Efficient Leakage-Resilient Secret Sharing

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Secret Sharing [Shamir'79, Blakley'79]

$$\sigma \xrightarrow{\text{Share}} sh_1, \ldots, sh_n$$

Reconstruction: Given at least t shares, can reconstruct σ

Secrecy: Given $(t-1)$ shares, no information about σ

Several applications: MPC, threshold crypto, leakage-resilient circuit compilers, ...

Efficient constructions, e.g., Shamir, which has rate $= \frac{|\sigma|}{|sh_i|} = 1$

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What if there are side-channels?

What if the adversary, in addition to $(t-1)$ full shares, has some information about the others?

Local Leakage Resilient Secret Sharing [GK'18, BDIR'18]

1. Adversary specifies:
   - Set $S \subseteq [n]$ of size at most $(t-1)$
   - For $i \notin S$, a *leakage function* f_i that outputs μ bits
2. Adversary is given shares sh_i for $i \in S$, and leakage $f(sh_i)$ for $i \notin S$
3. Its views for any two secrets should be *statistically* close

- Local - each f_i depends on one share
- Bounded - each f_i outputs few bits
- Otherwise arbitrary

$$leakage\ rate = \frac{\mu}{|sh_i|}$$

What was known

- Guruswami-Wootters ’16: Shamir over $GF[2^k]$ not leakage-resilient
- Benhamouda et al ’18: Shamir over large-characteristic fields *is* leakage-resilient with leakage rate $\Theta(1)$ for thresholds more than $n - o(\log n)$
- Constructions:
  - Goyal-Kumar ’18: 2-out-of-n with rate and leakage rate $\Theta\left(\frac{1}{n}\right)$
  - Badrinarayanan-Srinivasan ’18: $O(1)$-out-of-n with rate $\Theta\left(\frac{1}{\log n}\right)$ and leakage rate $\Theta\left(\frac{1}{n \log n}\right)$
- Other models of leakage-resilience for secret sharing have been studied, e.g., Boyle et al ‘14, Dziembowski-Pietrzak ’07, etc.

What we do

Leakage-resilient threshold secret sharing schemes

- for all thresholds,
- with constant rate,
- supporting any constant leakage rate

In this talk: simpler construction with slightly worse rate, supporting leakage rate up to $1/2$

Our construction

Threshold t, secret $\sigma \in \mathbb{F}$, leakage bound of μ bits

Sample $\boldsymbol{s}, \boldsymbol{w_1}, \dots, \boldsymbol{w_n} \leftarrow \mathbb{F}^m$, and $r \leftarrow \mathbb{F}$

(m specified later)

$$\sigma \xrightarrow[\text{Shamir}]{t\text{-out-of-}n} sh_1, \dots, sh_n$$

$$(\boldsymbol{s}, r) \xrightarrow[\text{Shamir}]{2\text{-out-of-}n} \boldsymbol{sr_1}, \dots, \boldsymbol{sr_n}$$

i^{th} share: $(\boldsymbol{w_i}, \; sh_i + \langle \boldsymbol{w_i}, \boldsymbol{s} \rangle + r, \; \boldsymbol{sr_i})$

Reconstruction

i^{th} share: $(\boldsymbol{w_i}\ ,\ sh_i + \langle \boldsymbol{w_i}, \boldsymbol{s} \rangle + r\ ,\ \boldsymbol{sr_i})$

Given shares of t different i's:

1. Reconstruct $\boldsymbol{s}$ and r from $\{\boldsymbol{sr_i}\}$
2. Recover sh_i from $(sh_i + \langle \boldsymbol{w_i}, \boldsymbol{s} \rangle + r)$
3. Reconstruct σ from $\{sh_i\}$

Leakage Resilience

Adversary knows:

- $(\boldsymbol{w_i}, sh_i + \langle \boldsymbol{w_i}, \boldsymbol{s} \rangle + r, \boldsymbol{sr_i})$ for $i \in S$, where $|S| < t$
- $f_i(\boldsymbol{w_i}, sh_i + \langle \boldsymbol{w_i}, \boldsymbol{s} \rangle + r, \boldsymbol{sr_i})$ for $i \notin S$
- Possibly $\boldsymbol{s}$ and r

Approach:

1. For the $i \notin S$, replace $(sh_i + \langle \boldsymbol{w_i}, \boldsymbol{s} \rangle)$ with random $u_i \in \mathbb{F}$
2. Show that adversary cannot tell this was done (by a hybrid argument)
3. By secrecy of t-out-of-n sharing, adversary's view is independent of secret σ

Leakage Resilience

Claim: For any $i \notin S$, even given $\boldsymbol{s}$ and r,

$$f_i(\boldsymbol{w_i}, sh_i + \langle \boldsymbol{w_i}, \boldsymbol{s} \rangle + r, \boldsymbol{sr_i}) \approx f_i(\boldsymbol{w_i}, u_i + r, \boldsymbol{sr_i})$$

Leftover Hash Lemma [ILL89]:

$\langle \boldsymbol{w_i}, \boldsymbol{s} \rangle$ is almost uniformly random given $\boldsymbol{s}$ and leakage $g(\boldsymbol{w_i})$, if $|g(\boldsymbol{w_i})| \ll |\boldsymbol{w_i}|$

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independent of $\boldsymbol{s}$ and r because 2-out-of-n share

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independent of $\boldsymbol{s}$
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determines $|\boldsymbol{w}_i|$ and $|\boldsymbol{s}|$ given bound on leakage

What we get

For local leakage resilient threshold secret sharing of:

- secrets in $\mathbb{F}$,
- among n parties ($n \leq |\mathbb{F}|$),
- against μ bits of leakage per share,
- with adversarial advantage at most ϵ,

$$|\boldsymbol{w_i}| = |\boldsymbol{s}| = m \approx 1 + \frac{\mu}{\log|\mathbb{F}|} + \frac{3\log(4n/\epsilon)}{\log|\mathbb{F}|}$$

Share size: $(2m + 2)$ field elements

Share size overhead

Share sizes for secrets in a field $\mathbb{F}$, with $|\mathbb{F}| \approx 2^{128}$, and $\epsilon = 1/2^{80}$

$n = 2$

Leakage	Share size (bits)	Overhead
1 bit	1024	8
100 bits	1280	10
10%	1280	10
30%	2560	20
45%	10240	80
49%	50688	396

$n = 100$

Leakage	Share size (bits)	Overhead
1 bit	1280	10
100 bits	1280	10
10%	1536	12
30%	2816	22
45%	10496	82
49%	52480	410

Computational overhead

Computational overhead in sharing time over Shamir secret sharing, for various leakage rates*

(n, t)	Shamir	0.1%	10%	30%	45%	49%
(2, 2)	4.16 μs	7.08	9.78	19.6	83.5	406
(100, 2)	41.4 μs	23.6	26.1	74.1	292	1319
(100, 50)	1.13 ms	1.72	1.75	2.83	9.78	46.1
(100, 100)	2.27 ms	1.36	1.44	2.13	5.01	21.2

* as observed on a machine with 4-core 2.9 GHz CPU and 16 GB of RAM

Improvements

- Generalisation to secret sharing for any monotone access structure
- Leakage rate up to 1, and constant-factor improvement in rate using better extractors than inner product

In full version:

- Rate-preserving transformation to non-malleable secret sharing
- Leakage-tolerant MPC for general interactions patterns

Concurrent work

Stronger leakage-resilient and non-malleable secret-sharing schemes for general access structures, Aggarwal et al

- general leakage-resilience transformation, with $O(1/n)$ rate loss, constant leakage rate,
- non-malleable secret sharing against concurrent tampering,
- leakage-resilient threshold signatures

Leakage-resilient secret sharing, Kumar et al

- secret sharing schemes resilient against adaptive leakage,
- non-malleable secret sharing against tampering with leakage

Thank You!