- OutputTag$([\![\tau]\!]) \to \tau$, where $[\![\tau]\!]$ is obtained from any thresholdized TagGen computation.

Symphony Modules



Selected Technical Details

rOHV preprocessing (1)

Length 16 using $GF(2^4)$

1. generate random $[\![\cdot]\!]$-shared bits r_0, r_1, r_2, r_3
2. compute partial products $r_i r_j$, $r_i r_j r_k$ and $r_0 r_1 r_2 r_3$
3. each element in $\boldsymbol{e}^{(r)}$ is a linear combination of partial products

Mult. check requires checking 2 $GF(2^{64})$ multiplications

Cost

- 11 GF(2) multiplications $\rightarrow$ 11 bits of communication
- in 2 communication rounds

rOHV preprocessing (2)

Length 256 using GF(2^8)

1. obtain 2 length-16 random one-hot vectors: $[\![u]\!], [\![\boldsymbol{e}^{(u)}]\!]$ and $[\![v]\!], [\![\boldsymbol{e}^{(v)}]\!]$
2. *local* tensor product $\langle \boldsymbol{e}^{(r)} \rangle \leftarrow [\![\boldsymbol{e}^{(u)}]\!] \otimes [\![\boldsymbol{e}^{(v)}]\!]$ where $r = u \| v$
3. output $([\![r]\!], \langle \boldsymbol{e}^{(r)} \rangle)$

Mult. check requires checking 4 GF(2^{64}) multiplications **+ AES S-box check for LUT**

Cost

- 22 GF(2) multiplications $\rightarrow$ 22 bits of communication
- in 2 communication rounds

Advanced Encryption Standard (AES)

Block cipher composed of 10 rounds (AES-128)
Let $\mathrm{GF}(2^8) = \mathbb{F}_2[X]/X^8 + X^4 + X^3 + X + 1$.

$$S = \begin{pmatrix} s_0 & s_4 & s_8 & s_{12} \\ s_1 & s_5 & s_9 & s_{13} \\ s_2 & s_6 & s_{10} & s_{14} \\ s_3 & s_7 & s_{11} & s_{15} \end{pmatrix}$$

only non-linear computation

1. SubBytes: $\text{S-box}(s_i) = f(s_i^{-1})$
2. ShiftRows: $$\begin{pmatrix} s_0 & s_4 & s_8 & s_{12} \\ s_1 & s_5 & s_9 & s_{13} \\ s_2 & s_6 & s_{10} & s_{14} \\ s_3 & s_7 & s_{11} & s_{15} \end{pmatrix} \to \begin{pmatrix} s_0 & s_4 & s_8 & s_{12} \\ s_5 & s_9 & s_{13} & s_1 \\ s_{10} & s_{14} & s_2 & s_6 \\ s_{15} & s_3 & s_7 & s_{11} \end{pmatrix}$$
3. MixColumns: $$\begin{pmatrix} 02 & 03 & 01 & 01 \\ 01 & 02 & 03 & 01 \\ 01 & 01 & 02 & 03 \\ 03 & 01 & 01 & 02 \end{pmatrix} \cdot S$$
4. AddRoundKey: $S + RK$

MAESTRO (1)

compute inversion $x^{-1} \in GF(2^8)$

Performance Mode: High Online Phase Throughput

1. use isomorphism between $GF(2^8)$ and $GF(2^4)^2$ (linear operation)
2. compute $v^{-1} \in GF(2^4)$ as table lookup (consume length 16 OHV from OHVerture)

Mult. check requires checking 1 $GF(2^{64})$ multiplication

Cost

- 3 $GF(2^4)$ mult. + 1 $GF(2^4)$ inversion $\rightarrow$ 16 bits of communication
- in 2 communication rounds

MAESTRO (2)

compute inversion $x^{-1} \in GF(2^8)$

Performance Mode: High Total Throughput

1. use isomorphism between $GF(2^8)$ and $GF(2^4)^2$ (linear operation)
2. compute $v^{-1} \in GF(2^4)$ as $v^2 \cdot v^4 \cdot v^8$

Mult. check requires checking 3 $GF(2^{64})$ multiplications

Cost

- 5 $GF(2^4)$ mult. $\rightarrow$ 20 bits of communication
- in 3 communication rounds

MAESTRO (3)

compute inversion $x^{-1} \in \mathrm{GF}(2^8)$

Performance Mode: Low Latency

1. compute $x^{-1} \in \mathrm{GF}(2^8)$ as table lookup (consuming length-256 OHV from OHVerture)

Mult. check requires checking 2 $\mathrm{GF}(2^{64})$ multiplications

Cost

- 16 bits of communication
- in 1 communication round

SHArp

SHA-2

compute as Boolean circuits

Cost (compression function of SHA-256)

- $\approx$ 2.8KB of communication
- in $\approx$ 1600 communication rounds

SHA-3

compute as Boolean circuits

Cost (24-round permutation Keccak-f)

- $\approx$ 4.8KB of communication
- in $\approx$ 24 communication rounds

MACnifico

GMAC

- implement $GF(2^{128})$ for GMAC
- mult. check requires 2 $GF(2^{64})$ inner-product checks

$\rightarrow$ remaining constructions make use of previously introduced modules

Preliminary Experimental Results

Benchmark from [MPS+25] (1)

Batched enciphering of 100000 AES blocks ($\approx$ 1.6 MB)

	Preprocessing		Online Phase		Throughput (blocks/s)	
Protocol	Time (s)	Data (MB)	Time (s)	Data (MB)	Online	Total
online tp.	0.23	22	2.24	$\approx$ 32	44624	40533
total tp.	–	–	2.34	$\approx$ 40	42799	42799
low latency	0.84	44	3.65	$\approx$ 32	27373	22280

run on 3 separate machines (16-core Intel Core i9-9900 3.10GHz, 128GB RAM) over a 9.47 Gbit/s LAN network

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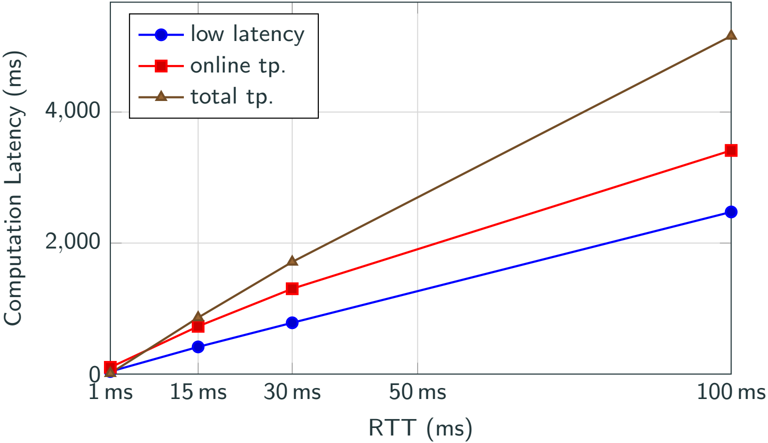
Protocol	Time (s)	Data (MB)	Time (s)	Data (MB)	Online	Total
online tp.	0.23	22	2.24	$\approx$ 32	$\approx$ 714 KB/s	$\approx$ 649 KB/s
total tp.	–	–	2.34	$\approx$ 40	$\approx$ 685 KB/s	$\approx$ 685 KB/s
low latency	0.84	44	3.65	$\approx$ 32	$\approx$ 438 KB/s	$\approx$ 356 KB/s

run on 3 separate machines (16-core Intel Core i9-9900 3.10GHz, 128GB RAM) over a 9.47 Gbit/s LAN network

Benchmark from [MPS+25] (2)

Computation latency of a single block enciphering



(same setup as previous slide; network delay and bandwidth altered with `tc`)

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References (1)

[BBC+19] Dan Boneh, Elette Boyle, Henry Corrigan-Gibbs, Niv Gilboa, and Yuval Ishai. Zero-knowledge proofs on secret-shared data via fully linear PCPs. In *CRYPTO 2019*. `https://ia.cr/2019/188`

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Some images from Flaticon.com

References (2)

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[MRS25] Fredrik Meisingseth, Christian Rechberger, and Fabian Schmid. Accelerating Multiparty Noise Generation Using Lookups. IACR ePrint 2025/805. https://ia.cr/2025/805

[MPS+25] Hiraku Morita, Erik Pohle, Kunihiko Sadakane, Peter Scholl, Kazunari Tozawa, and Daniel Tschudi. MAESTRO: Multi-party AES using Lookup Tables. In *Usenix Security 2025*. https://ia.cr/2024/1317

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