CacheQuote: Efficiently Recovering Long-term Secrets of SGX EPID via Cache Attacks

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Intel Software Guard Extensions

1. Set of instructions aiming to guarantee **confidentiality** and **integrity** of applications that run inside **untrusted environments**.
2. Protects *enclaves* of code and data.
Enclaves

• Enclaves are isolated from the software running on the computer.

• SGX controls the entry to and exit from enclaves.
Remote attestation: EPID

Trust is based on the EPID key!
Why need IAS? Revocation!
All quotes are encrypted by SGX.
Unlinkability

impossible to identify the platform that produced a signature on some message $m$. 
Unforgeability

impossible for an attacker to forge a valid signature on some previously-unsigned message, without knowing a non-revoked secret key.

\[ m \quad \sigma \quad \text{NO!} \]
Our results

• **First cache attacks** on Intel’s EPID protocol implemented inside SGX.

• Recover part of the enclave’s long term secret key.

• Malicious attestation server (Intel) can break the **unlinkability guarantees** of SGX’s remote attestation protocol.
EPID: setup

• An issuer:

• A revocation manager:

• A platform:

• A verifier:
EPID: algorithms

Setup

Issuer

Join

Platform

Sign

Platform

Verify

Verifier

Verifier

$1^k$

$(gpk, isk)$

$(gpk, isk)$

$gpk$

$m, sk$

$\sigma$

$\sigma$

$\sigma$

Yes/No

Verifier
The signing algorithm

• Secret key: \( f + \text{Intel's signature on } f \)
• Randomly choose: \( B \in G \) and compute

\[ K := B^f \]

• How to sign?

Non-interactive zero knowledge proof of knowledge:

“I know an unrevoked \( f \) such that \( K := B^f \)”

• Requires computing \( A^r \), where \( A \) is some value.
• Signature \( \sigma \) has the values \( K, B \) and \( s \leftarrow r + Hf \)
Attack idea

• Recover side-channel information about the length of the nonce $r$ from $A^r$.

• After many observations, use length data to mount a lattice attack to recover the value of $f$.

• Break unlinkability.
How unlinkability is broken?

• $f$ is unique per platform and private.
• The attacker knows a signature $\sigma = (K, B, \ldots)$ on some message $m$ and $f$.
• He can check if $K = B^f$.
• If yes, then the signature was issued by the platform whose key is $f$. 
Caches are used to bridge the gap.

- Divides memory into *lines*
- Stores recently used lines

- In a *cache hit*, data is retrieved from the cache
- In a *cache miss*, data is retrieved from memory and inserted to the cache
The Prime+Probe Attack

• Allocate a cache-sized memory buffer
  • *Prime*: fills the cache with the contents of the buffer
  • *Probe*: measure the time to access each cache set
    – Slow access indicates victim access to the set
In our attack

- The signing algorithm requires computing $A^r$.

- Exponentiation uses some variant of square and multiply with fixed windows of bits.

- Quoting enclave recodes the nonce $r$ to have fewer non-zero bits.
Scalar multiplication algorithm

\textbf{MultPoint}(point } P, \text{ window size } w, \text{ scalar } r):$

\textbf{Initialize} \ P : P_0 \leftarrow O$

\textbf{For} \ i \leftarrow 1 \ \textbf{to} \ 2^{w-1} \ \textbf{do}:$

\quad P_i \leftarrow P \cdot P_{i-1}$

\quad \ i \leftarrow \max(j : r_j \neq 0)$

\quad s \leftarrow P_{r_i}$

\quad i \leftarrow i - 1$

\textbf{While} \ i \geq 0 \ \textbf{do}:

\quad s \leftarrow r^{2^w}$

\quad s \leftarrow s \cdot P_{r_i}$

\quad i \leftarrow i - 1$

\textbf{End while}$

\textbf{Output: } s$

- Scalar of length 256 bits $\Rightarrow$ recoded scalar of length 52 $\Rightarrow$ 51 loop iterations.
- Bits 256 and 255 are 0 $\Rightarrow$ recoded scalar of length 51 $\Rightarrow$ 50 loop iterations.
Counting loops

• Monitor cache access patterns during the computation of the main loop.

• One period corresponds to one loop iteration.
• Number of periods gives us information on the number of iterations.
A lattice attack

Side channel information about the length of $r$.

Goal: Solve for $f$.

• Many samples $\{(s, H)\}_i$ such that:
  \[ s \equiv r + Hf \mod p \]

• Information about the number $l_i$ of most significant zero bits in $r_i$.

• We learn $|s_i - H_if| = |r_i| < \frac{p}{2^{l_i}}$

  ➔ hidden number problem and obtain $f$. 
Recovering $f$

10 600 signatures required if only using 49-loop samples to get 37 error-free samples.

- Use samples of different loop lengths
- Reduce the number of signatures with manual inspection: less than 7 500 observed signatures to obtain enough 49-loop observations for a full key recovery.
Conclusion

• We finally have $f$.

• **Limitations:** we can’t run the attack ourselves as all the EPID signatures are encrypted with Intel’s public key!

• A malicious Intel could break the unlinkability guarantee.

• Thank you!
Thank you!

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Key recovery with the hidden number problem

In our experiments, **8000 signatures** necessary to enough error-free samples for key recovery.
Recoding the nonces

• Non-adjacent form (NAF) encoding:
  a. no two sequential non-zero digits.
  b. signed digits
• Example:
  a. binary: \((0,1,1,1) = 2^2 + 2^1 + 2^0 = 7\)
  b. 2-NAF: \((1,0,0,−1) = 2^3 − 2^0 = 7\)

• Generalization to w-NAF: work in base \(2^w\).
• The quoting enclave \textit{recodes} the scalar \(r_f\) using some variant of w-NAF.

\(r_f = (r_1, \cdots r_n)\) s.t.:
\[
1. \quad r_f = \sum_i 2^{w \cdot i} r_i \\
2. \quad −2^w − 1 \leq r_i \leq 2^w − 1.
\]
• Example: \((0, 0, 1, −25) = 2^{5 \cdot 1} \cdot 1 + 2^{5 \cdot 0} \cdot (−25) = 7\)