Misusing Misuse-Resistance in APE

Dhiman Saha[1], Sukhendu Kuila[2], Dipanwita Roy Chowdhury[1]

[1]Dept. Of Computer Science & Engineering, IIT Kharagpur, INDIA
[2]Dept. Of Mathematics, Vidyasagar University, INDIA

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Nonce-based Encryption

- Formalized by Rogaway
- Primary Condition
  - ***Uniqueness*** of the nonce in every instantiation of the cipher
- Interesting Consequence
  - Automatic protection from Differential Fault Analysis (DFA)
- DFA assumption
  - Ability to induce faults in the intermediate state of the cipher while replaying the encryption with the same plaintext.
  - No longer holds due to introduction of nonce

Misuse-Resistance

- A desirable property for authenticated ciphers.
- Avoids maintaining a nonce-generator
- Suited for resource constrained environments
- Addressed in CAESAR selection portfolio
- However, there is some collateral damage.
  - Nonce assumption no longer holds
  - Opens up the ciphers for DFA
- This work explores this idea to mount efficient DFA on misuse-resistant AE scheme APE

APE

- Authenticated Permutation-based Encryption – APE
  - Introduced first in FSE 2014
  - First misuse-resistant permutation-based AE scheme
  - Inspired from SPONGE
  - Targeted for lightweight environments
  - Basically a mode of operation
  - Can be instantiated with permutations of hashes like SPONGENT/QUARK/PHOTON

- Reintroduced in CAESAR
  - Along with HANUMAN & GIBBON
  - Part of PRIMATEs family of authenticated ciphers
  - Now with new indigenous permutation called PRIMATE

The PRIMATE Permutation

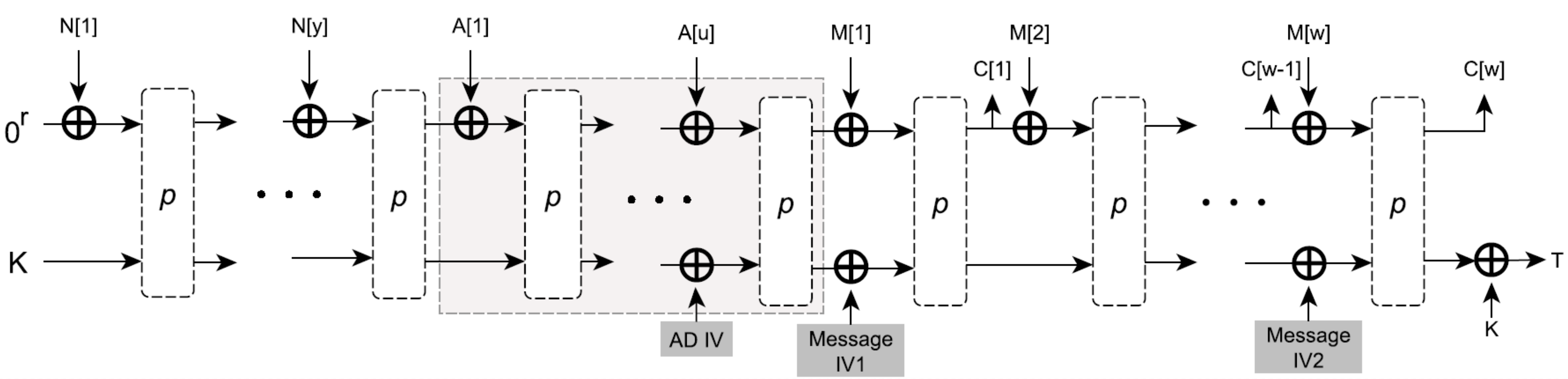
- Internal permutation for APE/HANUMAN/GIBBON
  - Inspired from FIDES authenticated cipher
  - Structurally follows AES round function

- Has two variants
  - PRIMATE-80/120
  - Internal state realized as (5 x 8) / (7 x 8) five-bit elements

- Component Transformations
  - SubBytes
  - ShiftRows
  - MixColumns
  - Round constant addition

PRIMATE-APE

- N[·] – Nonce block
- A[·] – Associated data block
- M[·]– message block
- K – Key (160 bit for APE-80)
- The IVs are predefined and vary according to the nature of the length of message and associated data.
- This work uses APE-80 (can be extended to APE-120)



Misusing Misuse-Resistance

- Concept of faulty collisions :
  - Not a real collision
  - Attacker induces a fault in the state of the cipher so that two different plaintexts produce the same tag.

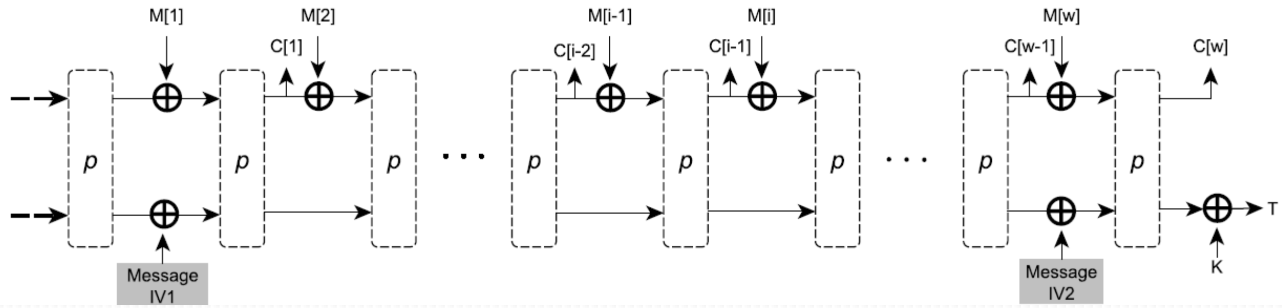
- Idea : To find faulty collisions
  - Feasible due to misuse-resistance
    - **Observation**: APE is misuse-resistant up to a common prefix.

- Common prefix implication:
  - Plaintexts can be of the following form:
    - $M1 = x_0 \,||\, x_1 \,||\, x_2 \,||\, \dots \,||\, \mathbf{x_i} \,||\, \dots \,||\, x_w$
    - $M2 = x_0 \,||\, x_1 \,||\, x_2 \,||\, \dots \,||\, \mathbf{x'_i} \,||\, \dots \,||\, x_w$

A Faulty Collision

- Exploits : Misuse-resistance + Online nature
  - Induce random word fault in (i-1)th ciphertext output
  - Observe faulty (i-1)th output & manipulate ith message input

```
Plaintext1  = M[1] || M[2] || ... || M[i] || M[i+1] || ... || M[w]
Ciphertext1 = C[1] || C[2] || ... || C[i] || C[i+1] || ... || C[w]
Tag = T
```

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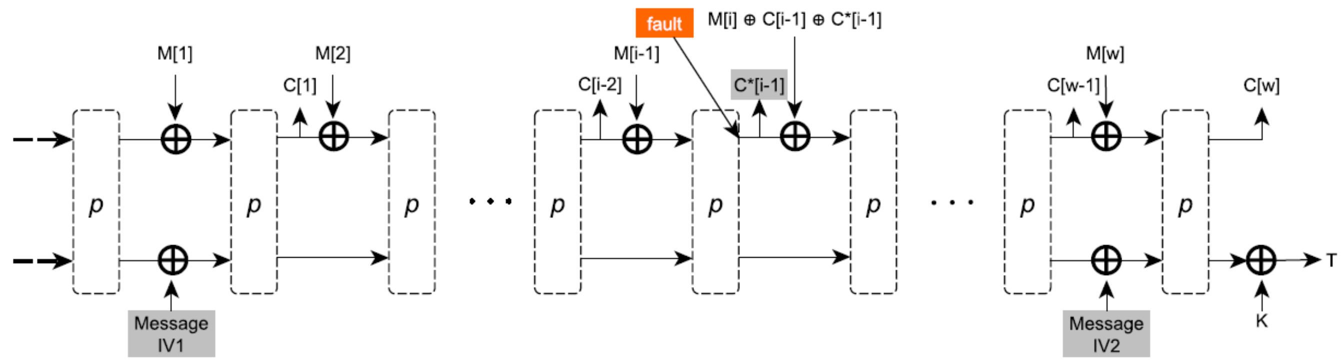
Plaintext2 = M[1] || M[2] || ... || M[i-1] || (M[i] ⊕ C[i-1] ⊕ C*[i-1]) || M[i+2] || ... || M[w]
Ciphertext2 = C[1] || C[2] || ... || C*[i-1] || C[i] || ... || C[w]
Tag = T
```

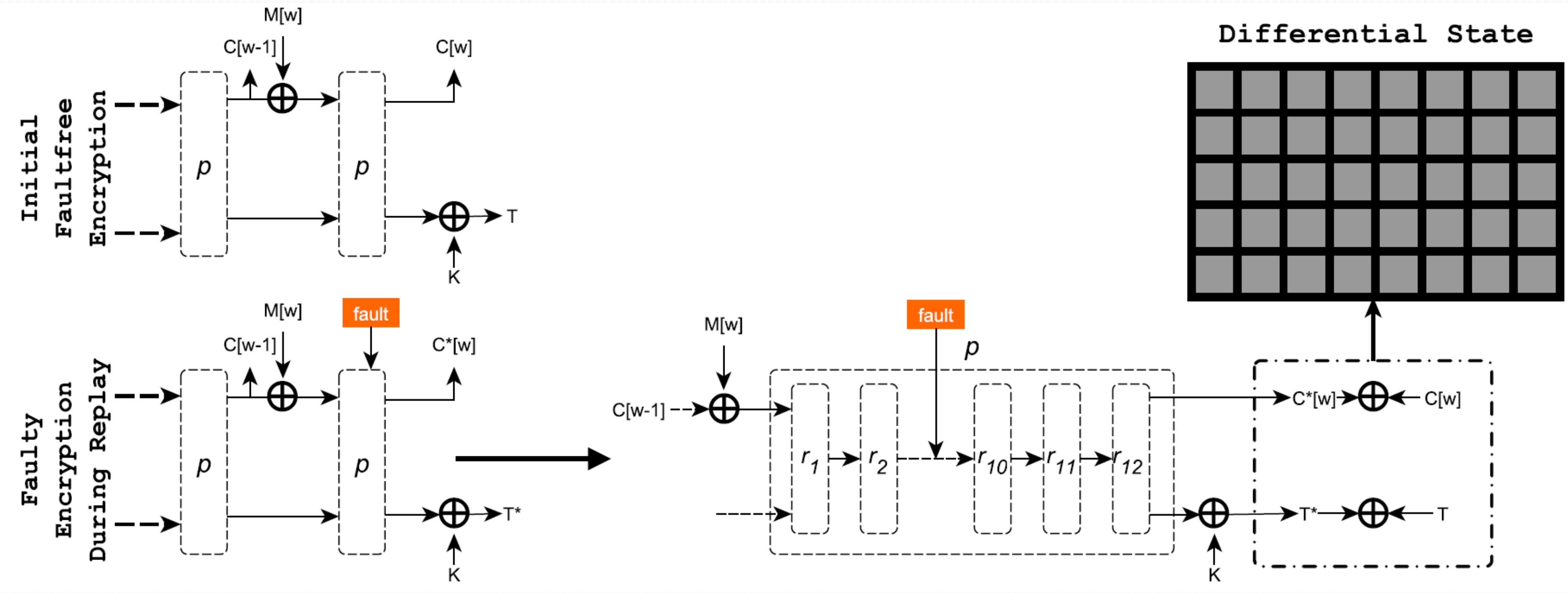


Implications of a Faulty Collision

- Ability to replay the encryption
- Recall
  - This is one of the fundamental requirements to mount differential fault analysis attacks
- Next, we explore the prospect of DFA in the presence of faulty collisions
- Fault model assumed is random word fault
  - Recall : word in case of APE is a 5-bit vector

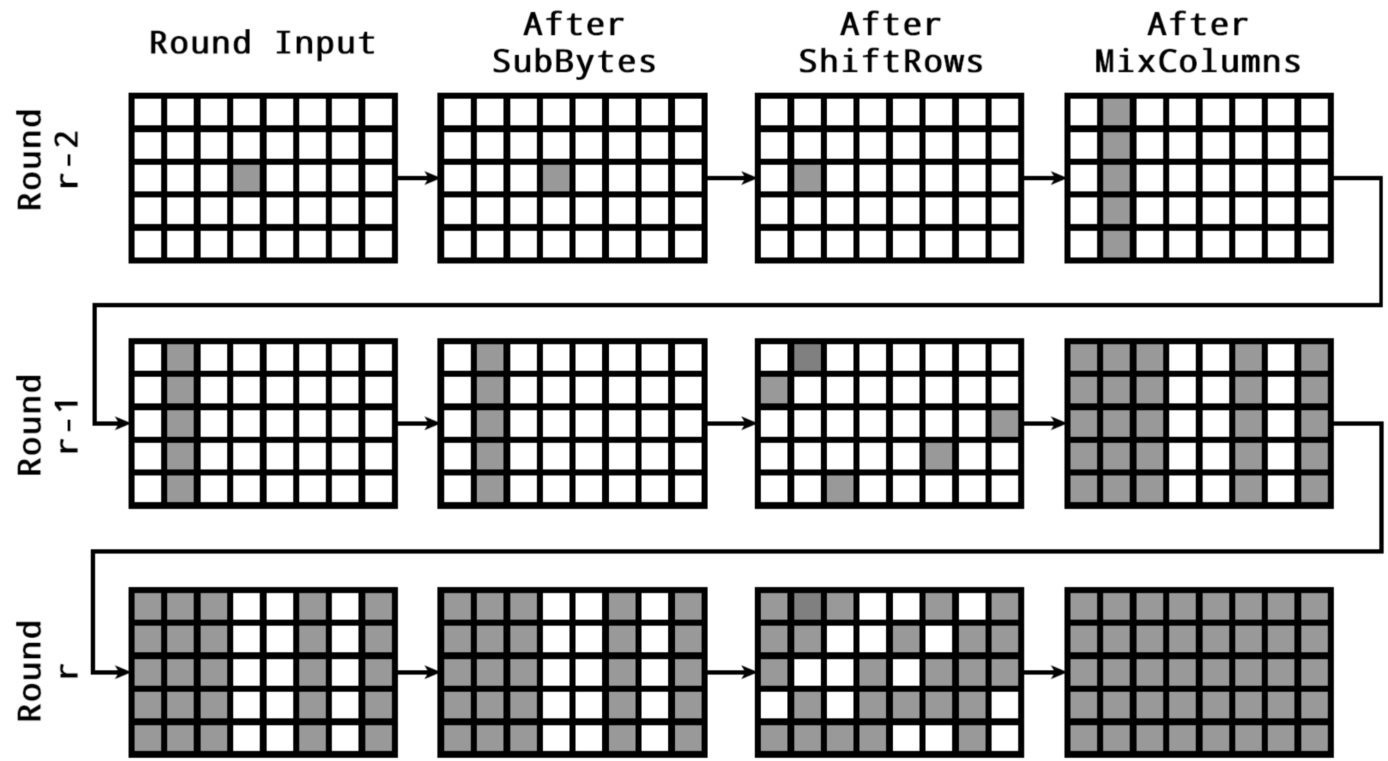
Fault Induction

- Fault induced at the input of 10th round of the final iteration of APE
- Next study the fault diffusion in the differential state in the remaining rounds



Fault Diffusion

- Observe: Exactly 3 specific unaffected columns at the start of r^{th} round due to diagonal word fault at the start of $(r-2)^{th}$ round.
  - Helps to identify fault source diagonal by observing differential state
  - Exploits the non-square nature of state matrix



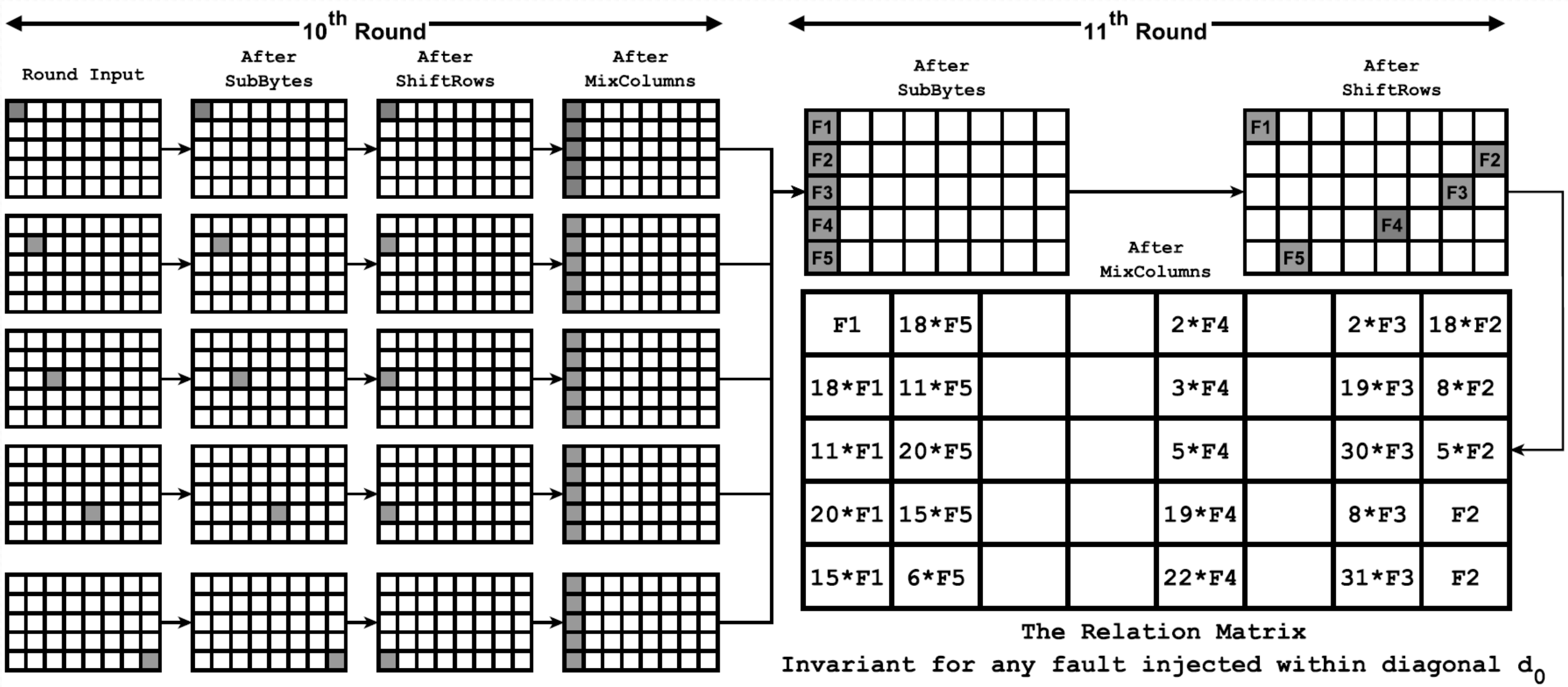
Diagonal Fault Analysis

- Advanced differential fault attack
  - Introduced in 2009, specially suited for AES-like constructions
  - Has been highlighted in the book Fault Analysis in Cryptography as one of the most efficient DFA on AES
    - Available on Eprint archive - https://eprint.iacr.org/2009/581
  - Exploits equivalence of fault induced in the same diagonal of the state matrix

- Can be applied on APE
  - But not directly
  - Last round MixColumn inclusion - major deviation from AES
  - Makes classical diagonal attack inefficient
  - Need some adaptation
    - Focus on recovering the state instead of the key

The Fault Invariant

- The diagonal principle :
  - *Equivalence of faults limited to a diagonal*
- The relation matrix is governed by MixColumns



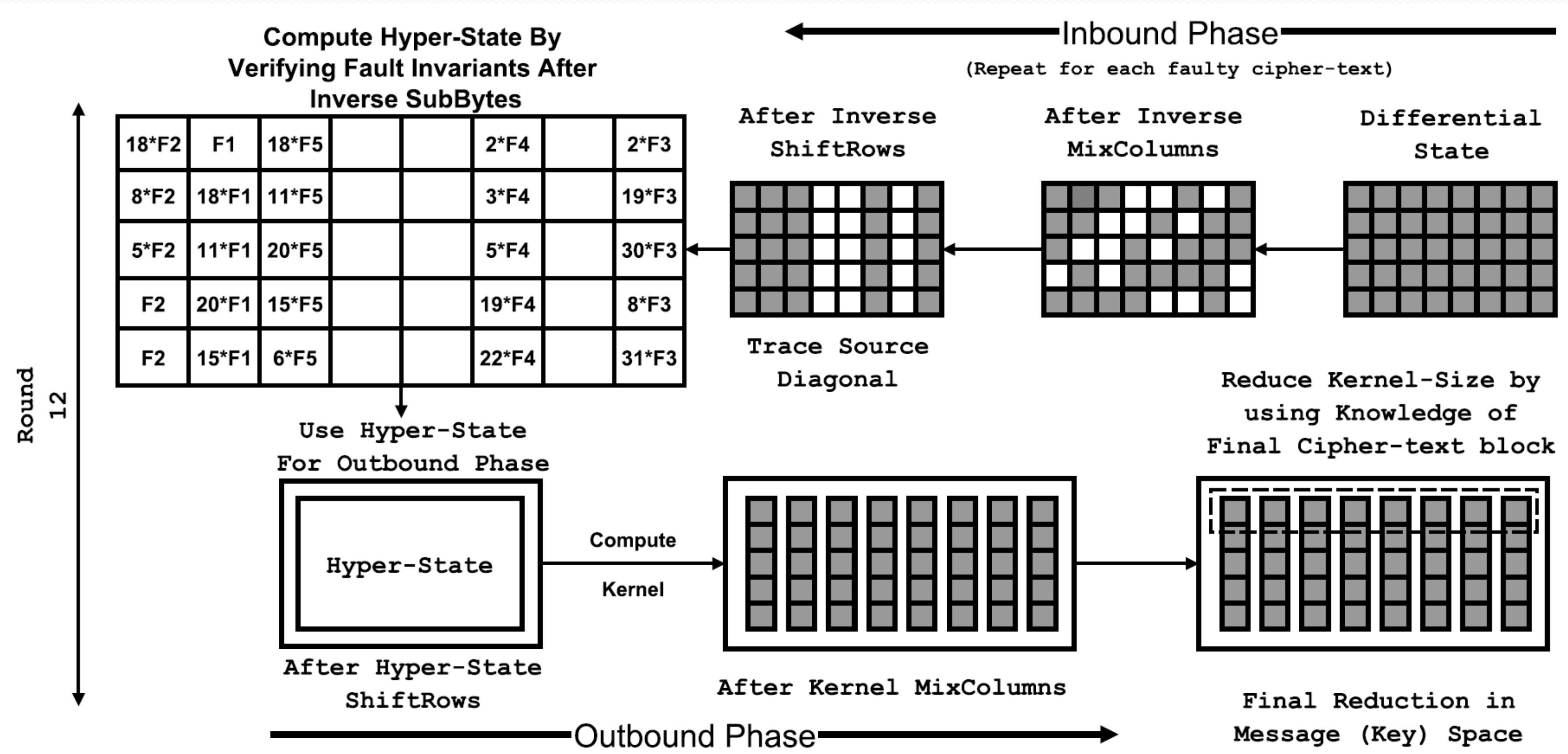
EscApe : Diagonal Fault Analysis of APE

- Inbound phase
  - Invert the differential state (computed from correct and faulty output) to reach up to state after last round SubBytes.
  - Use unaffected columns to identify source fault diagonal and load appropriate relation matrix
  - Solve equations involving fault invariant to generate hyper-state
  - Hyper-State is a special structure where every element is a set of candidates computed after equation solving
    - Helps capture the notion of candidate states for the correct state

EscApe (contd.)

- The Outbound phase
  - Apply ShiftRows to Hyper-state
  - Compute Kernel (Refer paper for details)
  - Apply MixColumns to Kernel
- Reduce message space by verifying candidates against last ciphertext block
  - Exploits the availability of last ciphertext block
  - Simulations confirm large-scale reduction due to this
- Reduced message space directly corresponds to reduced key space.

EscApe :The Final Picture



Results

- In the presence of faulty collision:

Fault Count	Fault Type	Avg. Final Key Space
1	Random word fault at the start of 10th round in the last iteration of APE	2^{80}
2		$\mathbf{2^{25}}$
3		2^{5}
4		1

Epilogue

- Shown how the desirable property of misuse-resistance becomes the gateway for DFA
- First fault analysis of SPONGE when used in the context of authenticated encryption
- EscApe : efficient diagonal attack on APE
  - 2 faults lead to a practical attack, 4 give the unique key
- Removal of final truncation of FIDES in APE makes EscApe highly efficient
- Finally, its evident that
  - Misuse-resistance,
  - Design of underlying permutation and
  - Choice of mode of operation

  can all contribute to the susceptibility of authenticated ciphers to fault attacks

Thank You

- Please forward any queries to

  crypto@dhimans.in

- Full version of the paper :

  http://de.ci.phe.red

  or, CAESAR mailing list