Nonce@Once: A Single-Trace EM Side Channel Attack on Several Constant-Time Elliptic Curve Implementations in Mobile Platforms

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Motivation

➢ Public key crypto is essential for modern security
  ➢ Secure exchange of session keys
  ➢ Verifying identity of systems and users
  ➢ And much, much more

➢ Private keys are a highly valuable asset
  ➢ Attackers want to get them
  ➢ But we don’t want them to
Public Key Crypto

- Good public key crypto (e.g. ECC)
  - Designed to make private keys very, very hard to recover

Diagram:

- Key
- ECC
- Positive outcome
- Negative outcome
Analog Side-Channel Attacks

- But cryptographic implementation runs on real hardware
  - Logic gates switch, causing current flow
  - Currents flowing create changes in surrounding EM field

Most attacks:
Side-channel information helps **eventually** recover the private key
Analog Side-Channel Attacks

- But cryptographic implementation runs on real hardware
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Nonce@Once:
Side-channel information
from only one signing/encryption operation allows recovery
the private key
**ECC Digital Signature Algorithm**

1. \( Q = d \cdot G \), where \( d \) is the secret key
2. \( z = \text{HASH}(\text{msg}) \)
3. Generate random ephemeral secret \( k \) (the “nonce”)
4. \( R = k \cdot Q \)
5. \( r = R \rightarrow x \mod n \)
6. \( s = k^{-1}(z + r \cdot d) \)
7. Signature = (r, s)

If attacker knows \( k \), a message, and its signature:
\[ d = (s \cdot k - z)/r \mod n \]

Nonce \( k \) must remain secret!
Point-by-Scalar Multiplication (R=k\cdot Q)

R=Point(0);
// For each bit of nonce k
for(b=nbits-1;b>=0;b--){
   R=2\cdot R;
   if(get_bit(k,b))
      R=R+Q;
}

R=Point(0);
// For each bit of nonce k
for(b=nbits-1;b>=0;b--){
   R=2\cdot R;
   T=R+Q;
   Swap_Cond(R,T,get_bit(k,b));
}

Easy target for side channel attacks, e.g. Flush+Reload

Constant Time Implementation
Conditional Swap (RFC 7748)

Swap_Cond(A,B,cond) {
    mask = 0 - cond;
    for (i = 0; i < nwords; i++) {
        Δ = (a[i] ^ b[i]) & mask;
        a[i] = a[i] ^ Δ;
        b[i] = b[i] ^ Δ;
    }
}

11..11 if cond, 00..00 if not cond

For each machine word of an EC point

Note this is also Constant-Time!

But… ~ 40 XOR operations with Δ in Swap_Cond

All have a zero operand when cond==0
That operand is ~50%-ones when cond==1
Measurement Setup

ZTE ZFIVE

Alcatel Ideal
Locating the Cond-Swap Signals (OpenSSL)
Recovering value of cond (OpenSSL)
Recovering value of cond
Nonce Recovery Algorithm

Training

- Record signal while signing with a few known nonces on device of same kind (but different instance of the device)
- Cluster training Cond_Swap signals (K-Means)
- Keep centroid and label (0 or 1) of each cluster

Attack

- Record signal from target device
- Identify Cond_Swap snippets
- Label each snippet (closest cluster)
- Brute-force labels of “missing” snippets
Nonce Recovery (GnuPG on ZTE)

Bit Recovery - Clusters

Erasure Recovery – Brute Force

ZTE GnuPG

Empirical PDF

$\log_2(\text{Number of Candidates})$
Mitigation

- Fundamental enabler of the attack
  - Leakage amplification
    - XOR with zero or non-zero operand leaks a little about the operand
    - But same leakage repeated 40 times in each Cond_Swap!

- Mitigation – randomization to avoid amplification
Mitigation

```c
Swap_Cond(A,B,cond){
    mask=0-cond;
    for(i=0;i<nwords;i++){
        Δ = (a[i]^b[i]) & mask;
        a[i]=a[i] ^ Δ;
        b[i]=b[i] ^ Δ;
    }
}
```

```c
Swap_Cond(A,B,cond){
    mask=0-cond;
    rand=random_word();
    for(i=0;i<nwords;i++){
        Δ’ = (a[i]^b[i]) & mask;
        Δ = Δ’ ^ rand;
        a[i]=a[i] ^ Δ ^ rand;
        b[i]=b[i] ^ Δ ^ rand;
    }
}
```

Problem: Mitigation optimized-out by compiler
Ask/trick the compiler not to do this (see paper)
Mitigation’s Effect on the Attack
Conclusions

- Analog side-channel attack on constant-time ECC implementations that use conditional swap (RFC 7748)
  - Highly accurate thanks to leakage amplification
  - Successful on OpenSSL, GnuPG, HACL*, and Curve25519-donna
- ECC private key recovered from only one use of that key
- Mitigation: randomization in Cond_Swap
  - Removes leakage amplification
  - Very low performance overhead
Thank you!

Questions?