

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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NIST Workshop on Multi-Party Threshold Schemes



AARHUS
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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)*

Techniques

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

Setting

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

Applications

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

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

Background

Replicated Secret Sharing (1)

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

Secret Sharing

- additive sharing, $\langle x \rangle_i = x_i$ where $x_1 + x_2 + x_3 = x$
- replicated sharing $\llbracket x \rrbracket_1 = (x_1, x_2)$, $\llbracket x \rrbracket_2 = (x_2, x_3)$ and $\llbracket x \rrbracket_3 = (x_3, x_1)$.

Linear Computation

- Linear operation L : $\llbracket L(x) \rrbracket_i = (L(\langle x \rangle_i), L(\langle x \rangle_{i+1}))$
- Squaring: $\llbracket x^2 \rrbracket = (\langle x \rangle_i^2, \langle x \rangle_{i+1}^2)$
- Bit decomposition: $\llbracket x \rrbracket = (\llbracket x_0 \rrbracket, \dots, \llbracket x_{k-1} \rrbracket)$, $x_j \in \{0, 1\}$

→ no communication

Replicated Secret Sharing (2)

Multiplication $\llbracket x \rrbracket \cdot \llbracket y \rrbracket$

Given $\langle 0 \rangle$ from preprocessing

(can be derived from correlated PRF keys)

- 1 Local multiplication $\langle xy \rangle_i = x_i y_i + (x_i + x_{i+1})(y_i + y_{i+1})$
→ obtain additive sharing of xy
- 2 Send $\langle xy \rangle_i + \langle 0 \rangle_i$ to P_{i-1} , set $\llbracket xy \rrbracket_i = (\langle xy \rangle_i + \langle 0 \rangle_i, \langle xy \rangle_{i+1} + \langle 0 \rangle_{i+1})$

Table Lookup LUT $\llbracket T[x] \rrbracket$

Table T , given *random one-hot vector* correlation from preprocessing $\llbracket r \rrbracket, \llbracket \mathbf{e}^{(r)} \rrbracket$

$$\llbracket \mathbf{e}^{(r)} \rrbracket = (\underbrace{\llbracket 0 \rrbracket, \dots, \llbracket 0 \rrbracket, \llbracket 1 \rrbracket, \llbracket 0 \rrbracket, \dots \rrbracket}_r)$$

- 1 Reveal value $c = r + x$
- 2 Local computation $\llbracket T[x] \rrbracket = \sum_i T[c - i] \cdot \llbracket \mathbf{e}_i^{(r)} \rrbracket$

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

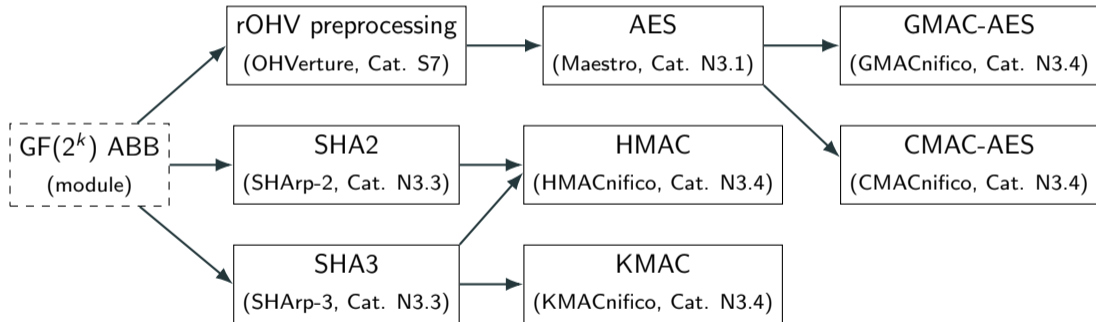
- recursive inner-product check (adapted to our setting from [BBC+19,BGIN20])
- for L inner-product triples $\sum_{i=1}^m \llbracket x_i \rrbracket \cdot \llbracket y_i \rrbracket = \llbracket z \rrbracket$; let $N = L \cdot m$

Cost

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

Symphony – Overview

Symphony Modules



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

- $\text{Input}(x, P_i) \rightarrow \llbracket x \rrbracket$: party P_i inputs $x \in GF(2^k)$ into the ABB
- $\text{Linop}(f, \llbracket x_1 \rrbracket, \dots) \rightarrow \llbracket f(x_1, \dots) \rrbracket$, for any $GF(2)$ -linear function f
- $\text{LocalMul}(\llbracket x \rrbracket, \llbracket y \rrbracket) \rightarrow \langle x \cdot y \rangle$
- $\text{Reshare}(\langle x \rangle) \rightarrow \llbracket x \rrbracket$
- $\text{BitMul}(\llbracket x \rrbracket, \llbracket y \rrbracket) \rightarrow \llbracket x \cdot y \rrbracket$ where $x \in GF(2)$ and $y \in GF(2^k)$.
- $\text{Reconst}(\llbracket x \rrbracket) \rightarrow x$: unverified opening of the secret-shared $\llbracket x \rrbracket$.
- $\text{VerifyRecon}()$: verifies all opened values (via Reconst) so far.
- $\text{VerifyMul}()$: verifies all multiplications (via LocalMul and BitMul) so far.
- $\text{Output}(\llbracket x \rrbracket) \rightarrow x/\perp$: verified output

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



Output

$(\llbracket r \rrbracket, \llbracket \mathbf{e}^{(r)} \rrbracket)$ or $(\llbracket r \rrbracket, \langle \mathbf{e}^{(r)} \rangle)$

where $\mathbf{e}^{(r)} = (0, \dots, 0, \underbrace{1}_r, 0, \dots)$ 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](#)]
- ...

- $\text{rOHVrss}(N = 2^k, L) \rightarrow (\llbracket r_j \rrbracket, \llbracket \mathbf{e}^{(r_j)} \rrbracket)_{j=1}^L$ outputs shares of L correlations, where $r_j \leftarrow \mathbb{GF}(2^k)$
- $\text{rOHVadd}(N = 2^k, L) \rightarrow (\llbracket r_j \rrbracket, \langle \mathbf{e}^{(r_j)} \rangle)_{j=1}^L$ outputs shares of L correlations, where $r_j \leftarrow \mathbb{GF}(2^k)$



Output

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

- $\text{DistKeyGen}() \rightarrow \llbracket \text{ks} \rrbracket$: outputs the key schedule ks of a fresh random AES-128/-256 key as shares to the parties
- $\text{InputKey}(k, P_i) \rightarrow \llbracket k \rrbracket$: inputs the key by party P_i
- $\text{ComputeKS}(\llbracket k \rrbracket) \rightarrow \llbracket \text{ks} \rrbracket$: computes the key schedule
- $\text{InputBlock}(m, P_i) \rightarrow \llbracket m \rrbracket$: inputs a 128-bit block by party P_i
- $\text{OutputBlock}(\llbracket m \rrbracket) \rightarrow m$
- $\text{Encipher}(\llbracket \text{ks} \rrbracket, \llbracket m \rrbracket) \rightarrow \llbracket \text{AES}(\text{ks}, m) \rrbracket$: computes AES enciphering
with performance mode $\left\{ \begin{array}{l} \bullet \text{ "online phase throughput"} \\ \bullet \text{ "total throughput"} \\ \bullet \text{ "low latency"} \end{array} \right.$

Output

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

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

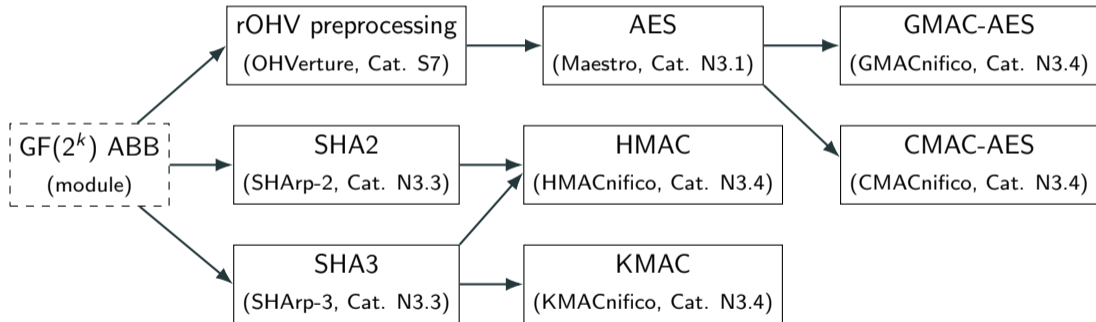


Output

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
-
- $\text{InputKey}(k, P_i) \rightarrow \llbracket k \rrbracket$: inputs the MAC key by party P_i
 - $\text{InputMessage}(m, P_i) \rightarrow \llbracket m \rrbracket$: inputs the message by party P_i
 - $\text{TagGen}(\llbracket k \rrbracket, \llbracket m \rrbracket) \rightarrow \llbracket \tau \rrbracket$: computes the threshold MAC tag generation on the given key and message
 - $\text{OutputTag}(\llbracket \tau \rrbracket) \rightarrow \tau$, where $\llbracket \tau \rrbracket$ 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 $\mathbf{e}^{(r)}$ 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: $[[u], [e^{(u)}]]$ and $[[v], [e^{(v)}]]$
- ② *local* tensor product $\langle e^{(r)} \rangle \leftarrow [[e^{(u)}]] \otimes [[e^{(v)}]]$ where $r = u||v$
- ③ output $([[r], \langle e^{(r)} \rangle])$

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 $GF(2^8) = \mathbb{F}_2[X]/X^8 + X^4 + X^3 + X + 1$.

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

only non-linear computation

① SubBytes: $S\text{-box}(s_i) = f(s_i^{-1})$

② ShiftRows: $\begin{pmatrix} s_0 & s_4 & s_8 & s_{12} \\ s_1 & s_5 & s_9 & s_{13} \\ s_2 & s_6 & s_{10} & s_{14} \\ s_3 & s_7 & s_{11} & s_{15} \end{pmatrix} \rightarrow \begin{pmatrix} s_0 & s_4 & s_8 & s_{12} \\ s_5 & s_9 & s_{13} & s_1 \\ s_{10} & s_{14} & s_2 & s_6 \\ s_{15} & s_3 & s_7 & s_{11} \end{pmatrix}$

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

Performance Mode: High Online Phase Throughput

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

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

Cost

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

MAESTRO (2)

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

Performance Mode: High Total Throughput

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

Mult. check requires checking 3 $\text{GF}(2^4)$ multiplications

Cost

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

MAESTRO (3)

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

Performance Mode: Low Latency

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

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

Cost

- 16 bits of communication
- in 1 communication round

SHA-2

compute as Boolean circuits

Cost (compression function of SHA-256)

- ≈ 2.8 KB of communication
- in ≈ 1600 communication rounds

SHA-3

compute as Boolean circuits

Cost (24-round permutation Keccak-f)

- ≈ 4.8 KB of communication
- in ≈ 24 communication rounds

GMAC

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

→ remaining constructions make use of previously introduced modules

Preliminary Experimental Results

Benchmark from [MPS+25] (1)

Batched enciphering of 100000 AES blocks (≈ 1.6 MB)

Protocol	Preprocessing		Online Phase		Throughput (blocks/s)	
	Time (s)	Data (MB)	Time (s)	Data (MB)	Online	Total
online tp.	0.23	22	2.24	≈ 32	44624	40533
total tp.	–	–	2.34	≈ 40	42799	42799
low latency	0.84	44	3.65	≈ 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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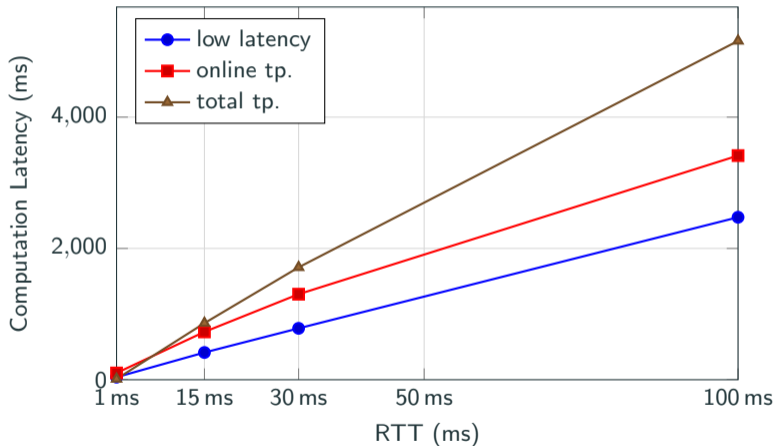
Batched enciphering of 100000 AES blocks (≈ 1.6 MB)

Protocol	Preprocessing		Online Phase		Throughput (blocks/s)	
	Time (s)	Data (MB)	Time (s)	Data (MB)	Online	Total
online tp.	0.23	22	2.24	≈ 32	≈ 714 KB/s	≈ 649 KB/s
total tp.	–	–	2.34	≈ 40	≈ 685 KB/s	≈ 685 KB/s
low latency	0.84	44	3.65	≈ 32	≈ 438 KB/s	≈ 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 t_c)

Summary

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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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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, Kunihiro Sadakane, Peter Scholl, Kazunari Tozawa, and Daniel Tschudi. MAESTRO: Multi-party AES using Lookup Tables. In *Usenix Security 2025*. <https://ia.cr/2024/1317>