NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

pace Physical Analysis and Cryptographic Engineering

SITM: See In The Middle

Side-Channel Assisted Middle Round Differential Cryptanalysis on SPN Block Ciphers

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About Me

- Dr. Shivam Bhasin
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- Sr. Research Scientist,
  - Center For Hardware Assurance @ Temasek Labs, NTU, Singapore
- PhD from Telecom Paristech, France (2011)
- Research Interest:
  - Physical Attacks (Side-Channel, Fault Injection,, Hardware Trojan, Combinations)
  - Countermeasure & Certification
  - Hardware Security of AI

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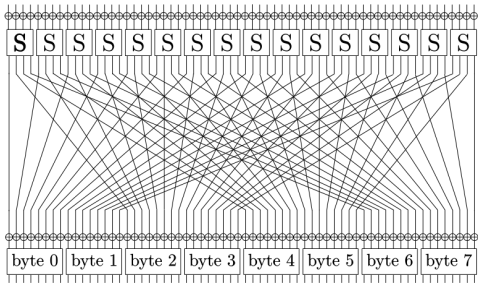
Side-Channel Analysis (SCA)

- **Simple SCA (SSCA)**
  - Adversary learns secret information **by visual inspection** of (usually single) power/EM measurement
  - Ex: observe square & multiply in exponentiation etc.
- **Differential SCA (DSCA)**
  - **Statistical attack** with known input/output to recover **secret key K**
  - Leakage model assumption like **Hamming Weight (HW)**
  - Mostly applied on corner rounds
  - Ex: correlation power analysis on AES first or last round

Side-Channel Assisted Differential Plaintext Attack (SCADPA)



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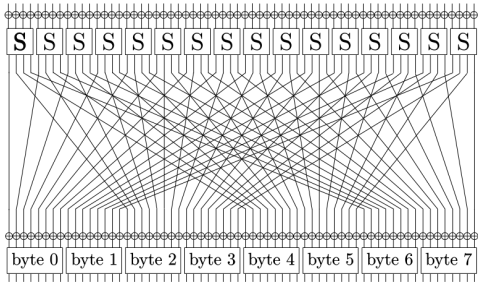

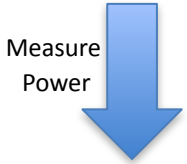

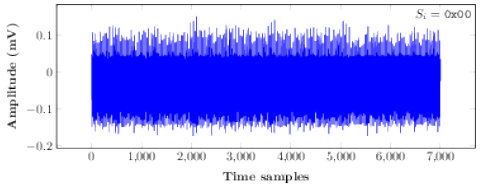

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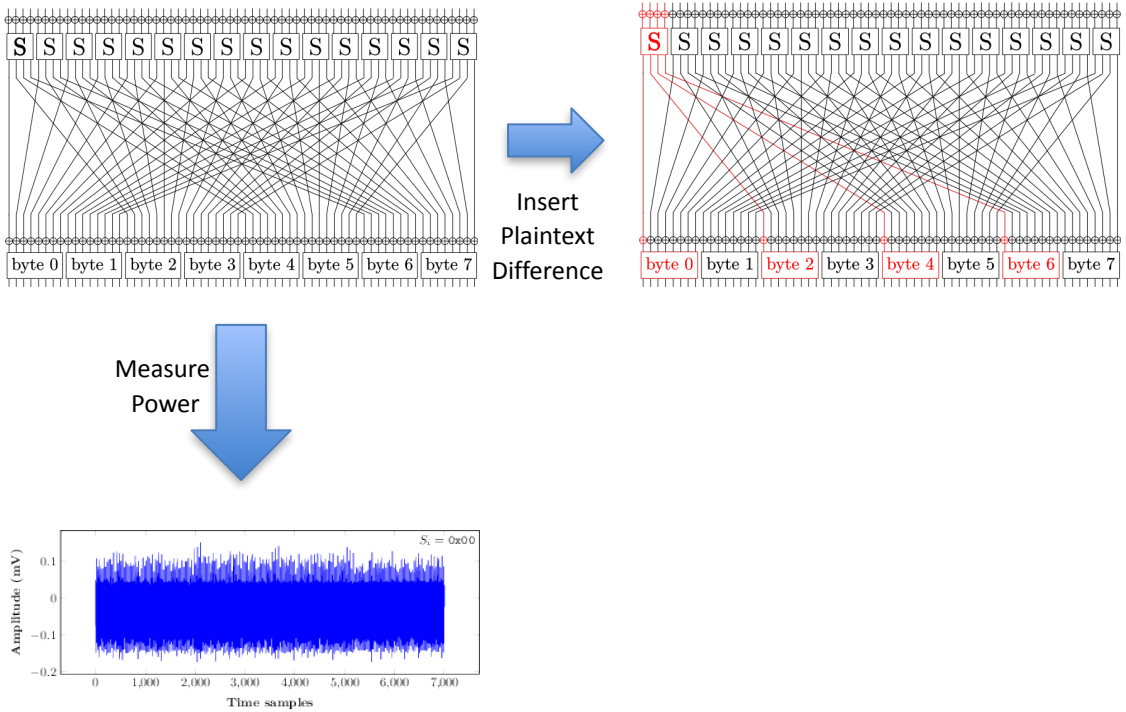

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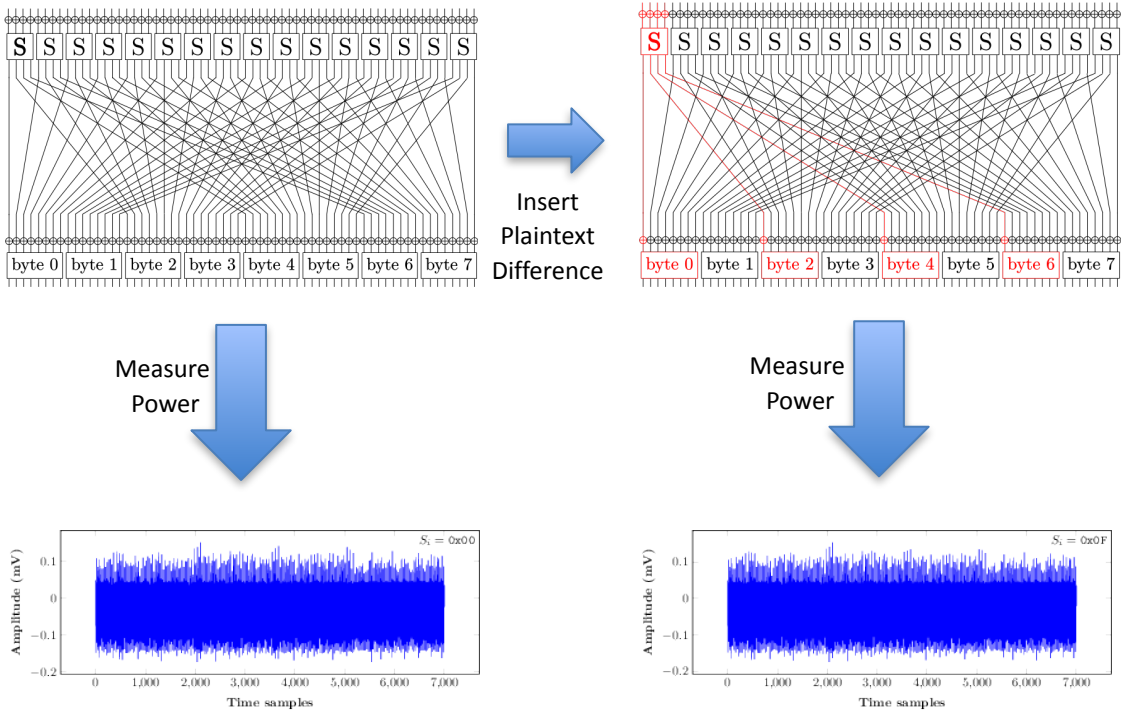

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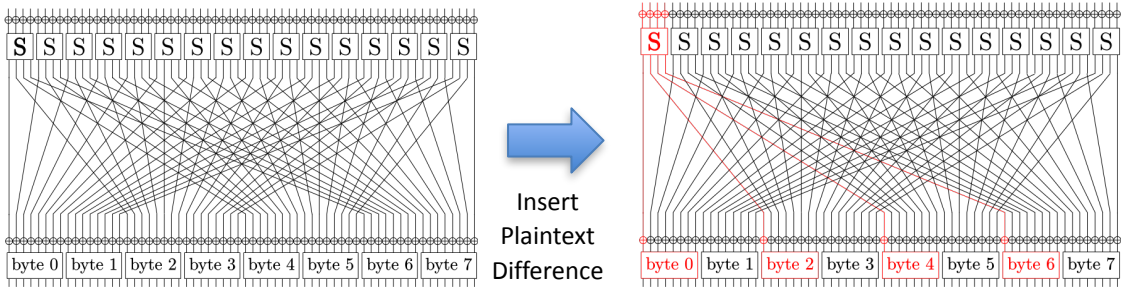
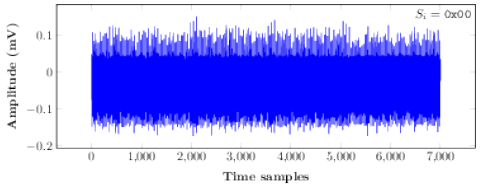


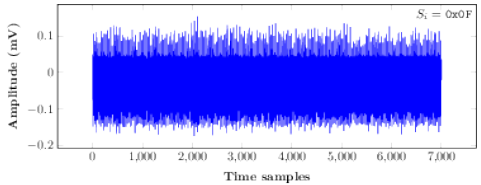
Insert Plaintext Difference

Measure Power

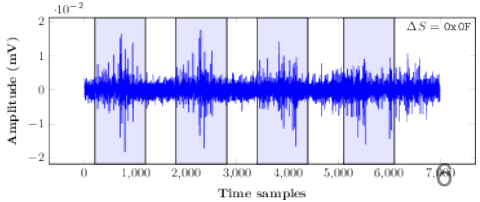
Measure Power

Bit Permutation allows observation of deep round propagation





Power Difference



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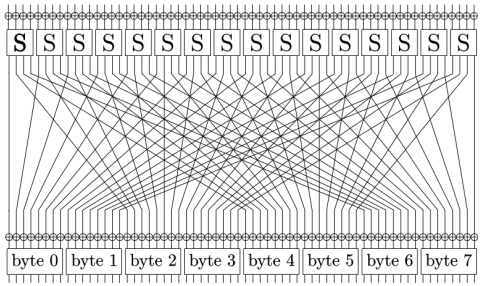

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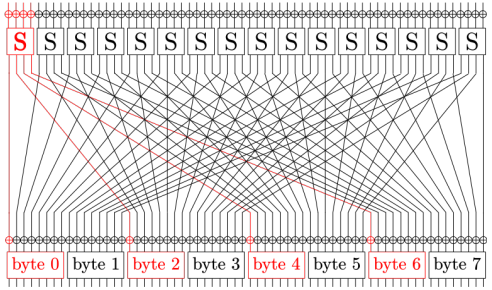

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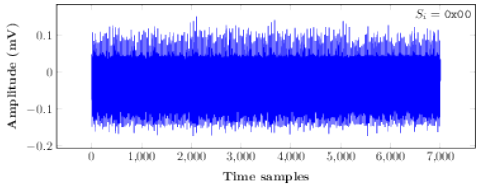

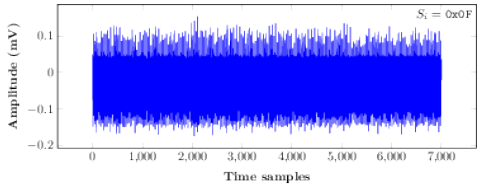

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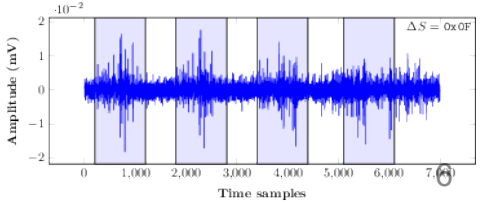
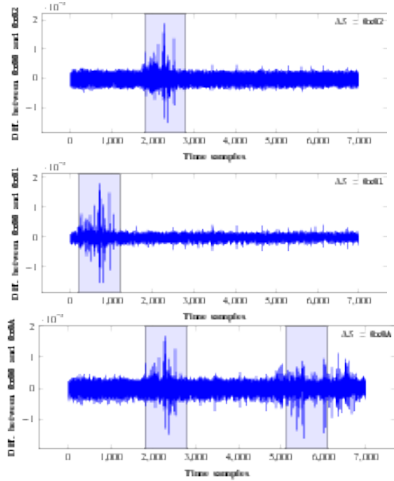


Other differences



Contributions of this work

- We generalize SCADPA to SITM (See-in-the-middle) as middle/deep round attacks on a wider class of SPN block ciphers.
- Validated on 8-bit AVR and 32-bit ARM microcontrollers
- First demonstrated attack on middle rounds protected with shuffling countermeasure.
- First side-channel attack on AES-128 up to 4 rounds

Other Contributions

- Also present results on SKINNY, PRESENT.
- Applicable to other ciphers with similar structure, such as GIFT, RECTANGLE, and MIDORI.
- We propose a method to determine minimum number of rounds to mask to mitigate SITM.

Attacker Model

- Sequential software implementation (ex. Microcontroller)
- **Chosen plaintext attack**
- Observable side-channel leakage in **middle rounds**.
- Detect through side-channel if intermediate value has changed between two different encryptions.
- Targets heterogenous countermeasures → Corner rounds well protected (ex. Masking), Middle rounds unprotected or light countermeasures (ex. Shuffling)

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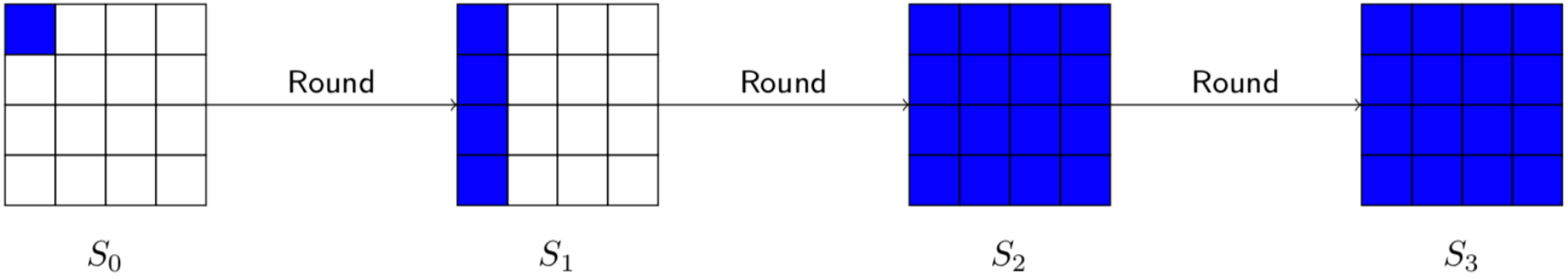
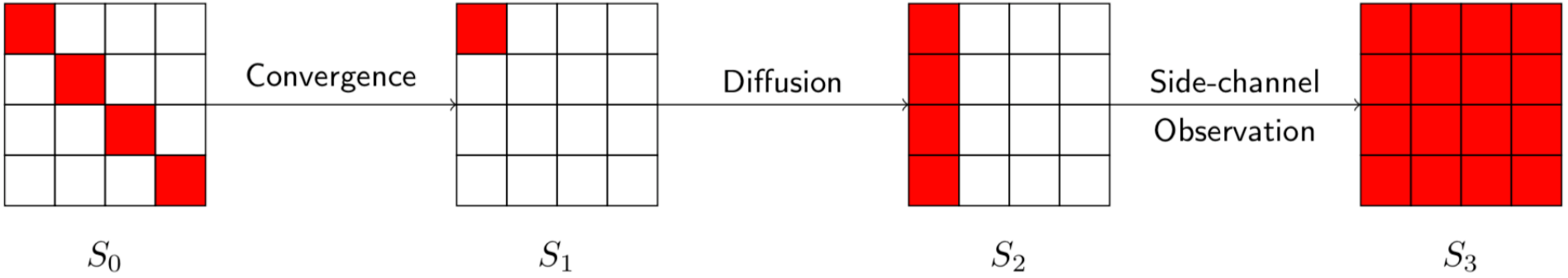
AES Differential Pattern



Normal Plaintext Difference Propagation in AES

One Byte Difference spreads over the state in 2 rounds with very high probability

AES Differential Pattern



Plaintext Pair With Special Difference Pattern

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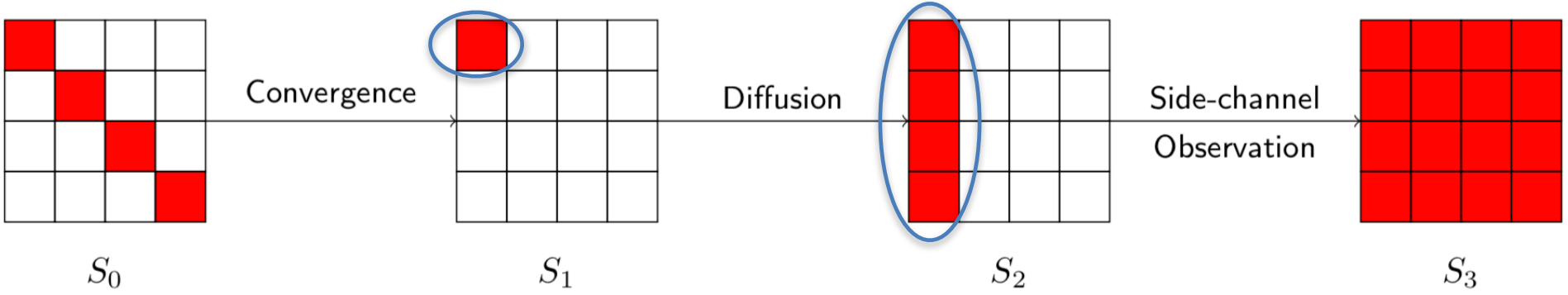

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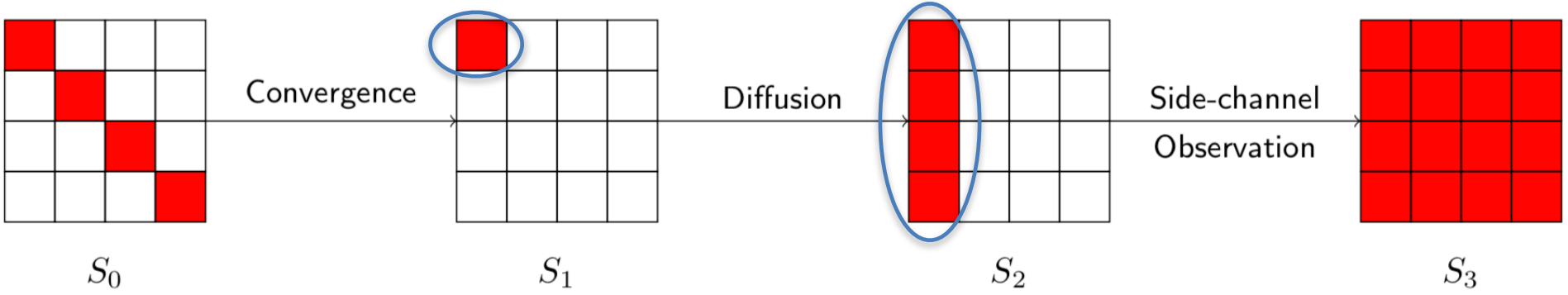
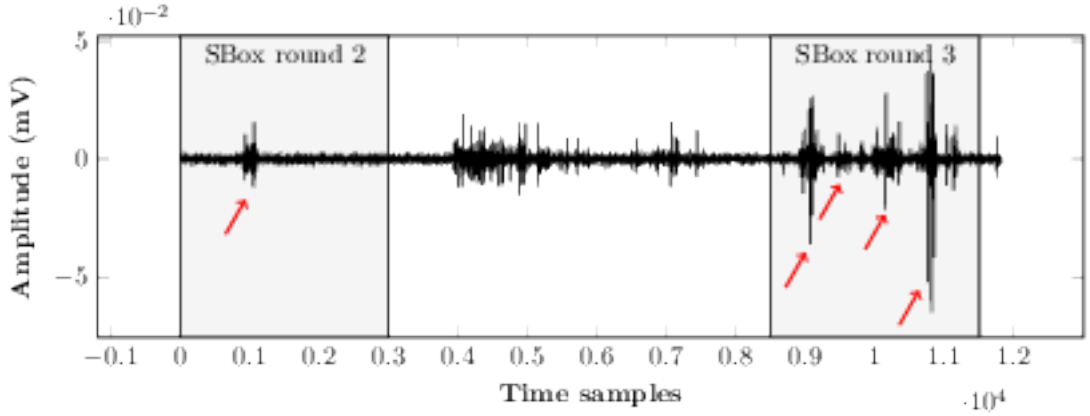


Plaintext Pair With Special Difference Pattern

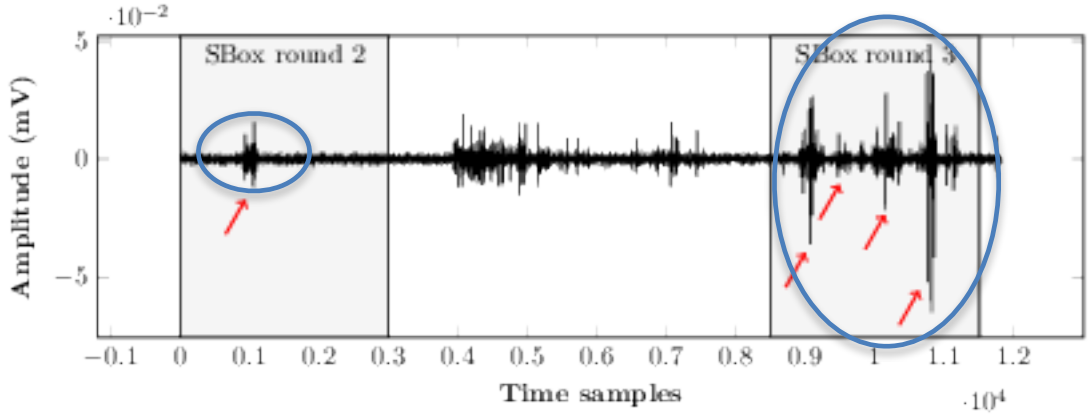
- **Few Plaintext differences lead to convergence**
- **Convergence can be detected by side-channel in middle rounds**

Experimental Validation



8-bit ATMEGA AVR328P

Experimental Validation



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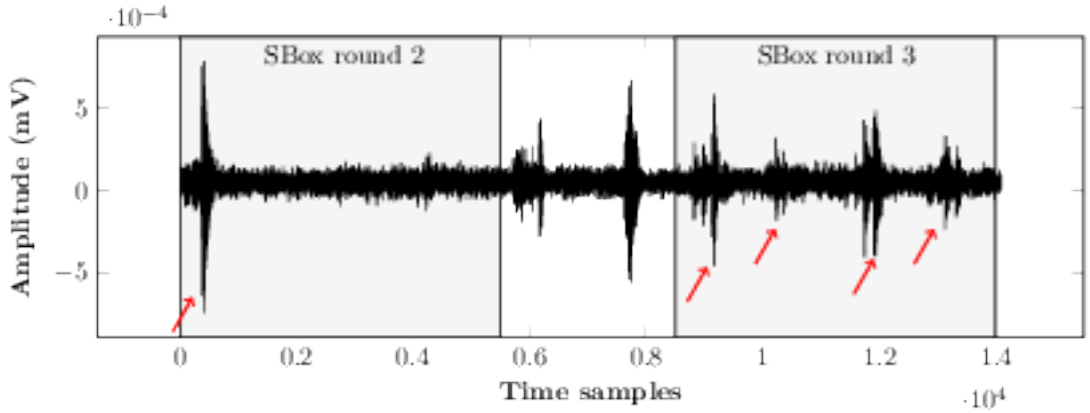

32-bit ARM CORTEX-M3

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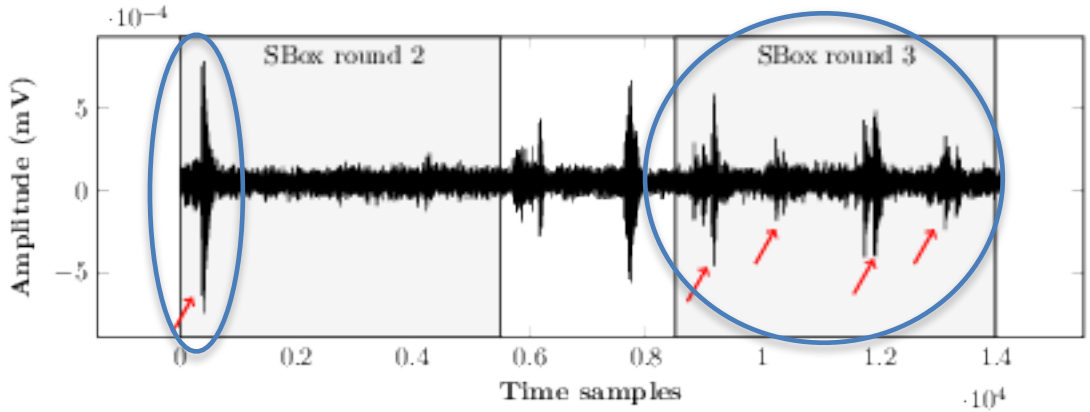

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SITM Methodology

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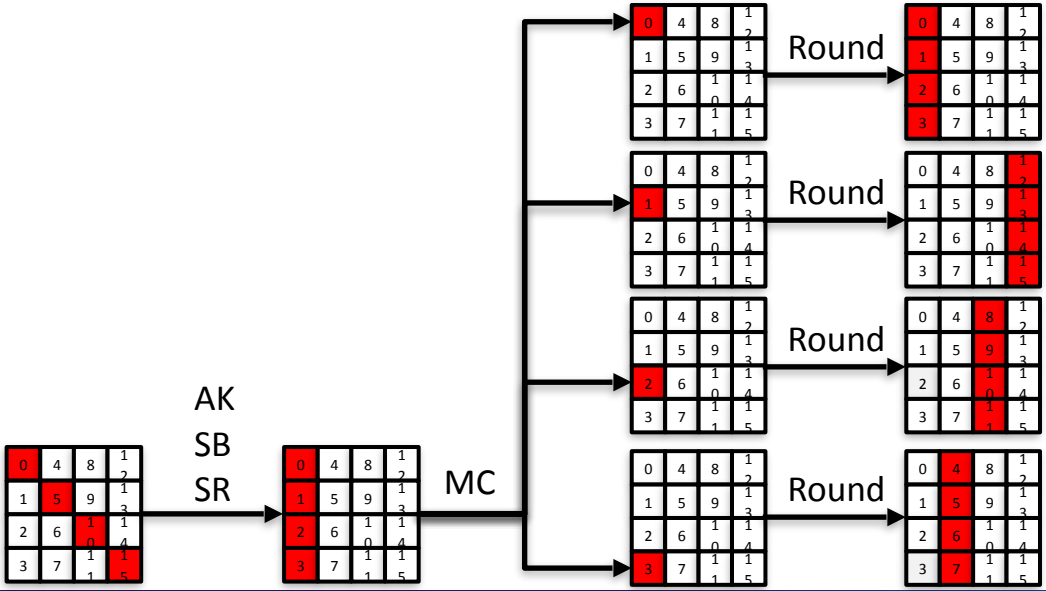
5. Extend to other rounds for master key recovery, if applicable

Key Recovery For AES-128



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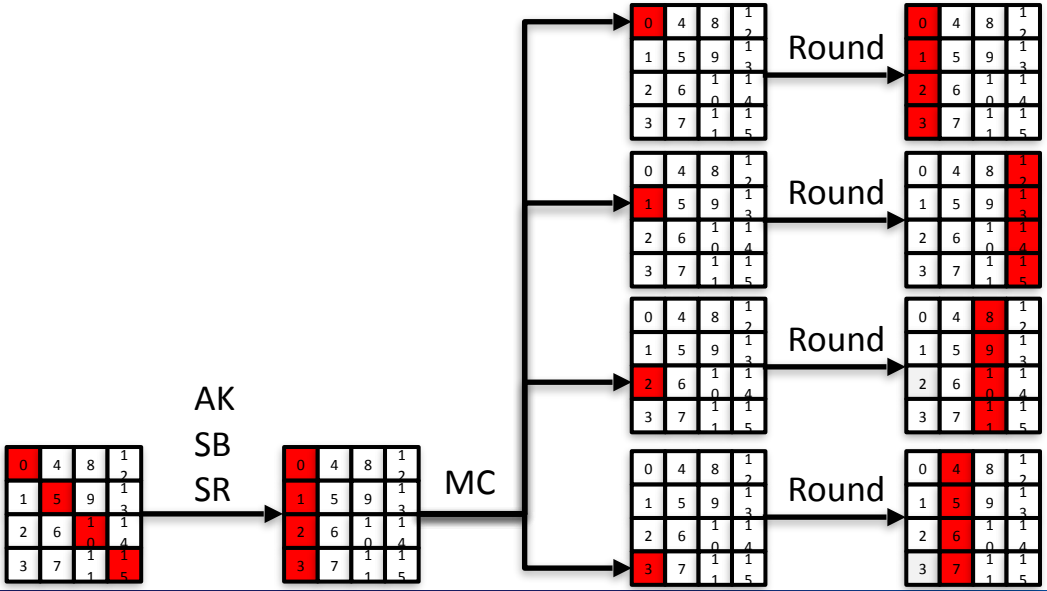
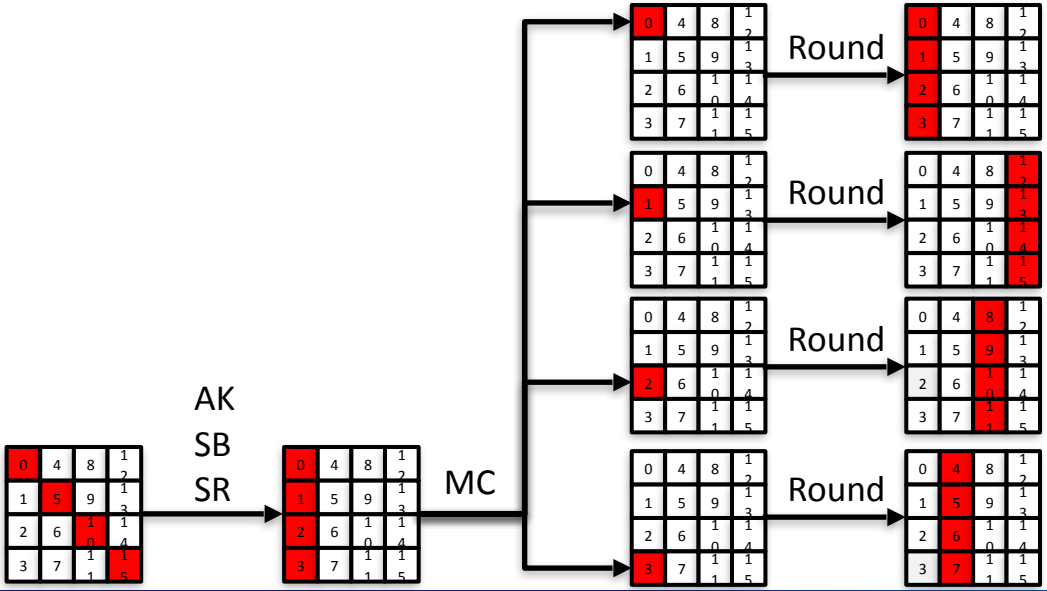


Key Recovery For AES-128

Step 1: Insert differences

- Have differences in byte 0,5,10,15



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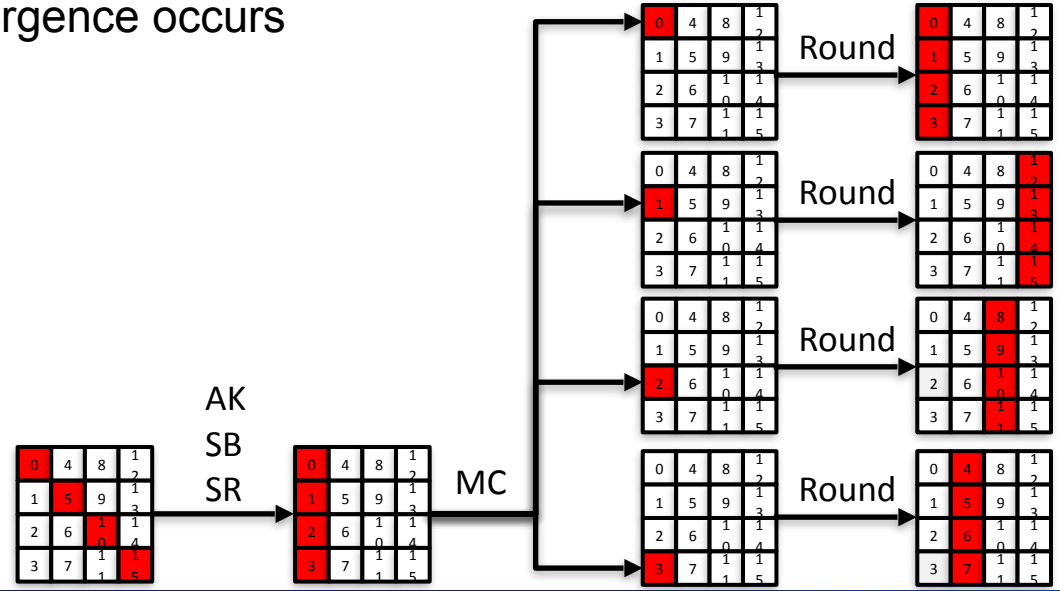
Step 1: Insert differences

- Have differences in byte 0,5,10,15
- With prob. $\approx 2^{-22}$, convergence occurs



Key Recovery For AES-128

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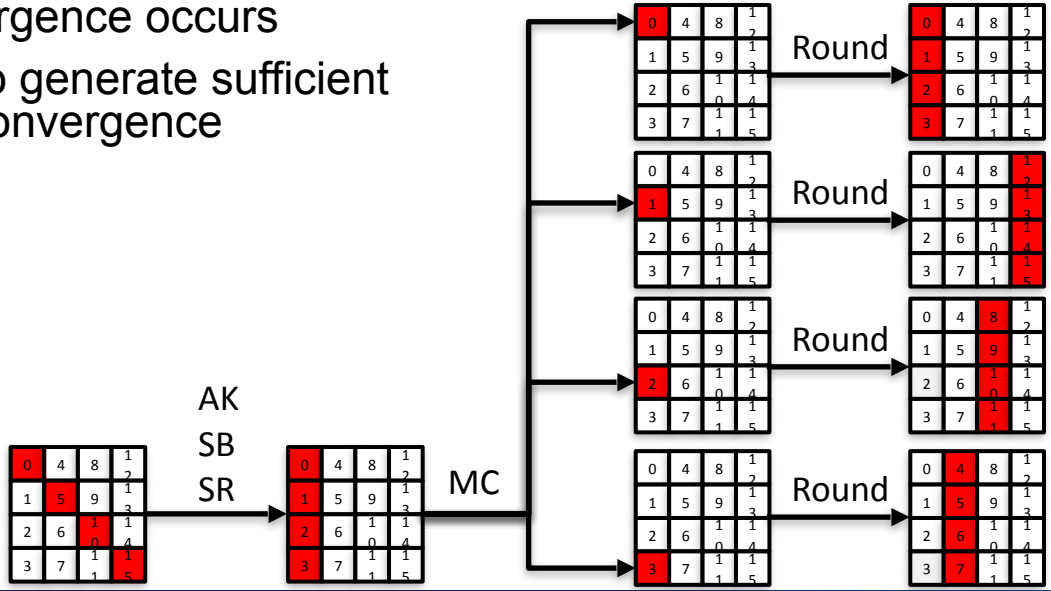
- Need $\approx 2^{11.5}$ plaintexts to generate sufficient differential pairs to get a convergence



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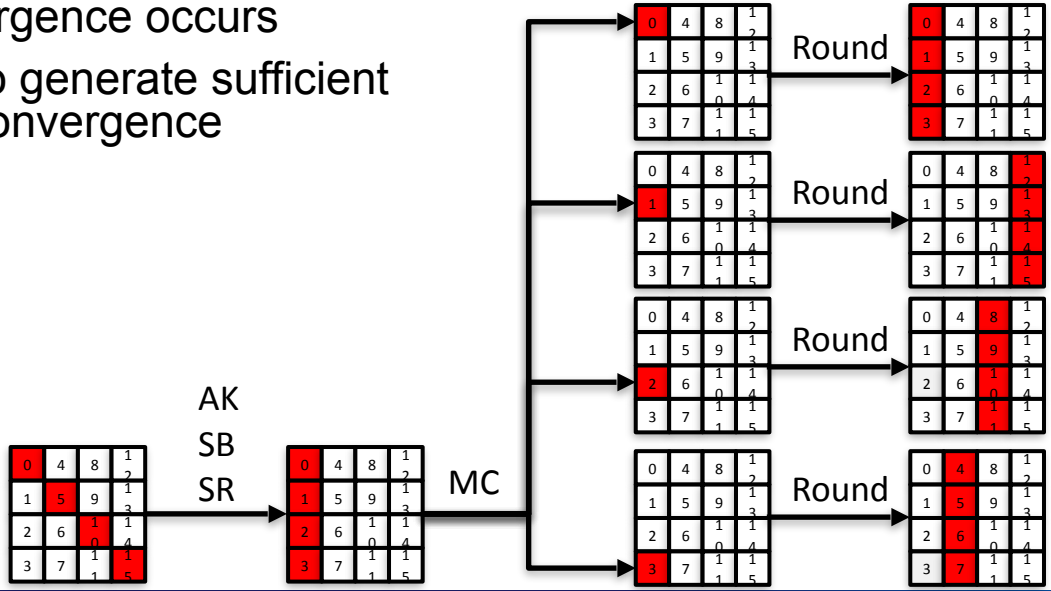

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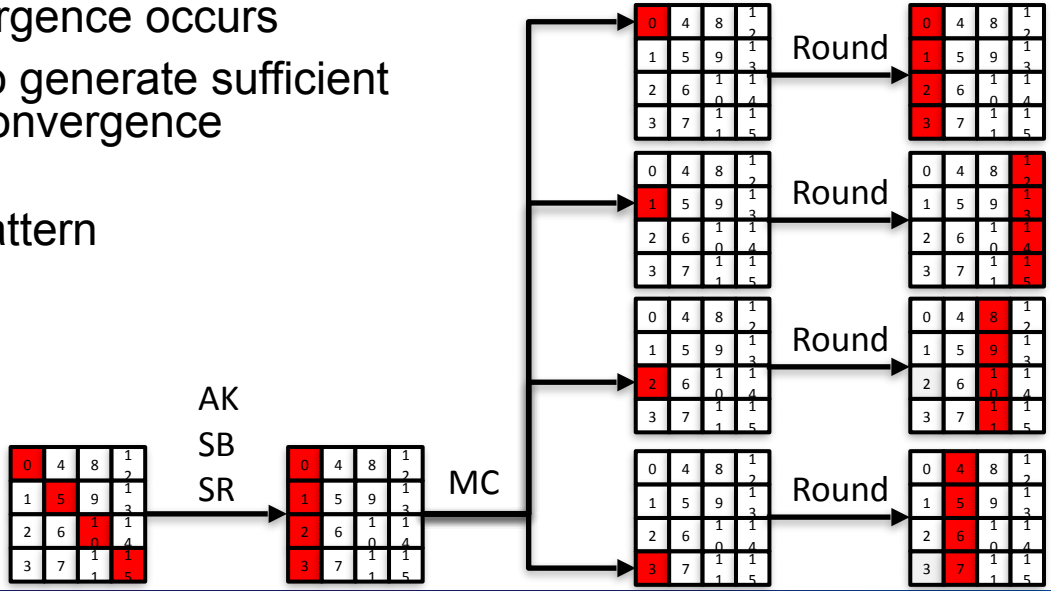
Step 2: Observe differential pattern



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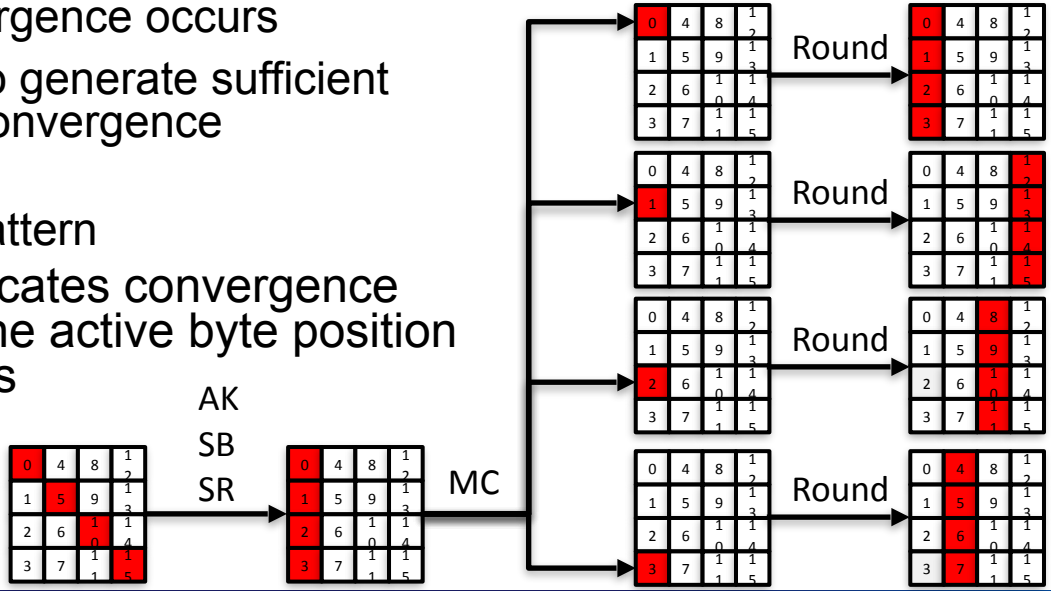
- Single active column indicates convergence and its position reveals the active byte position after round 1 MixColumns



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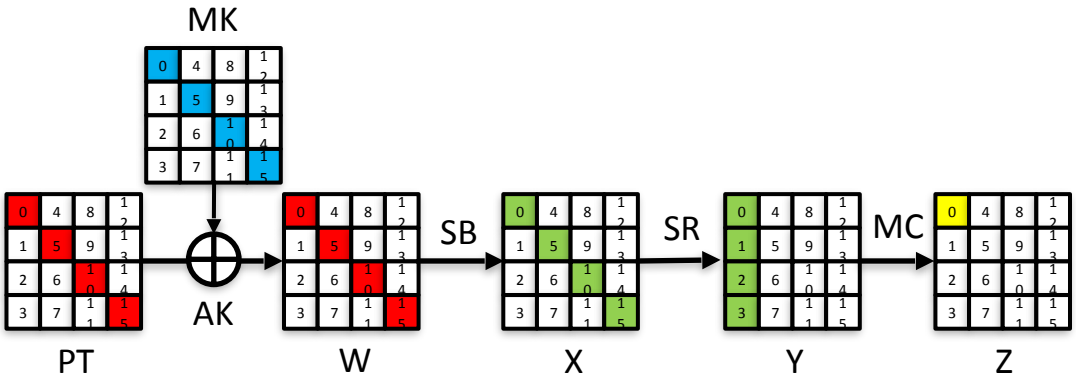
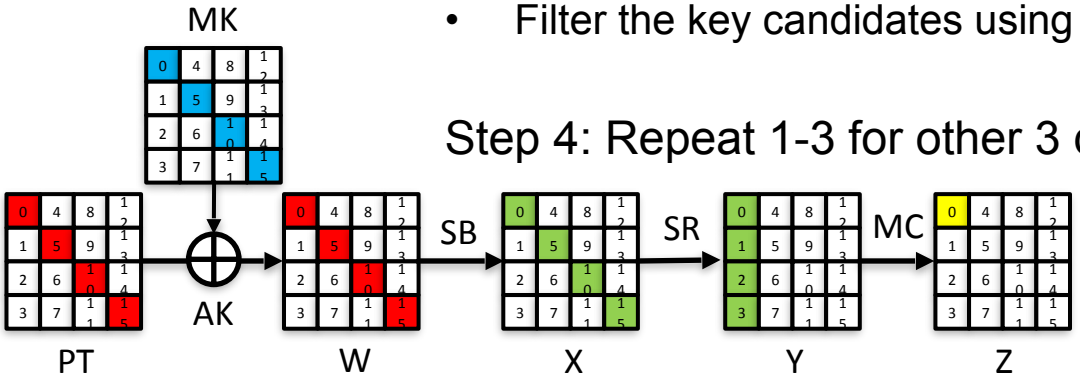


Key Recovery For AES-128

Step 3: Partial key recovery

- Guess single byte difference in Z (yellow)
- Propagate the difference back to X (green)
- For each active byte in W & X, solve for x satisfying $S(x) \oplus S(x \oplus \Delta_i) = \Delta_o$
- Recover partial key (blue) $MK = PT \oplus x$
- Filter the key candidates using new plaintext-pair

Step 4: Repeat 1-3 for other 3 diagonals



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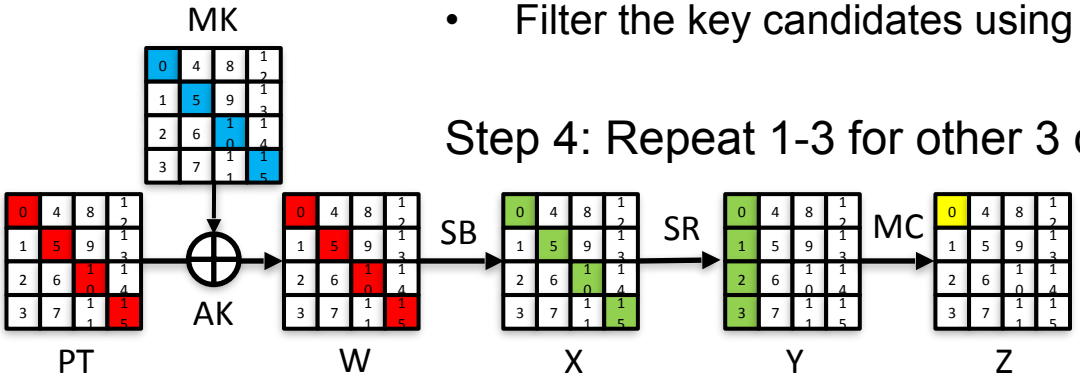

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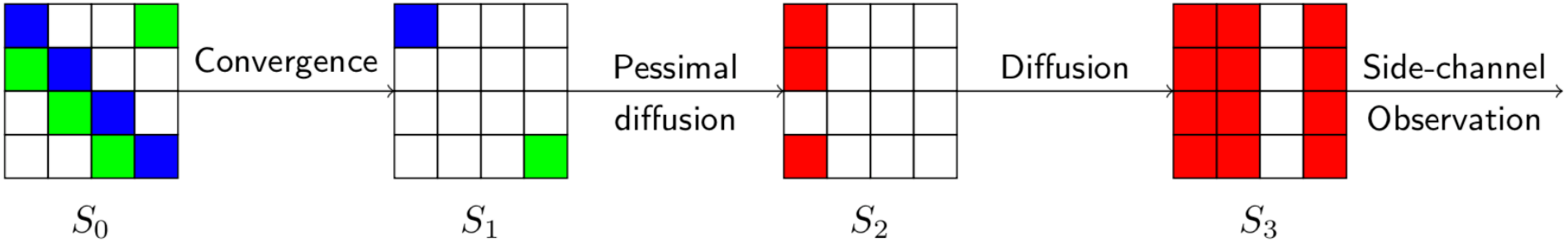
Data complexity

$$4 \times \left(2^{11.5} + 2^{9}\right) = 2^{13.73}$$ chosen PTs

Key candidates filtering

Deeper AES Differential Pattern



Plaintext Pair With Special Difference Pattern

Targeting AES in the 4th round
Requires $2^{27.5}$ plaintext

Summary of Results

Cipher	Block size	Key size	Target depth	Data (chosen PTs)	Memory (bytes)	Time
AES	128	128	3	$2^{13.73}$	2^{10}	$\mathcal{O}(2^{11.5})$
		192	3,4	$2^{14.73}$	2^{10}	$\mathcal{O}(2^{11.5})$
		256	3,4	$2^{14.73}$	2^{10}	$\mathcal{O}(2^{11.5})$
	128	128	4	$2^{27.5}$	2^{12}	$\mathcal{O}(2^{26.5})$
		192	4,5	$2^{28.5}$	2^{12}	$\mathcal{O}(2^{26.5})$
		256	4,5	$2^{28.5}$	2^{12}	$\mathcal{O}(2^{26.5})$
SKINNY	64	64	7,8	$2^{13.02}$	$2^{9.58}$	$\mathcal{O}(2^{10})$
		128	7-10	$2^{14.02}$	$2^{9.60}$	$\mathcal{O}(2^{10})$
		192	7-12	$2^{14.61}$	$2^{9.61}$	$\mathcal{O}(2^{10})$
	128	128	7,8	$2^{25.17}$	$2^{19.58}$	$\mathcal{O}(2^{22})$
		256	7-10	2^{26}	$2^{19.58}$	$\mathcal{O}(2^{22})$
		384	7-12	$2^{26.58}$	$2^{19.59}$	$\mathcal{O}(2^{22})$
PRESENT	64	80	3,4	$2^{12.32}$	2^{9}	$\mathcal{O}(2^{9})$
		128	3,4	2^{13}	$2^{9.02}$	$\mathcal{O}(2^{9})$

Applicable on other SPN ciphers like GIFT, Rectangle, Midori etc

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		384	7-12	$2^{26.58}$	$2^{19.59}$	$\mathcal{O}(2^{22})$
PRESENT	64	80	3,4	$2^{12.32}$	2^{9}	$\mathcal{O}(2^{9})$
		128	3,4	2^{13}	$2^{9.02}$	$\mathcal{O}(2^{9})$

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SKINNY	64	64	7,8	$2^{13.02}$	$2^{9.58}$	$\mathcal{O}(2^{10})$
		128	7-10	$2^{14.02}$	$2^{9.60}$	$\mathcal{O}(2^{10})$
		192	7-12	$2^{14.61}$	$2^{9.61}$	$\mathcal{O}(2^{10})$
	128	128	7,8	$2^{25.17}$	$2^{19.58}$	$\mathcal{O}(2^{22})$
		256	7-10	2^{26}	$2^{19.58}$	$\mathcal{O}(2^{22})$
		384	7-12	$2^{26.58}$	$2^{19.59}$	$\mathcal{O}(2^{22})$
PRESENT	64	80	3,4	$2^{12.32}$	2^{9}	$\mathcal{O}(2^{9})$
		128	3,4	2^{13}	$2^{9.02}$	$\mathcal{O}(2^{9})$

Applicable on other SPN ciphers like GIFT, Rectangle, Midori etc

Minimum Number of Rounds To Mask

Cipher	Block size	Key size	♯ of rounds	b_p	f_d	Rounds to be masked	% of masking
AES	128	128	10	4	2	10	100%
		192	12			12	100%
		256	14			12	85.7%
SKINNY	64	64	32	8	6	28	87.5%
		128	36			28	77.8%
		192	40			28	70%
	128	128	40	15	6	40	100%
		256	48			42	87.5%
		384	56			42	75%
PRESENT	64	80/128	31	16	3	31	100%

Protect All Rounds!!!

Table of Contents

Shuffling Against Side-Channel

Unprotected Case

Execution 1

Shuffling Against Side-Channel

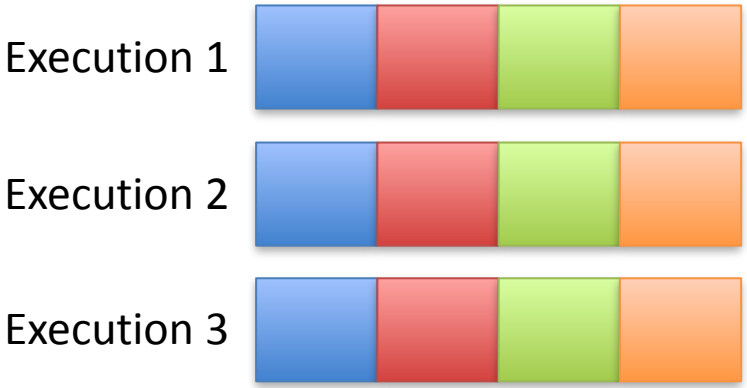
Unprotected Case

Execution 1

Execution 2

Shuffling Against Side-Channel

Unprotected Case



Shuffling Against Side-Channel

Unprotected Case

Execution 1

Execution 2

Execution 3

Shuffled Case

Shuffling Against Side-Channel

Unprotected Case

Execution 1

Execution 2

Execution 3

Shuffled Case

Execution 1

Shuffling Against Side-Channel

Unprotected Case

Execution 1

Execution 2

Execution 3

Shuffled Case

Execution 1

Execution 2

Shuffling Against Side-Channel

Unprotected Case

Execution 1

Execution 2

Execution 3

Shuffled Case

Execution 1

Execution 2

Execution 3

Shuffling Against Side-Channel

Unprotected Case

Execution 1

Execution 2

Execution 3

Shuffled Case

Execution 1

Execution 2

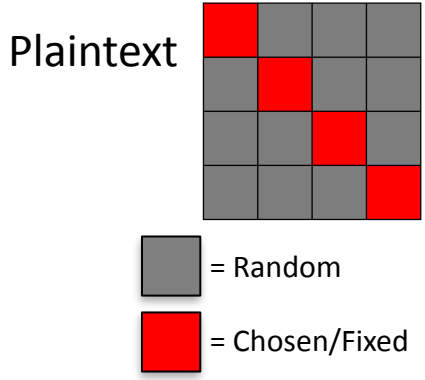
Execution 3

n! possibilities (n=4 here)

Attack Setting

- Corner Rounds → Masking + Shuffling
- Middle Rounds → Only Shuffling
- 16 Sbox → 16! (2^{44}) Execution sequence
- Averaging not possible → Low SNR

Attack Procedure



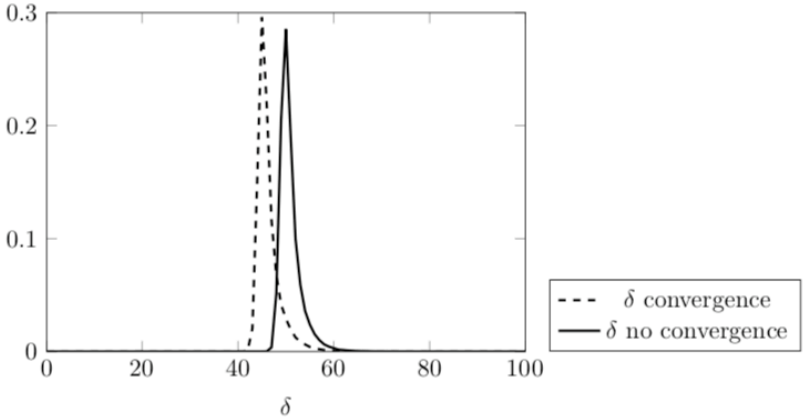
1. Get traces T_{r0}^{i} and T_{r1}^{i} with plaintext difference
2. Find 16 PoI for 16 shuffled Sboxes (non-profiled)
3. Compute:

$$Ds_i=(T_{r0}^{i}(0)-T_{r1}^{i}(0),\ T_{r0}^{i}(1)-T_{r1}^{i}(1),\ldots,\ T_{r0}^{i}(15)-T_{r1}^{i}(15))$$

4. **A lower value of $D=|\sum_{i=0}^{15} Dsi|$ detects convergence**
5. Enumerate from **min(D)** to find converging pairs
6. Key recovery follows SITM on unprotected AES

Experimental Results

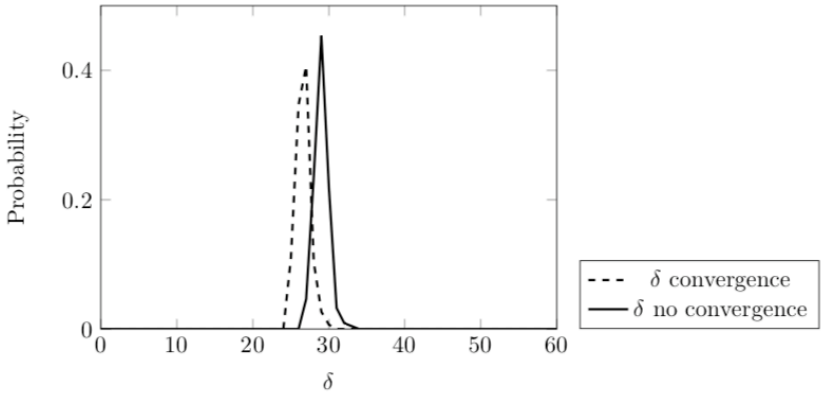
Simulated Traces



N_{traces}=2000

SNR=0.018

Real Traces



N_{traces}=1000

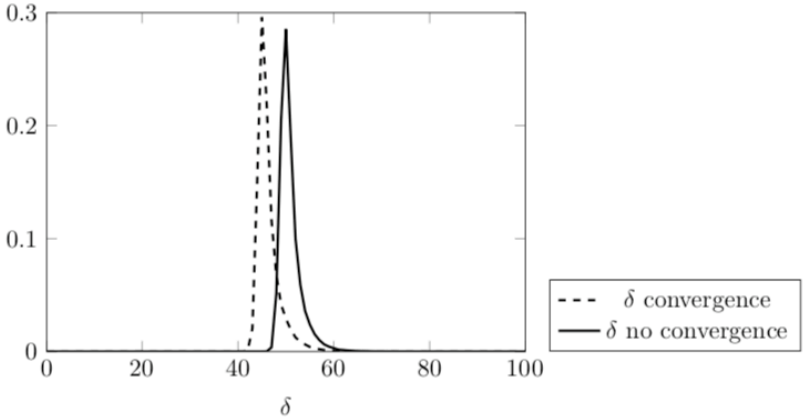
SNR=0.09375

Experimental Results

Simulated Traces

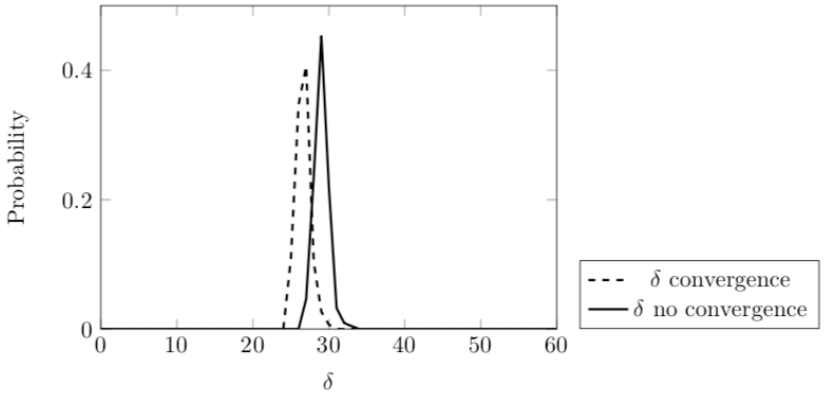
Real Traces

In non-profiled setting, simply enumerate from the Min(D) until 2 collisions are detected



N_{traces}=2000

SNR=0.018



N_{traces}=1000

SNR=0.09375

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Comparison With Other Attacks

Attack	Targets Middle Round	SNR Senstivity	Profiling Needed
DSCA	✗	Low	✗
Collison Based	✓	High	✗
ASCA	✓	Very High	✗
SASCA	✓	Low	✓
SITM	✓	Low	✗

Conclusions

- Presented SITM (Side-Channel Assisted Middle Round Differential Cryptanalysis) as a generalised **deep round attack** on SPN ciphers
- Target AES up to 5 rounds, Skinny up to 12 rounds
- First attack on middle round shuffling
- Reinstates need for protecting all rounds of the ciphers.

Thank You !!!

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