Automated Fault Analysis of Block Cipher Implementations

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Outline

- Fault Analysis in Cryptography
- Differential Fault Analysis (DFA) of Symmetric Block Ciphers
- Automation of DFA for Software Implementations
- Countermeasure Implementation
Fault Analysis in Cryptography
Physical Attacks in Cryptography

• Cryptography provides algorithms that enable secure communication in theory

• In real world, these algorithms have to be implemented on real devices:
  – software implementations - general-purpose devices
  – hardware implementations - dedicated secure hardware devices

• To evaluate security level of cryptographic implementations, it is necessary to include physical security assessment
First IC Disturbances – Cosmic Rays and Satellites

Fault Injection Techniques in Practice

- Voltage Glitching
- EM Pulse Injection
- Laser Fault Injection
Why Fault Attacks?

- The best cryptanalysis of AES needs complexity of $2^{126.1}$
  
  
  - A. Bogdanov et al. Biclique cryptanalysis of the full AES, ASIACRYPT 2011.

- The best fault attack on AES needs just one faulty and one correct ciphertext pair

  
  
Differential Fault Analysis of Symmetric Block Ciphers
Attacker injects a fault in a chosen round of the algorithm to get the desired fault propagation at the end of an encryption.

The secret key can then be determined by examining the differences between a correct and a faulty ciphertext.

E. Biham and A. Shamir: Differential fault analysis of secret key cryptosystems, CRYPTO’97.
Example – SIMON Block Cipher

Non-linear operation → exploitable by DFA

Legend

∧ bitwise AND
⊕ bitwise XOR
\ll m m-bit rotation to the left

R. Beaulieu et. al. The SIMON and SPECK Families of Lightweight Block Ciphers, ePrint 2013/404.
Exploiting AND Operation by DFA

<table>
<thead>
<tr>
<th>a</th>
<th>b</th>
<th>c = a &amp; b</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Flip bit ‘a’

<table>
<thead>
<tr>
<th>a’</th>
<th>b</th>
<th>c’= a’&amp; b</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
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<td>1</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

- If the result does not change → ‘b’ is 0
- If the result changes → ‘b’ is 1
Different cipher families can be exploited by similar attack procedure, e.g.:

- In SPN designs, Sbox is targeted
- In ARX designs, modular addition is targeted
- If a cipher uses MDS matrix, such as MixColumns in AES, this can be exploited for more efficient attack with lesser faults

There is normally a trade-off between the computational complexity and the number of faults:

- Last round attack – many faults, low complexity
- 2\textsuperscript{nd}/3\textsuperscript{rd} last round attack – fewer faults, higher complexity
Automation of DFA for Software Implementations
Why Automation of DFA?

- All the current symmetric block ciphers have been shown vulnerable against fault attacks (especially DFA).
- The question is not whether the algorithm is secure or not, but which part of it is insecure.
- Automated methods can provide an answer fast and with minimal need of human intervention.
Tool for Automated DFA on Assembly – TADA

- The main idea – feed the assembly code to the tool and get the vulnerabilities, together with a way how to exploit them
- Static analysis module analyzes the propagation of the fault and determines what information can be extracted from known data
- SMT solver module solves the DFA equations, verifying whether an attack exists

Analyze assembly file → Generate custom DFG → Construct DFA attack → Find the key
Sample Cipher and DFG Construction

<table>
<thead>
<tr>
<th>#</th>
<th>Instruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>LD r0 X+</td>
</tr>
<tr>
<td>1</td>
<td>LD r1 X+</td>
</tr>
<tr>
<td>2</td>
<td>LD r2 key1+</td>
</tr>
<tr>
<td>3</td>
<td>LD r3 key1+</td>
</tr>
<tr>
<td>4</td>
<td>AND r0 r1</td>
</tr>
<tr>
<td>5</td>
<td>EOR r0 r2</td>
</tr>
<tr>
<td>6</td>
<td>EOR r1 r3</td>
</tr>
<tr>
<td>7</td>
<td>ST x+ r0</td>
</tr>
<tr>
<td>8</td>
<td>ST x+ r1</td>
</tr>
</tbody>
</table>
Properties of the DFG – Explained

Linear edge

Non-linear edge

Node r3 (3) affects node r1 (6)

Distance between r0 (0) and r0 (4) is 1
Distance between r0 (0) and x+ (7) is also 1
Real Example – DFG of AES Implementation
TADA – Detailed Process Flow

1. **Inputs**
   - Number of round keys (m)
   - Assembly code

2. Create customized data flow graph

3. Calculate/update known nodes

4. If found vulnerable instruction?
   - Yes, go back to next instruction
   - No, output the attack details

5. Is vulnerable instruction exploitable?
   - Yes, calculate/update known nodes
   - No, recover last m round keys?
     - Yes, finish (success)
     - No, analyze updated DFG

6. Formulate SMT constraints
7. Call Z3 SMT solver

8. Finish
Vulnerable Instructions

- Non-linear

- For a vulnerable instruction, each of its input nodes that is not known can be a target node or/and a vulnerable node.

- A fault will be injected into the vulnerable node so that it might reveal information about the target node.

- TADA creates a subgraph for each pair of target and vulnerable node.
# RSAC

## Find Vulnerable Instruction

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</tr>
<tr>
<td>8</td>
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</tr>
</tbody>
</table>

Recall that r2 (2) and r3 (3) are the key nodes.
TADA – Detailed Process Flow

1. **Inputs**
   - Number of round keys (m)
   - Assembly code

2. Create customized data flow graph

3. Calculate/update known nodes

4. **Found vulnerable instruction?**
   - Yes: Create DFA equations
   - No: Go to next instruction

5. **Vulnerable instruction exploitable?**
   - Yes: Output the attack details
   - No: Call Z3 SMT solver

6. Recovered last m round keys?
   - Yes: Finish (success)
   - No: Calculate/update known nodes

7. Analyze updated DFG

8. Finish
Create DFA Equations

<table>
<thead>
<tr>
<th>Correct execution</th>
<th>Faulted execution</th>
<th>Fault mask</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) $r_0(4) = r_0(0) &amp; r_1(1)$</td>
<td>(d) $r_0(4)' = r_0(0)' &amp; r_1(1)$</td>
<td>$r_0(0)' = r_0(0) \oplus \delta$</td>
</tr>
<tr>
<td>(b) $r_0(5) = r_0(4) \oplus r_2(2)$</td>
<td>(e) $r_0(5)' = r_0(4)' \oplus r_2(2)$</td>
<td></td>
</tr>
<tr>
<td>(c) $r_1(6) = r_1(1) \oplus r_3(3)$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Diagram:**

- **Legend:**
  - Vulnerable node
  - Target node

Node connections:

- **r0 (0) to r1 (1):** and (4)
- **r0 (4) to r2 (2):** eor (5)
- **r0 (5) to r0 (5):** eor (5)
TADA – Detailed Process Flow

1. **Inputs**
   - Number of round keys (m)
   - Assembly code

2. **Create customized data flow graph**

3. **Calculate/update known nodes**

4. **Find vulnerable instruction?**
   - No
     - Finish
   - Yes
     - Create DFA equations

5. **Formulate SMT constraints**

6. **Call Z3 SMT solver**

7. **Is vulnerable instruction exploitable?**
   - No
     - Go to next instruction
   - Yes
     - Output the attack details

8. **Calculate/update known nodes**

9. **Analyze updated DFG**

10. **Recovered last m round keys?**
    - Yes
       - Finish (success)
    - No
       - Go to next instruction
TADA – Detailed Process Flow

- **inputs**
  - number of round keys (m)
  - assembly code

- create customized data flow graph

- calculate/update known nodes

- **found vulnerable instruction?**
  - yes
    - create DFA equations
    - formulate SMT constraints
    - call Z3 SMT solver

  - no

- finish

- go to next instruction

- is vulnerable instruction exploitable?
  - yes
    - output the attack details
  - no
    - calculate/update known nodes

- recovered last m round keys?
  - yes
    - finish (success)
  - no
Update Known Nodes

Legend:
- Round key
- Key node
- Known node
- Ciphertext node

Diagram showing nodes and operations:
TADA – Detailed Process Flow

Not yet!
One More Iteration
Evaluation Results

<table>
<thead>
<tr>
<th>Cipher implementation</th>
<th>SIMON</th>
<th>SPECK</th>
<th>AES</th>
<th>PRIDE</th>
</tr>
</thead>
<tbody>
<tr>
<td># of lines of code (unrolled)</td>
<td>1,272</td>
<td>663</td>
<td>2,057</td>
<td>1590</td>
</tr>
<tr>
<td># of nodes in DFG</td>
<td>1,595</td>
<td>843</td>
<td>2,060</td>
<td>1763</td>
</tr>
<tr>
<td># of edges in DFG</td>
<td>2,709</td>
<td>1,562</td>
<td>3,209</td>
<td>2586</td>
</tr>
<tr>
<td>evaluation time (min)</td>
<td>17.2</td>
<td>9.8</td>
<td>298.7</td>
<td>4.6</td>
</tr>
<tr>
<td>fault attack found</td>
<td>[TBM14]</td>
<td>new</td>
<td>[Gir05]</td>
<td>new</td>
</tr>
<tr>
<td># of known nodes before attack</td>
<td>66</td>
<td>32</td>
<td>69</td>
<td>16</td>
</tr>
<tr>
<td># of known nodes after attack</td>
<td>162</td>
<td>117</td>
<td>149</td>
<td>196</td>
</tr>
<tr>
<td># of round keys found</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>


Countermeasures

How many rounds to protect?
Standard Duplication/Triplication Countermeasure

- Popular in industrial applications
- Either area or time redundancy
- Expensive overheads
- Resources can be saved in case it is not necessary to protect the entire cipher
Countermeasure implementation based on TADA

- We know which nodes are provably exploitable by TADA
- We are now trying to find the *earliest* node possible to affect the target node, such that there are no collisions
- This information will tell us what is the earliest round where the fault can be injected
Back to the Example – with 2 rounds

<table>
<thead>
<tr>
<th>Target node</th>
<th>Vulnerable node</th>
</tr>
</thead>
<tbody>
<tr>
<td>r0 (5)</td>
<td>r1 (6)</td>
</tr>
<tr>
<td>r1 (6)</td>
<td>r0 (5)</td>
</tr>
</tbody>
</table>

How can we attack r0 (5)?
- r0 (4)
- r0 (0)
- r1 (1) → collision

As a result, we have extended the attack to the second last round.
How Many Rounds to Protect?

<table>
<thead>
<tr>
<th>Cipher implementation</th>
<th>SIMON</th>
<th>SPECK</th>
<th>AES</th>
<th>PRIDE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earliest round attacked</td>
<td>$R - 2$</td>
<td>$R - 3$</td>
<td>$R - 3$</td>
<td>$R - 3$</td>
</tr>
</tbody>
</table>

- Resources for countermeasures can be saved as follows:
  - SIMON – over 90% (3 out of 32 rounds)
  - SPECK – over 81% (4 out of 22 rounds)
  - AES – over 60% (4 out of 10 rounds)
  - PRIDE – over 80% (4 out of 20 rounds)
Summary
Short Recap

- All the block ciphers have been shown to be vulnerable against Differential Fault Analysis
- Automated methods can help to accurately find vulnerabilities in implementations without the need of human intervention
- Application of countermeasures can be iteratively tested until the implementation is secure
Apply It

● Next week you should:
  – Identify embedded block cipher implementations that are deployed in the field and are susceptible to fault injection attacks (e.g. in IoT devices)

● In the first three months following this presentation you should:
  – Being able to automatically analyze these implementations

● Within six months you should:
  – Have a policy for applying automated analysis for every new block cipher implementation
Resources


- Future works: http://jbreier.com/research.html
Book on the Topic


Offers a complete perspective on protecting block ciphers against fault attacks – from analysis to deployment.
Thanks for attention!

Any questions?

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