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Overview of side-channel and fault injection attacks on ML-KEM CRYSTALS-KYBER implementations

Simon Pontie

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Simon Pontie. Overview of side-channel and fault injection attacks on ML-KEM CRYSTALS-KYBER implementations. Post-Quantum Cryptography conference by DGA at European Cyber Week, Nov 2024, Rennes, France. cea-04810887

HAL Id: cea-04810887

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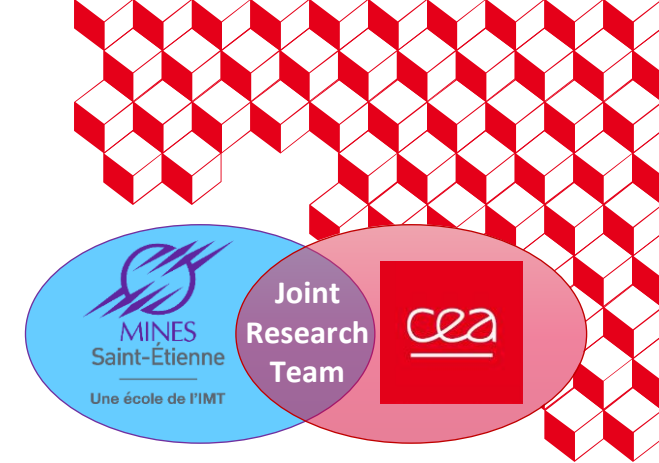
Submitted on 29 Nov 2024

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Laboratoire Sécurité des Composants
(LETI/DSYS/SSSEC/LSCO)



Overview of side-channel and fault injection attacks on ML-KEM (CRYSTALS-KYBER) implementations

Simon Pontié

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Outline



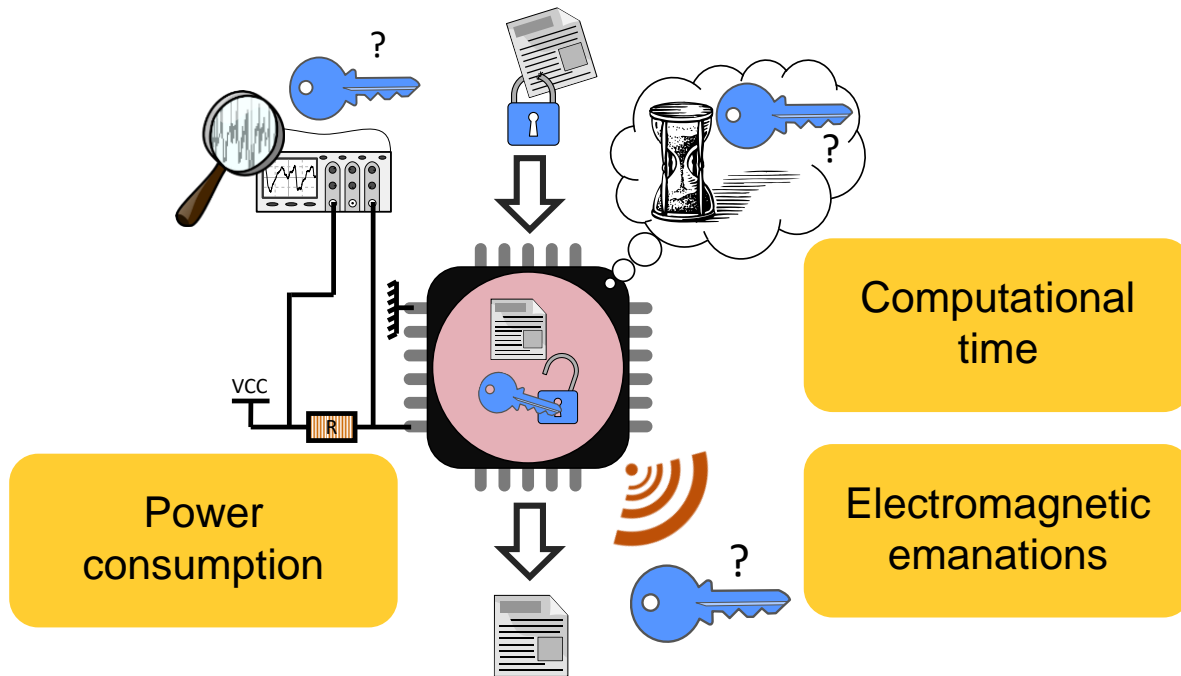
- I. Side Channel Analysis and Fault Injection
- II. ML-KEM
- III. 3 examples of Fault Injection attack on ML-KEM implementation
- IV. 2 examples of Side-Channel Analysis attack on ML-KEM implementation
- V. Conclusion

Existing survey in the literature: *Ravi, Prasanna, et al. "Side-channel and fault-injection attacks over lattice-based post-quantum schemes (Kyber, Dilithium): Survey and new results." ACM Transactions on Embedded Computing Systems 23.2 (2024): 1-54.*

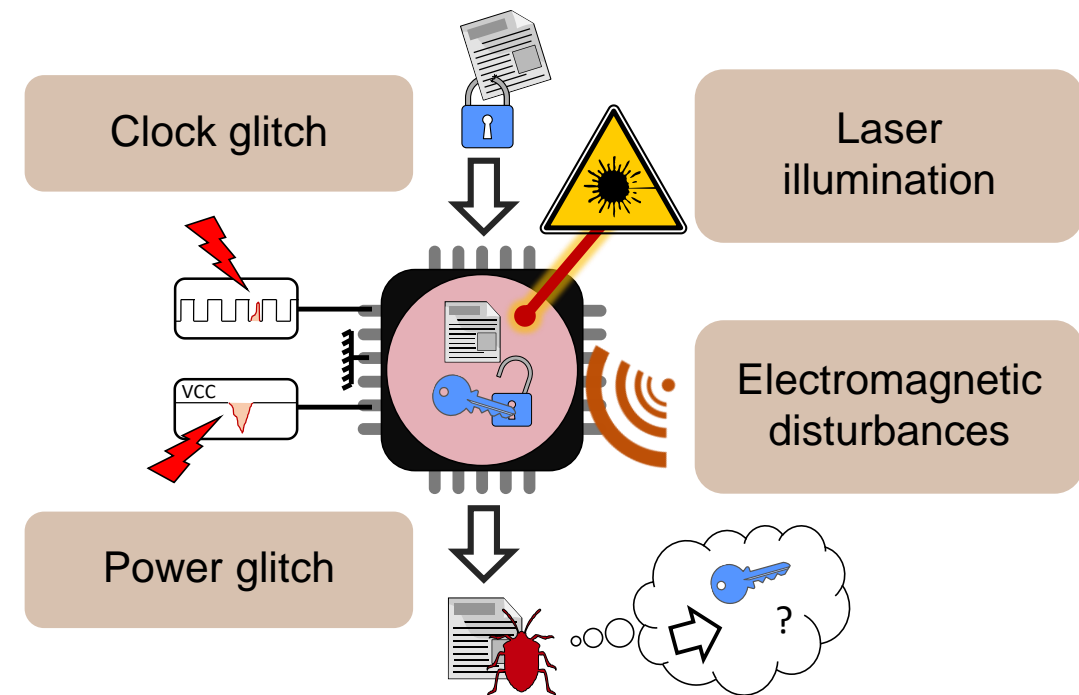
Side Channel Analysis and Fault Injection

A cryptographic implementation can leak information about a secret even if it is an implementation of a secure cryptographic algorithm.

Side-channel analysis (SCA) attacks



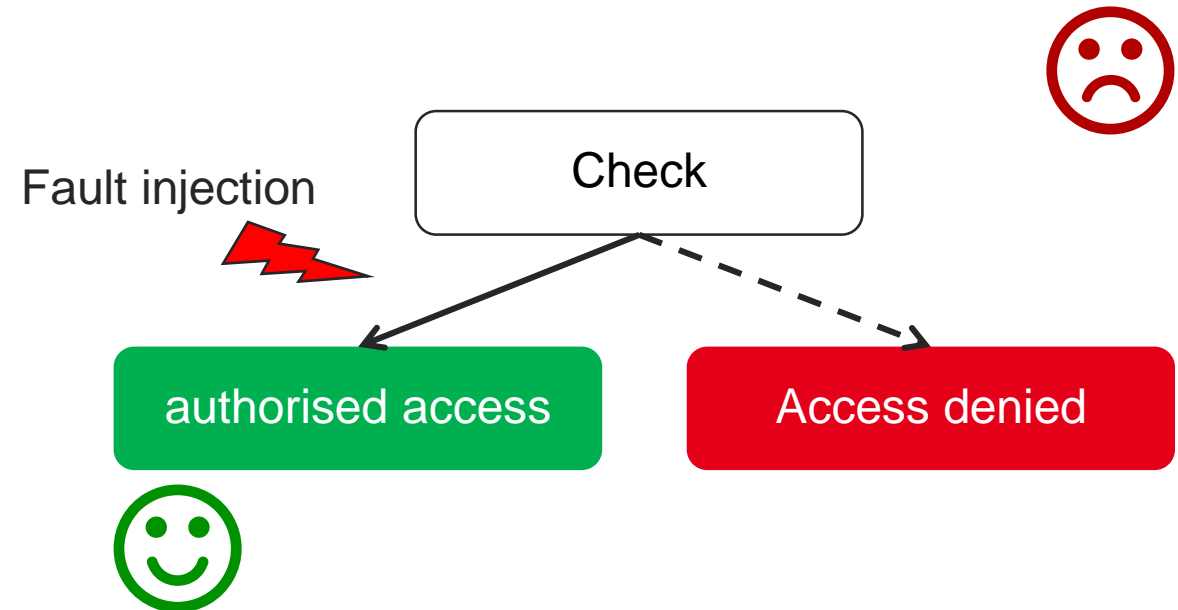
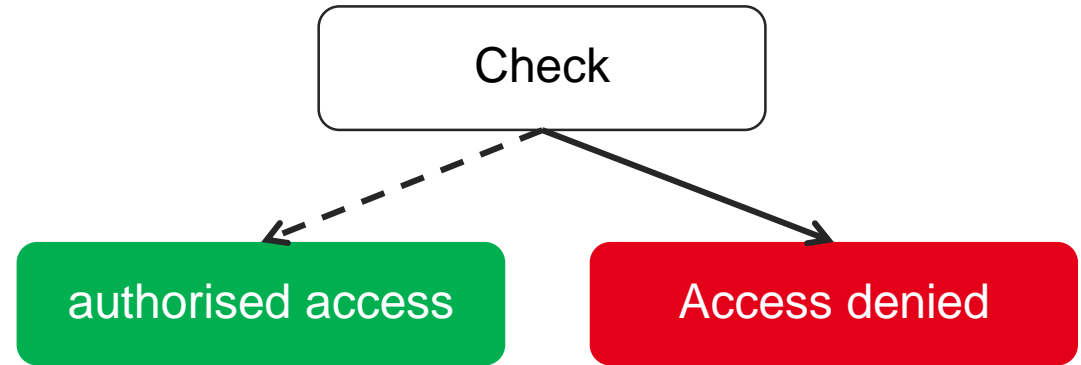
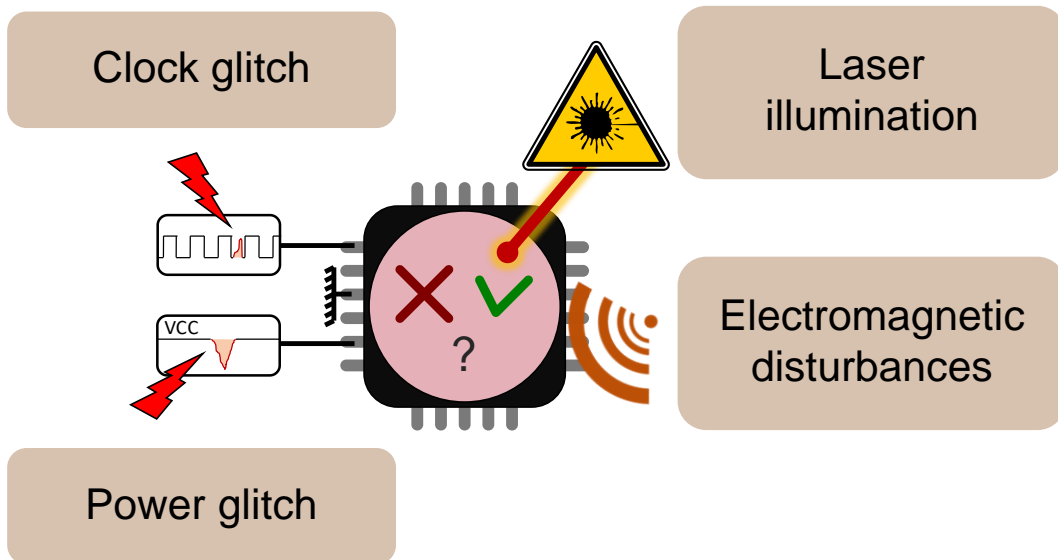
Fault injection (FI) attacks



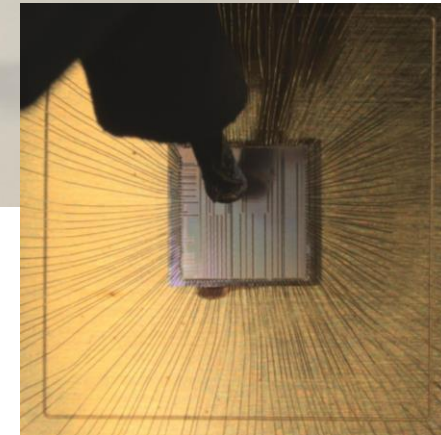
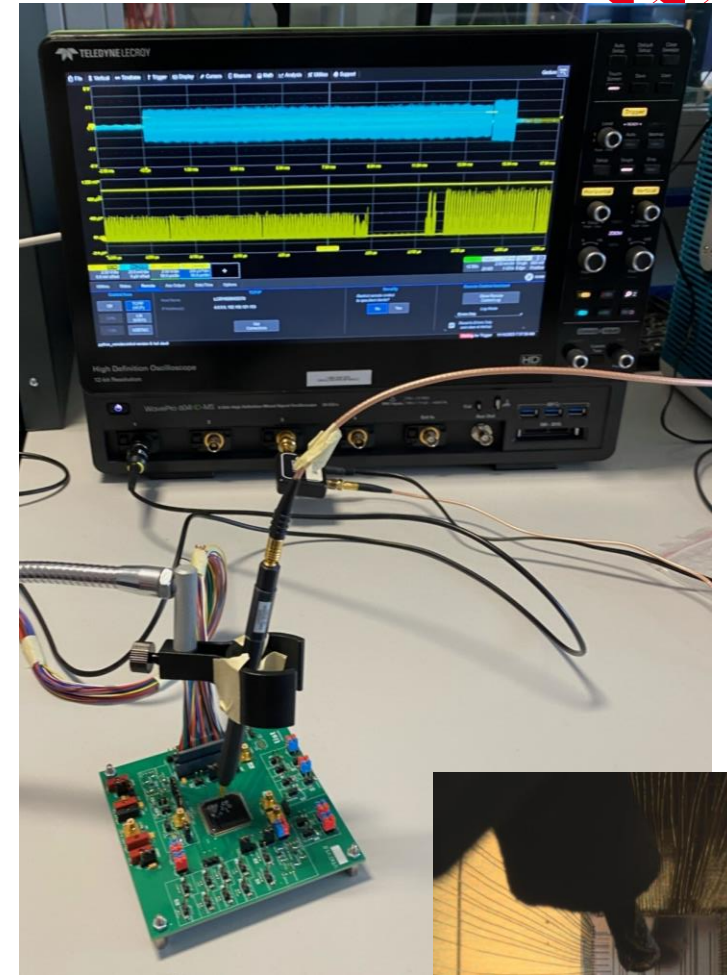
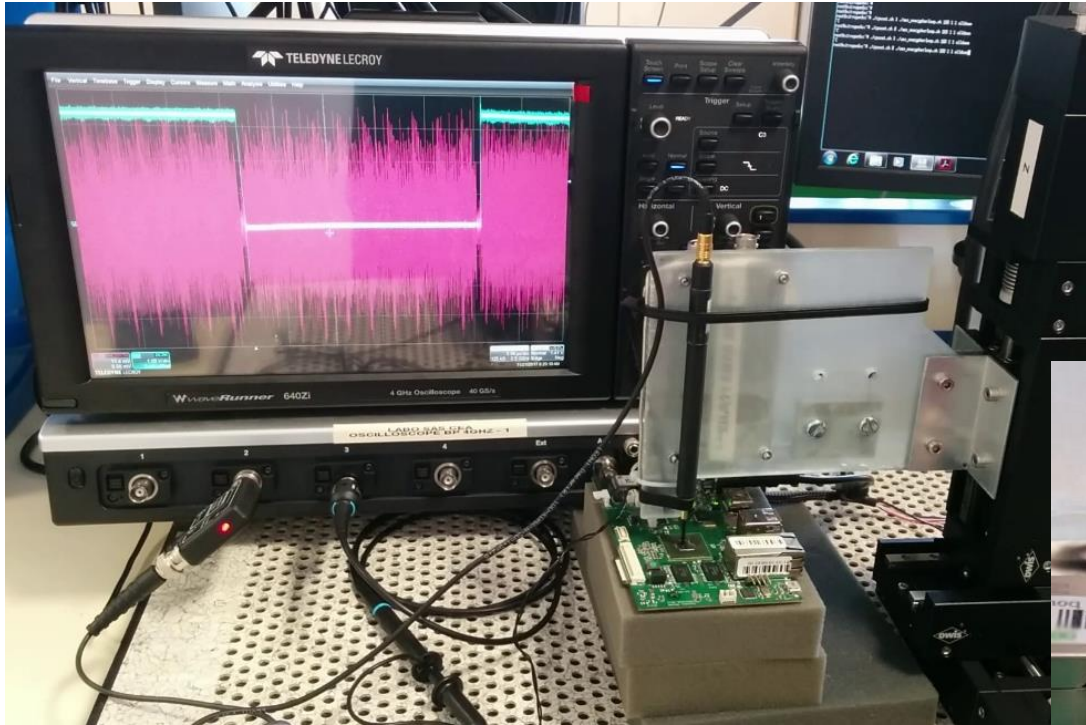
Side Channel Analysis and Fault Injection

Fault injection attacks can also be used to bypass a security mechanism

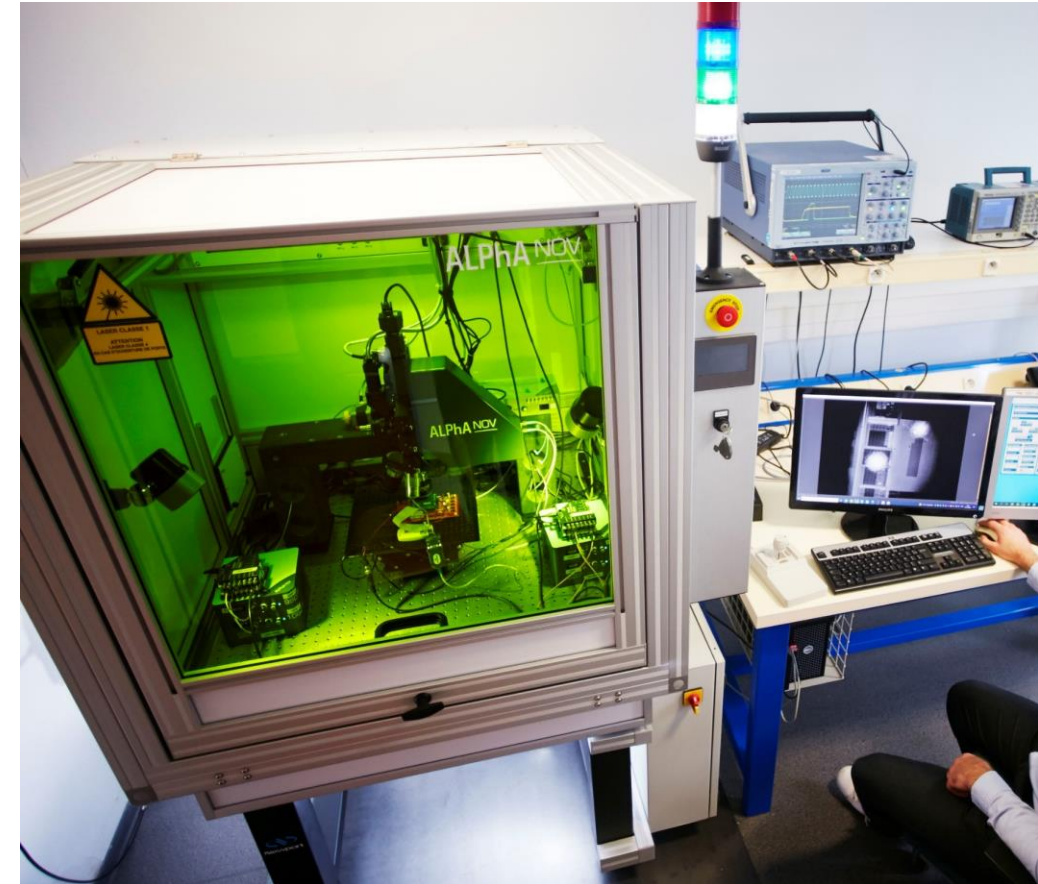
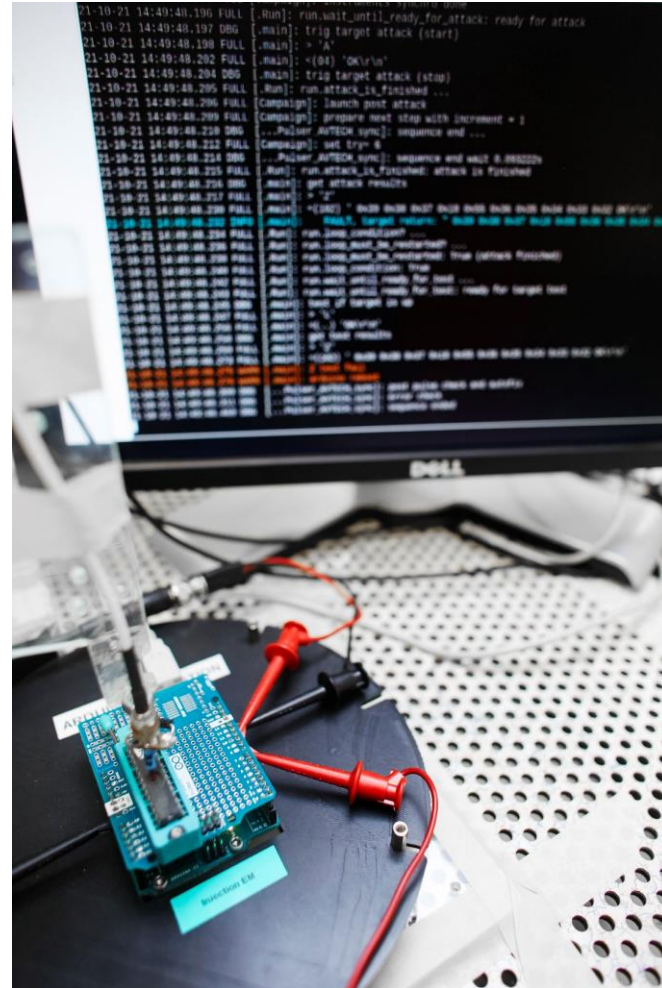
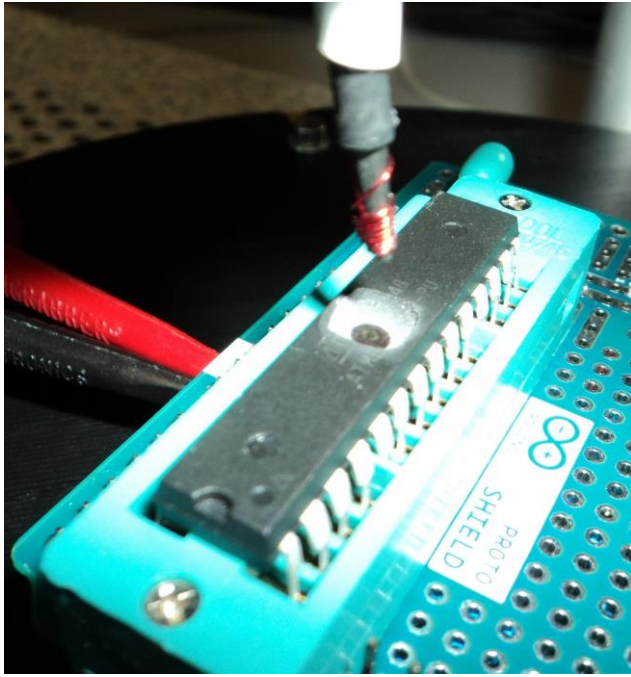
Fault injection (FI) attacks



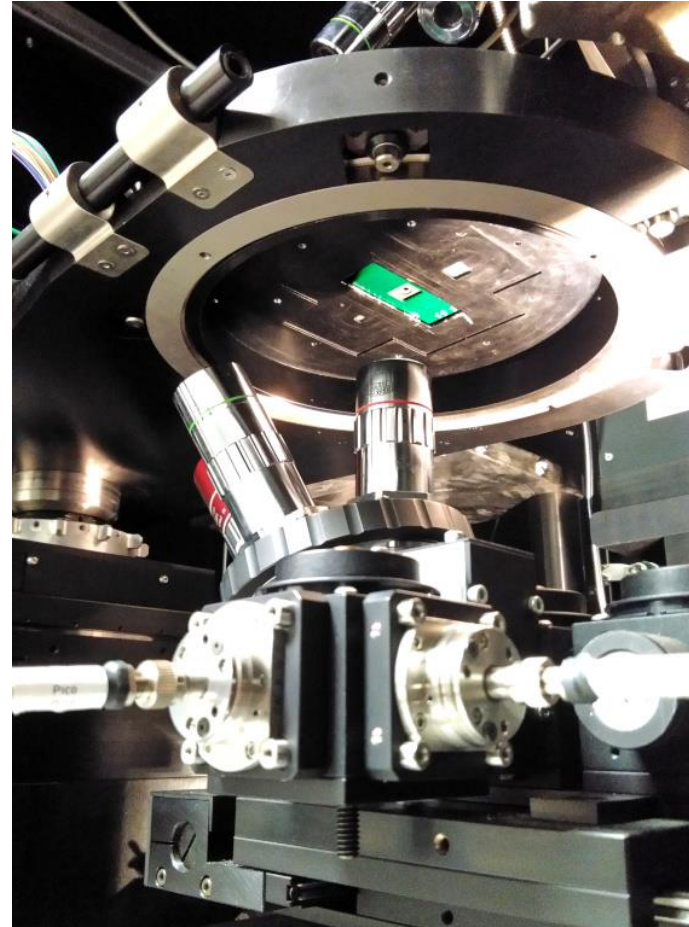
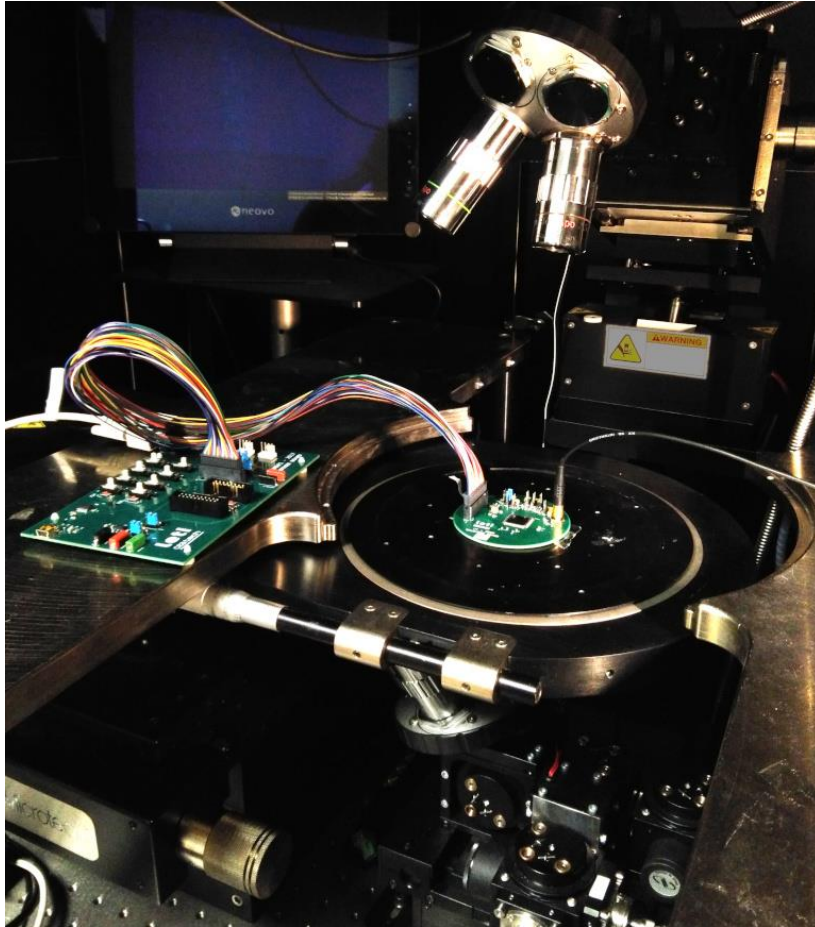
Side Channel Analysis



Fault Injection



Fault Injection



ML-KEM (close to Crystal-Kyber)

ML-KEM-512
Security level = 1
$q = 3329$
$n = 256$
$k = 2$
$\eta_1 = 3$
$\eta_2 = 2$
$d_u = 10$
$d_v = 4$

ML-KEM-768
Security level = 3
$q = 3329$
$n = 256$
$k = 3$
$\eta_1 = 2$
$\eta_2 = 2$
$d_u = 10$
$d_v = 4$

ML-KEM-1024
Security level = 5
$q = 3329$
$n = 256$
$k = 4$
$\eta_1 = 2$
$\eta_2 = 2$
$d_u = 11$
$d_v = 5$

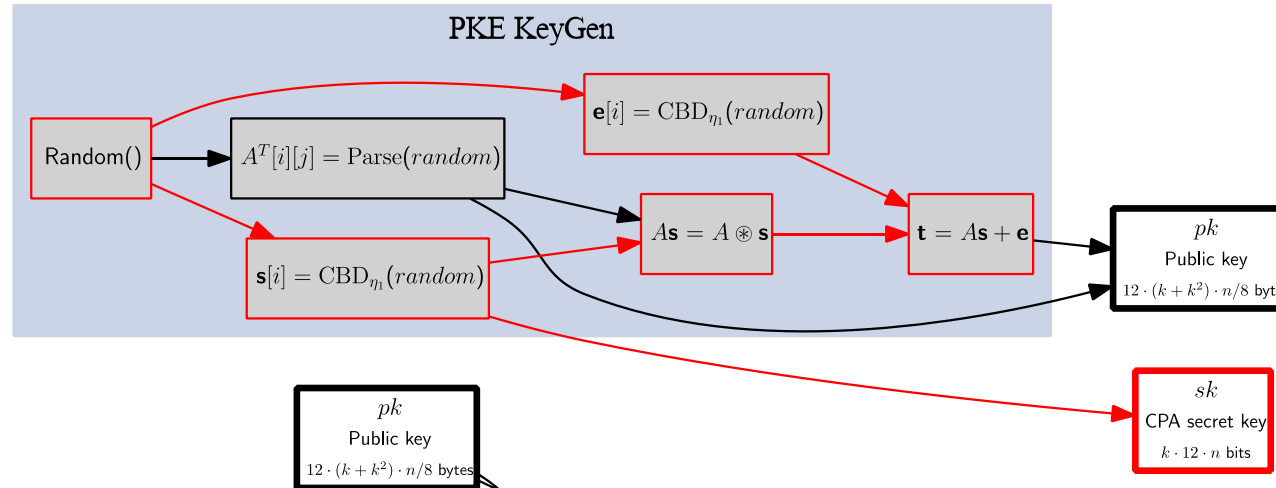
$\mathbb{Z}_q = \mathbb{Z}/q\mathbb{Z}$ (integer ring)
$R_q = \mathbb{Z}_q[X]/(X^n + 1)$ (polynomial ring, n -degree polynomial)
R_q^k (a k -dimensional vector of polynomials with polynomials in R_q)
$R_q^{k \times k}$ (module of dimension $k \times k$, k -by- k matrix of polynomials with polynomials in R_q)
$\zeta = 17$ (primitive n -th root of unity modulo q)

FIPS 203, Module-Lattice-Based Key-Encapsulation Mechanism Standard

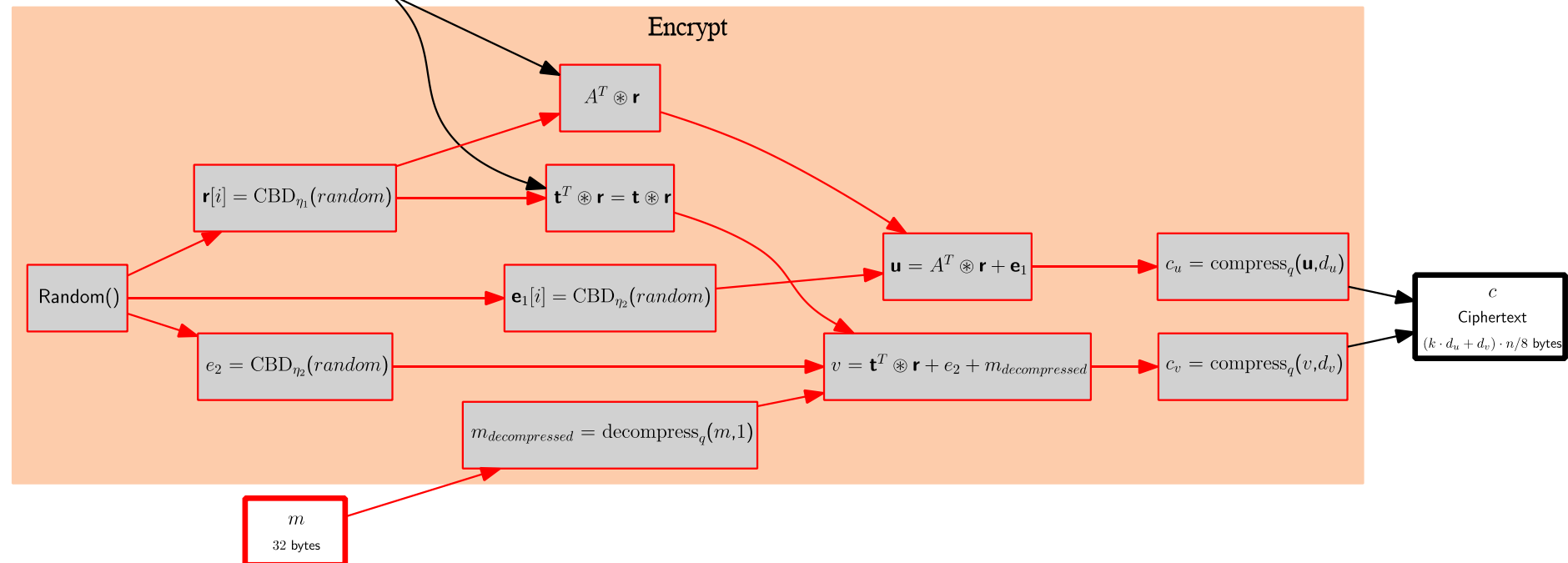
<https://doi.org/10.6028/NIST.FIPS.203>, Published August 13, 2024

Simplified PKE in ML-KEM

- Key generation

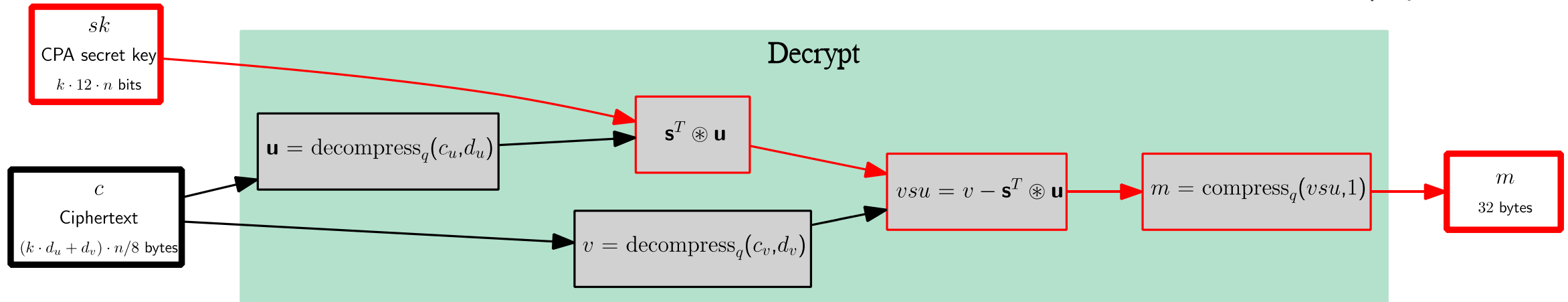
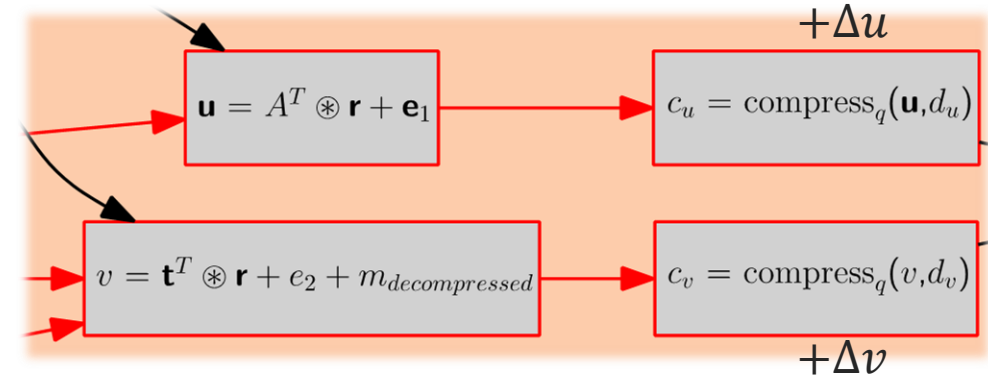
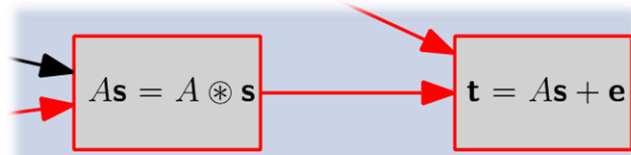


- Message Encryption



Simplified PKE in ML-KEM

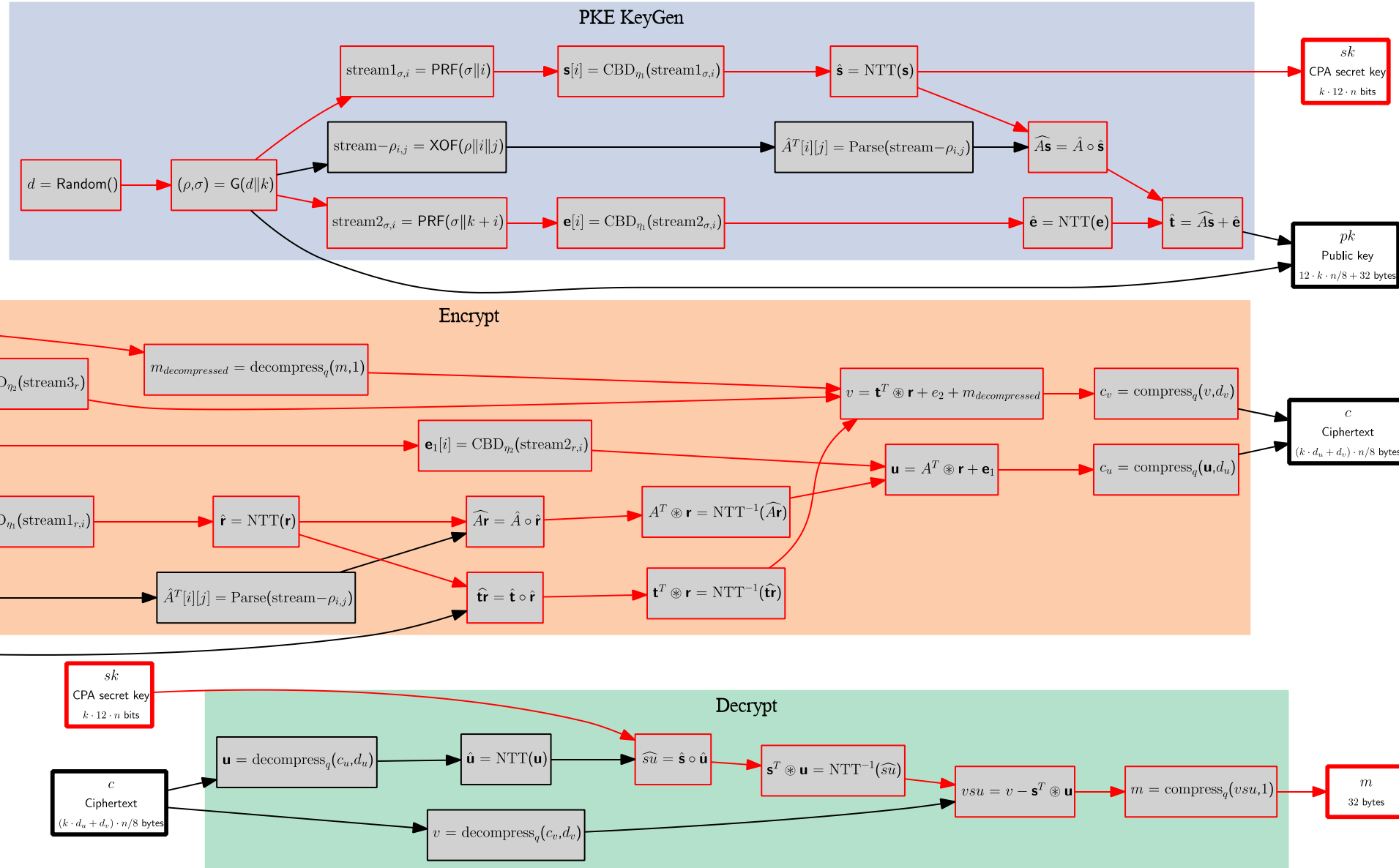
- Message decryption



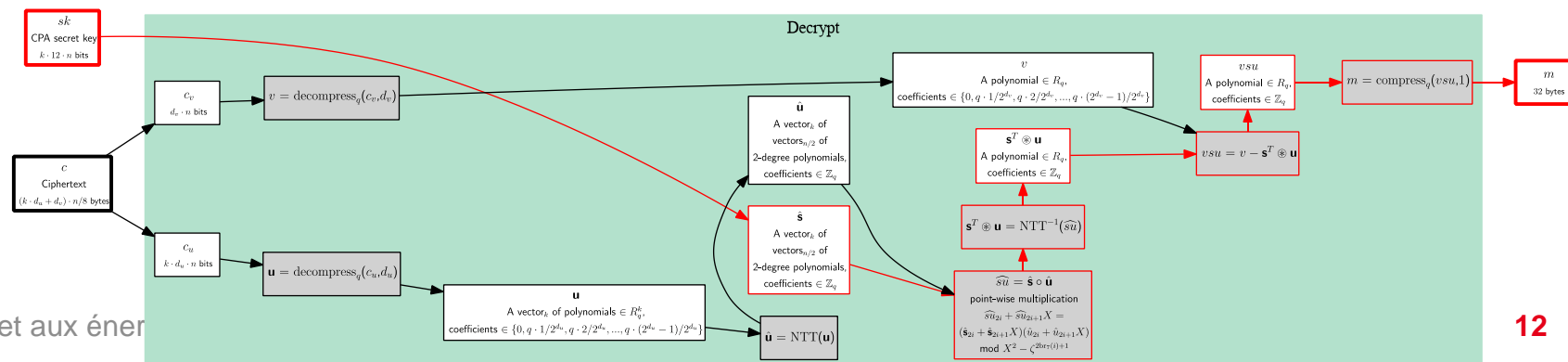
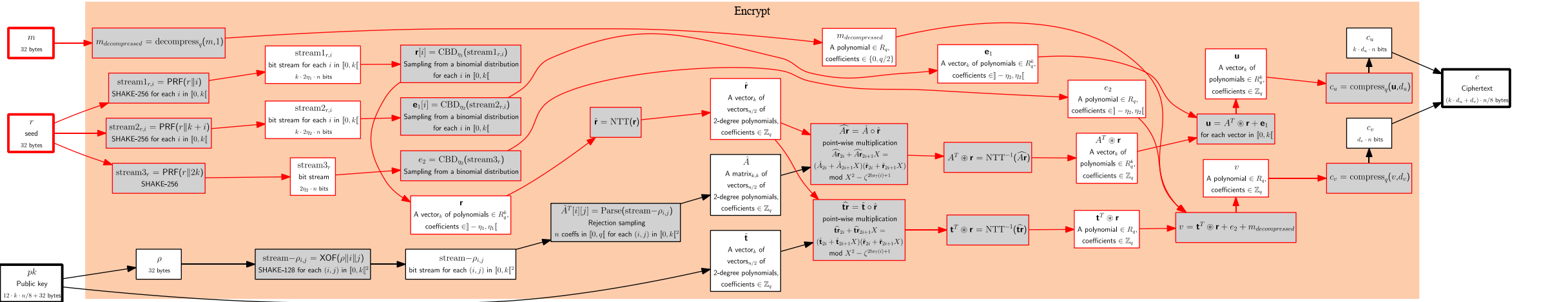
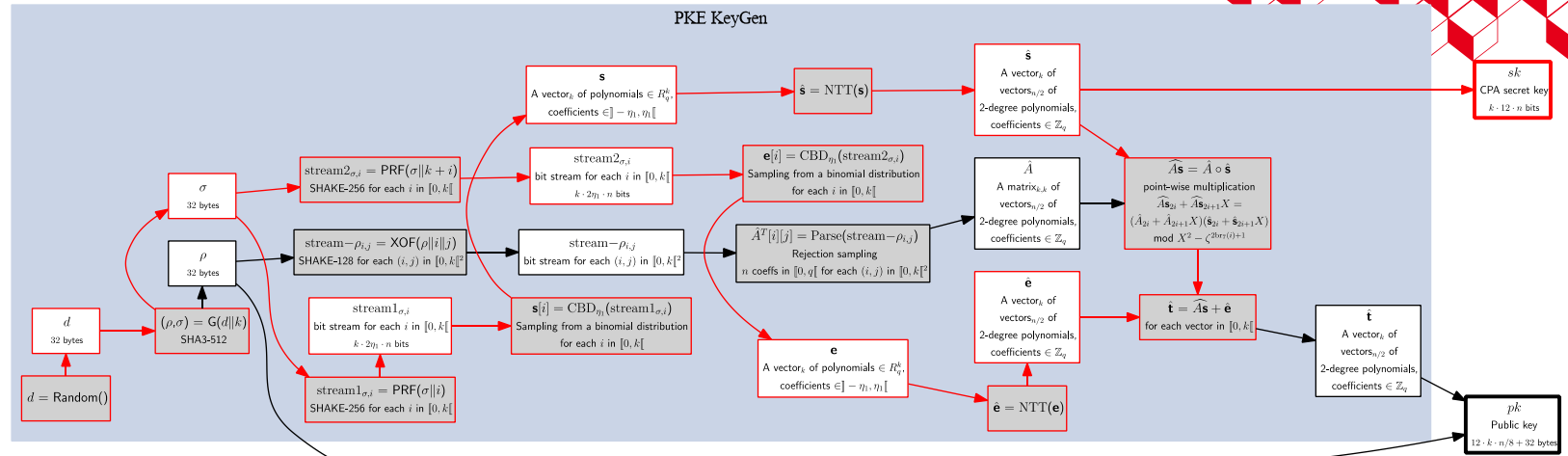
$$\begin{aligned}
 vsu &= v - s^T \otimes u \\
 &= (s^T \otimes A^T \otimes r + e^T \otimes r + e_2 + m + \Delta v) - (s^T \otimes A^T \otimes r + s^T \otimes e_1 + s^T \otimes \Delta u) \\
 &= m + e^T \otimes r + e_2 + \Delta v - s^T \otimes e_1 - s^T \otimes \Delta u \\
 &\simeq m
 \end{aligned}$$

PKE in ML-KEM

- ρ seed in KeyGen
- r seed in Encrypt
- NTT



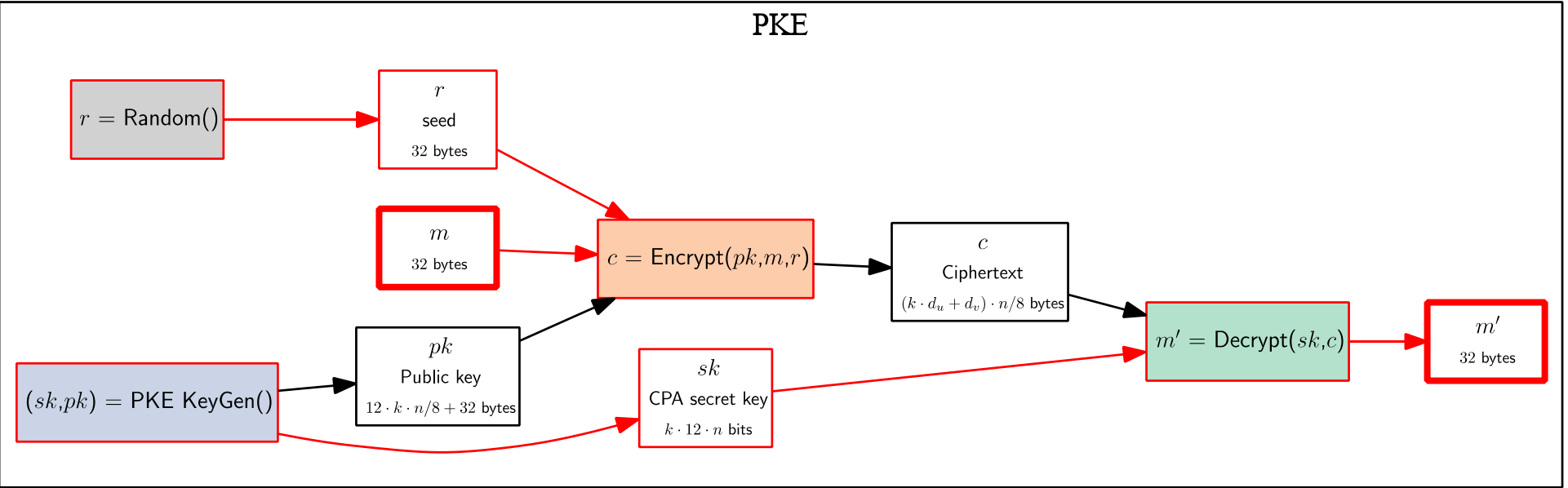
PKE in ML-KEM



PKE in ML-KEM



ML-KEM-768
Security level = 3
$q = 3329$
$n = 256$
$k = 3$
$\eta_1 = 2$
$\eta_2 = 2$
$d_u = 10$
$d_v = 4$
$\mathbb{Z}_q = \mathbb{Z}/q\mathbb{Z}$ (integer ring)
$R_q = \mathbb{Z}_q[X]/(X^n + 1)$ (polynomial ring, n -degree polynomial)
R_q^k (a k -dimensional vector of polynomials with polynomials in R_q)
$R_q^{k \times k}$ (module of dimension $k \times k$, k -by- k matrix of polynomials with polynomials in R_q)
$\zeta = 17$ (primitive n -th root of unity modulo q)



PKE = a Public-Key Encryption scheme from the MLWE problem.

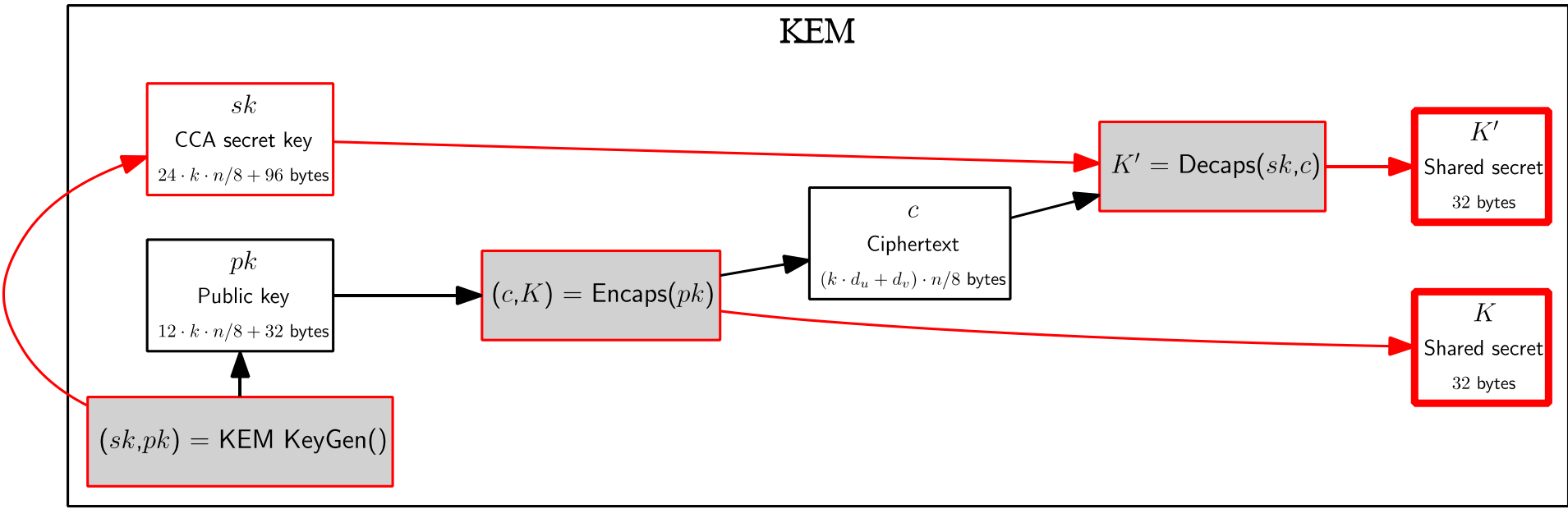
This PKE is indistinguishability under chosen plaintext attack (IND-CPA)
(under the MLWE hardness assumption)

ML-KEM (Crystal-Kyber)



ML-KEM-768
Security level = 3
$q = 3329$
$n = 256$
$k = 3$
$\eta_1 = 2$
$\eta_2 = 2$
$d_u = 10$
$d_v = 4$
$\mathbb{Z}_q = \mathbb{Z}/q\mathbb{Z}$ (integer ring)
$R_q = \mathbb{Z}_q[X]/(X^n + 1)$ (polynomial ring, n -degree polynomial)
R_q^k (a k -dimensional vector of polynomials with polynomials in R_q)
$R_q^{k \times k}$ (module of dimension $k \times k$, k -by- k matrix of polynomials with polynomials in R_q)
$\zeta = 17$ (primitive n -th root of unity modulo q)

Parameter set	Decapsulation failure rate
ML-KEM-512	$2^{-138.8}$
ML-KEM-768	$2^{-164.8}$
ML-KEM-1024	$2^{-174.8}$

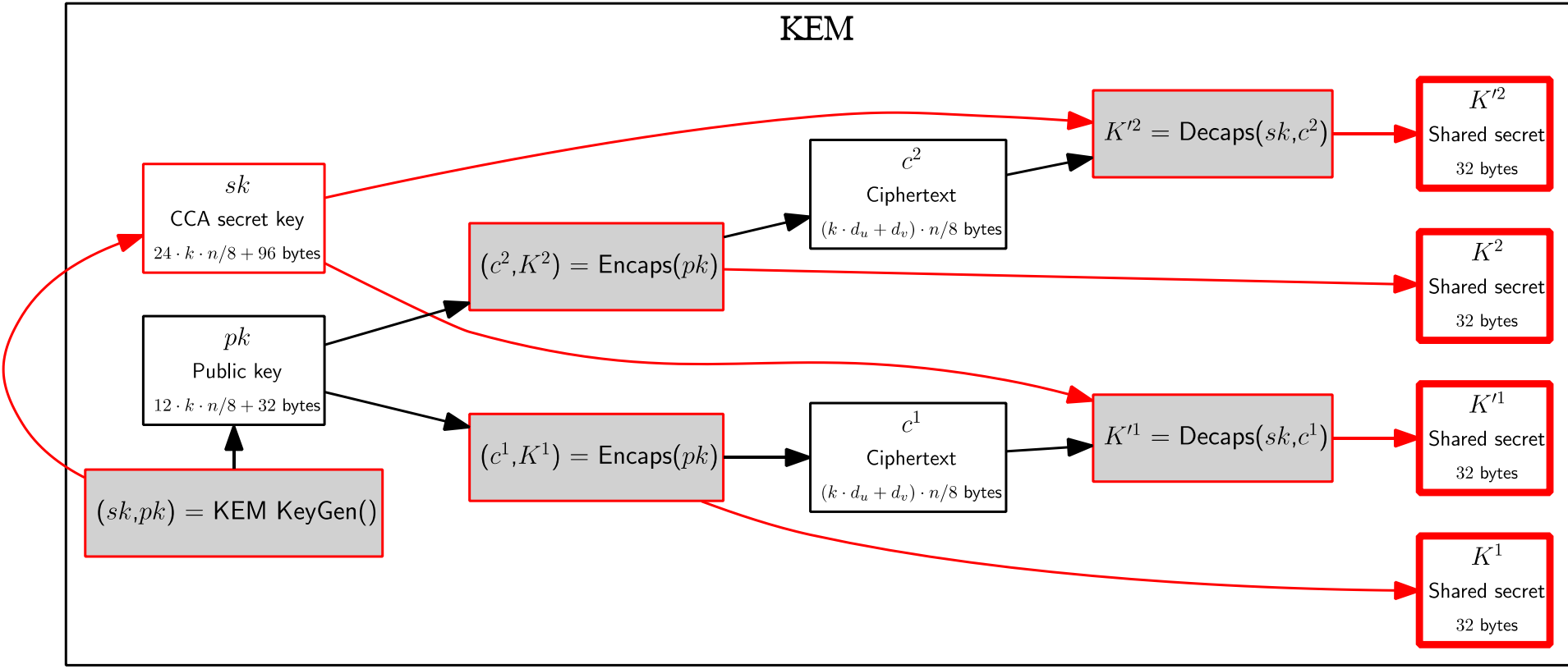


KEM = Key Encapsulation Mechanism

ML-KEM (Crystal-Kyber)



ML-KEM-768
Security level = 3
$q = 3329$
$n = 256$
$k = 3$
$\eta_1 = 2$
$\eta_2 = 2$
$d_u = 10$
$d_v = 4$
$\mathbb{Z}_q = \mathbb{Z}/q\mathbb{Z}$ (integer ring)
$R_q = \mathbb{Z}_q[X]/(X^n + 1)$ (polynomial ring, n -degree polynomial)
R_q^k (a k -dimensional vector of polynomials with polynomials in R_q)
$R_q^{k \times k}$ (module of dimension $k \times k$, k -by- k matrix of polynomials with polynomials in R_q)
$\zeta = 17$ (primitive n -th root of unity modulo q)

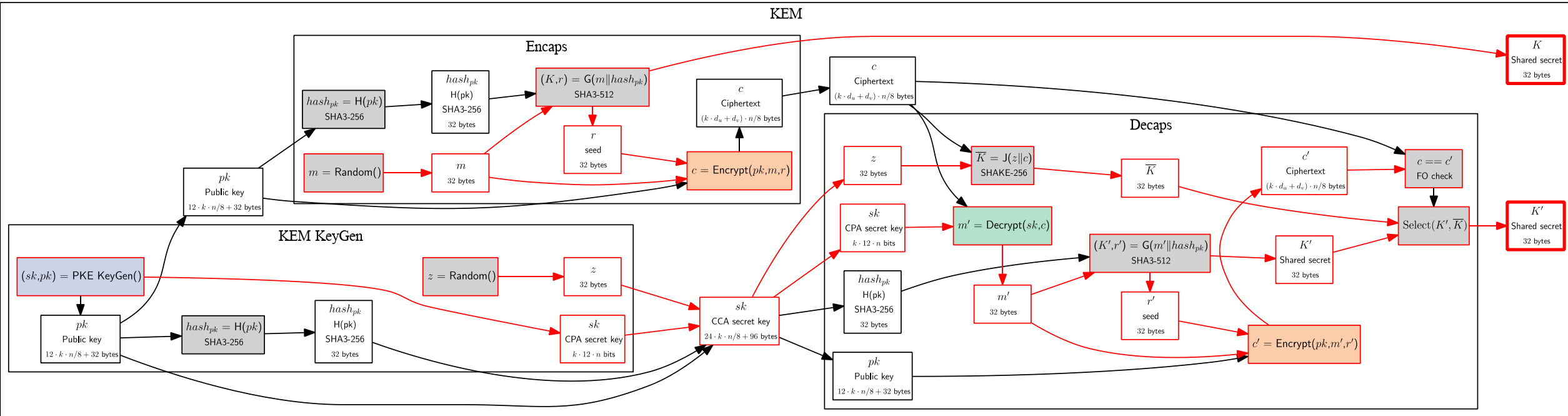


ML-KEM is indistinguishability under non-adaptative chosen ciphertext attacks (IND-CCA1).
 ML-KEM is indistinguishability under adaptative chosen ciphertext attacks (IND-CCA2).

Almeida, José Bacelar, et al. "Formally Verifying Kyber: Episode V: Machine-Checked IND-CCA Security and Correctness of ML-KEM in EasyCrypt." Annual International Cryptology Conference. Cham: Springer Nature Switzerland, 2024.



ML-KEM (Crystal-Kyber)



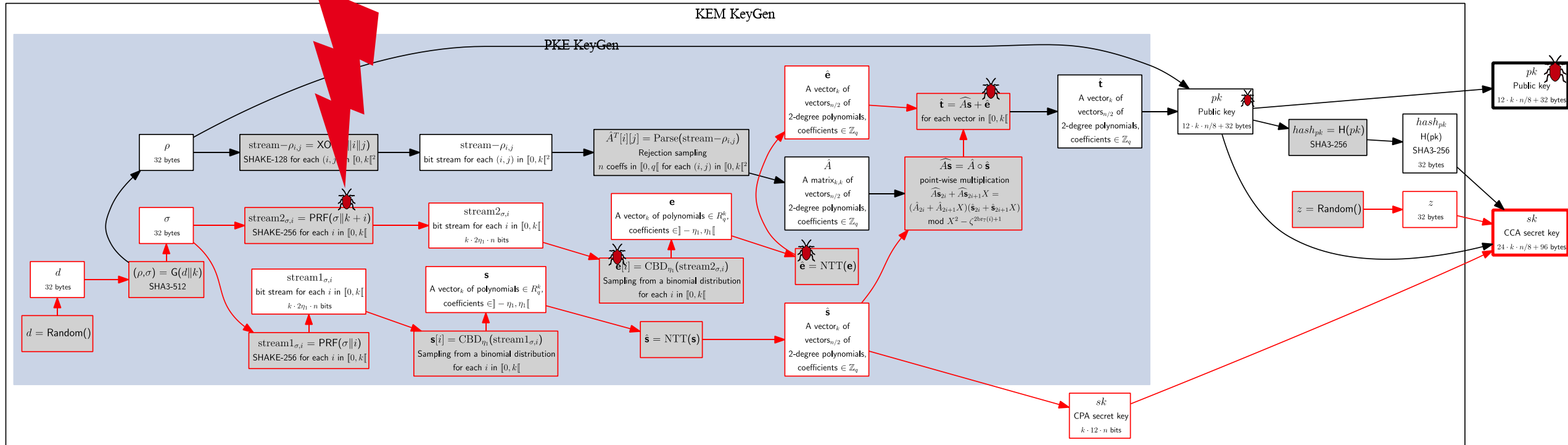
Fujisaki-Okamoto (FO) transform with implicit rejection except that the hash of the public key is fed as an additional argument into G

Fujisaki, Eiichiro, and Tatsuaki Okamoto. "Secure integration of asymmetric and symmetric encryption schemes." *Journal of cryptology* 26 (2013): 80-101.

<https://groups.google.com/a/list.nist.gov/g/pqc-forum/c/C0D3W1KoINY/m/99klvydoAwAJ>

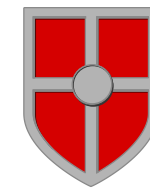
PKE KeyGen, Fault injection attack

Encrypt can also be attacked



$$t = A \circledast s + e \quad \rightarrow \quad t = A \circledast s + s \quad \rightarrow \quad s$$

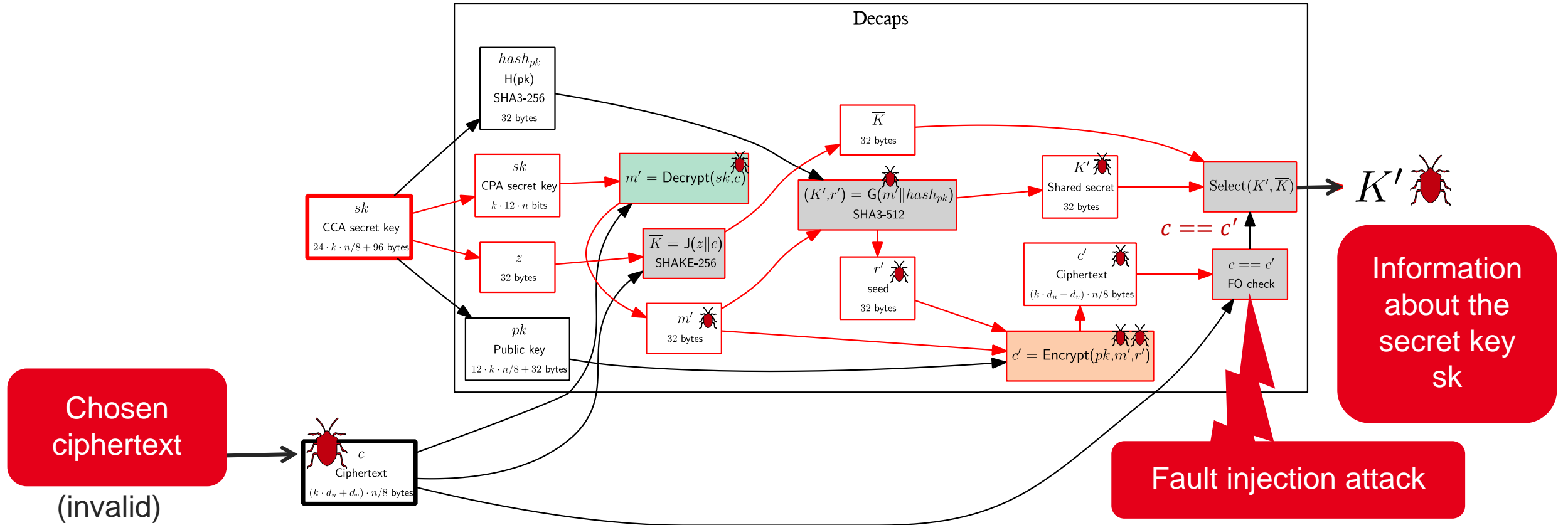
$$= (A + id) \circledast s$$



Check counter coin final value after all executions of PRF functions

Ravi, Prasanna, et al. "Number "not used" once-practical fault attack on pqm4 implementations of NIST candidates." *Constructive Side-Channel Analysis and Secure Design: 10th International Workshop, COSADE 2019, Darmstadt, Germany, April 3–5, 2019, Proceedings 10*. Springer International Publishing, 2019.
Target = STM32F407, FI = EMFI.

FO transform, Fault injection attack



Compare K' to 2 candidates \Rightarrow 1536 queries to recover sk for ML-KEM 512
 Compare K' to 2^a candidates $\Rightarrow \frac{1536}{a}$ queries to recover sk for ML-KEM 512

 Redundancy
 Ciphertext sanity check

Xagawa, Keita, et al. "Fault-injection attacks against NIST's post-quantum cryptography round 3 KEM candidates." *Advances in Cryptology—ASIACRYPT 2021: 27th International Conference on the Theory and Application of Cryptology and Information Security, Singapore, December 6–10, 2021, Proceedings, Part II 27*. Springer International Publishing, 2021.
 Target = STM32F415, FI = CW Clock glitch.

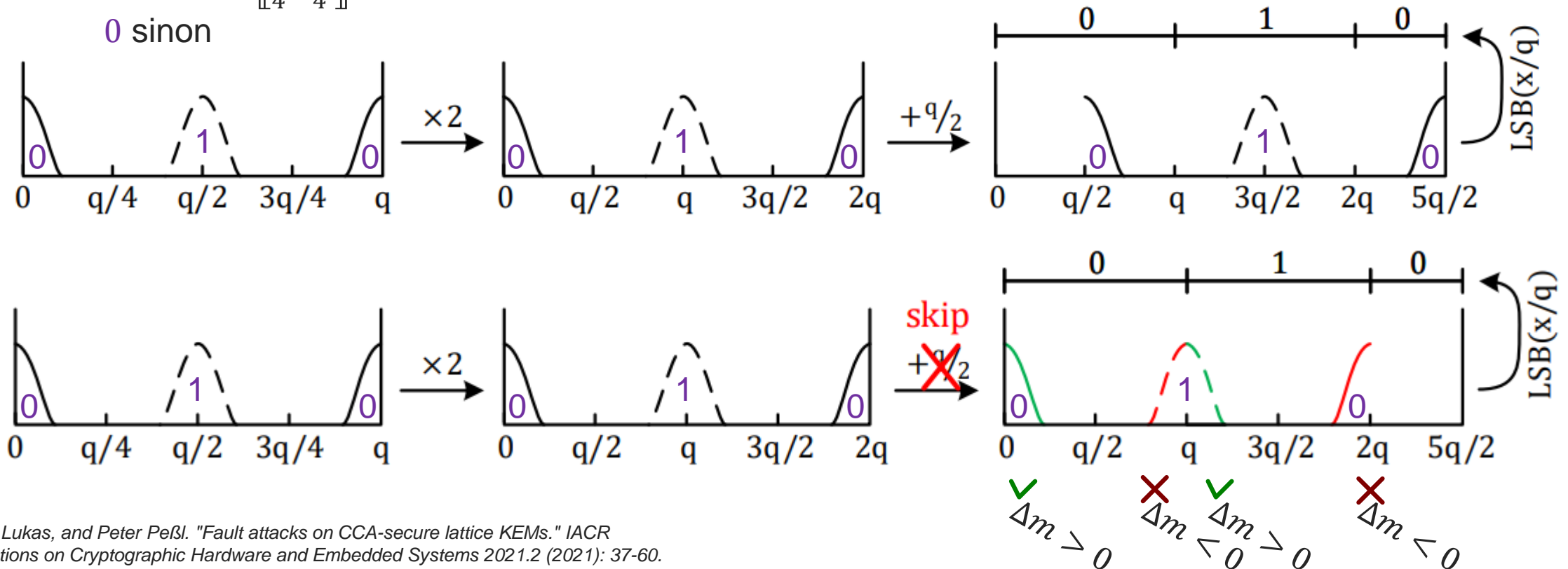
Decrypt, Fault injection attack

$$vsu = m + \Delta m \quad \Delta m = e^T \circledast r + e_2 + \Delta v - s^T \circledast e_1 - s^T \circledast \Delta u$$

$$\Delta m \in \left[-\frac{q}{4}, \frac{q}{4} \right] \text{ for valid message decoding.}$$

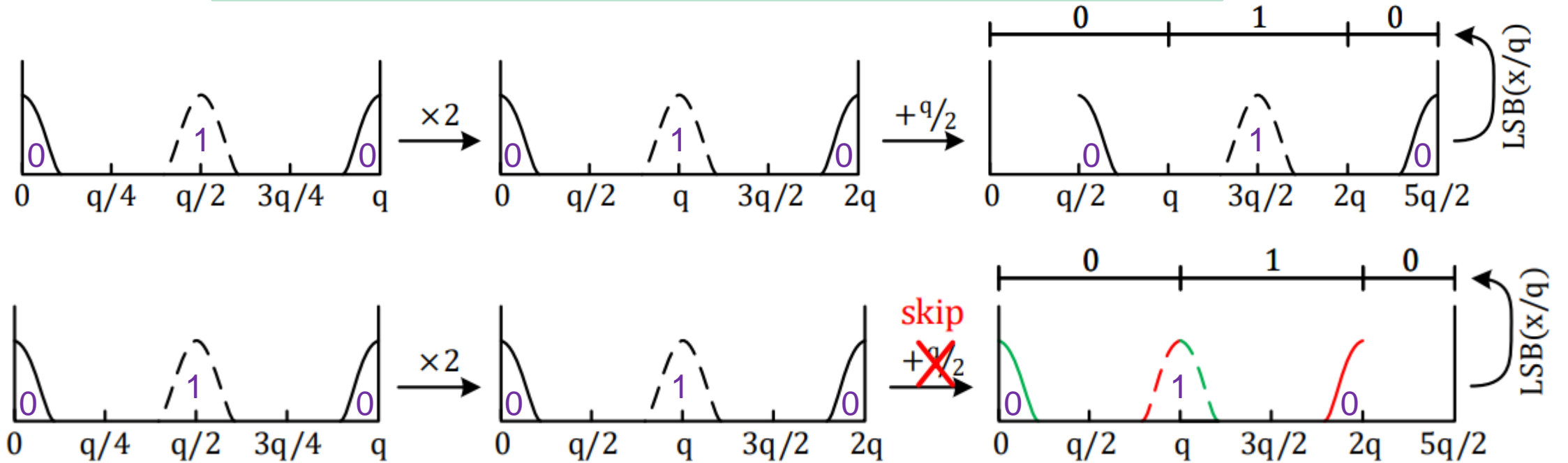
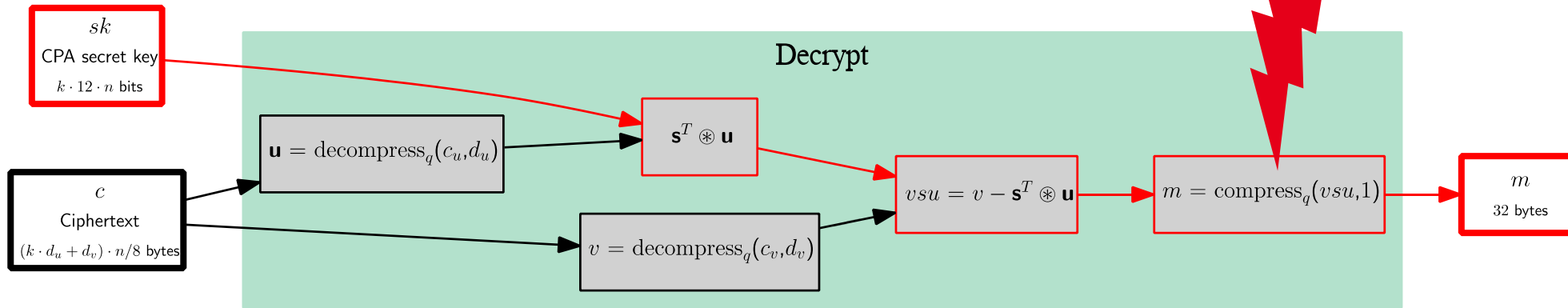
$$m[i] = 1 \text{ if } vsu \in \left[\frac{q}{4}, \frac{3q}{4} \right]$$

0 sinon



Prokop, Lukas, and Peter Peßl. "Fault attacks on CCA-secure lattice KEMs." IACR Transactions on Cryptographic Hardware and Embedded Systems 2021.2 (2021): 37-60.
Target = STM32F405, FI = CW Clock glitch.

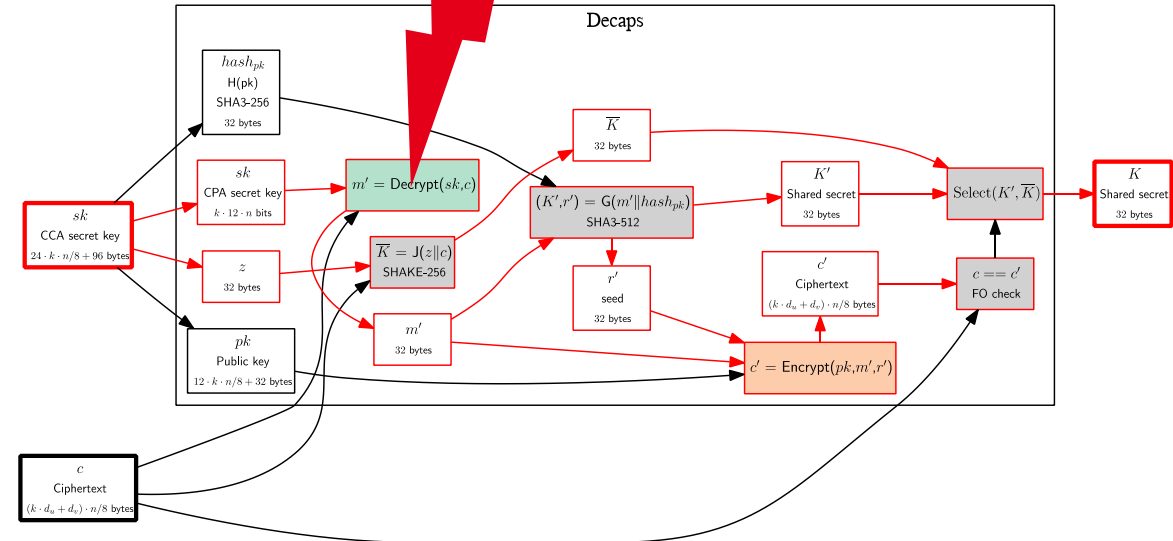
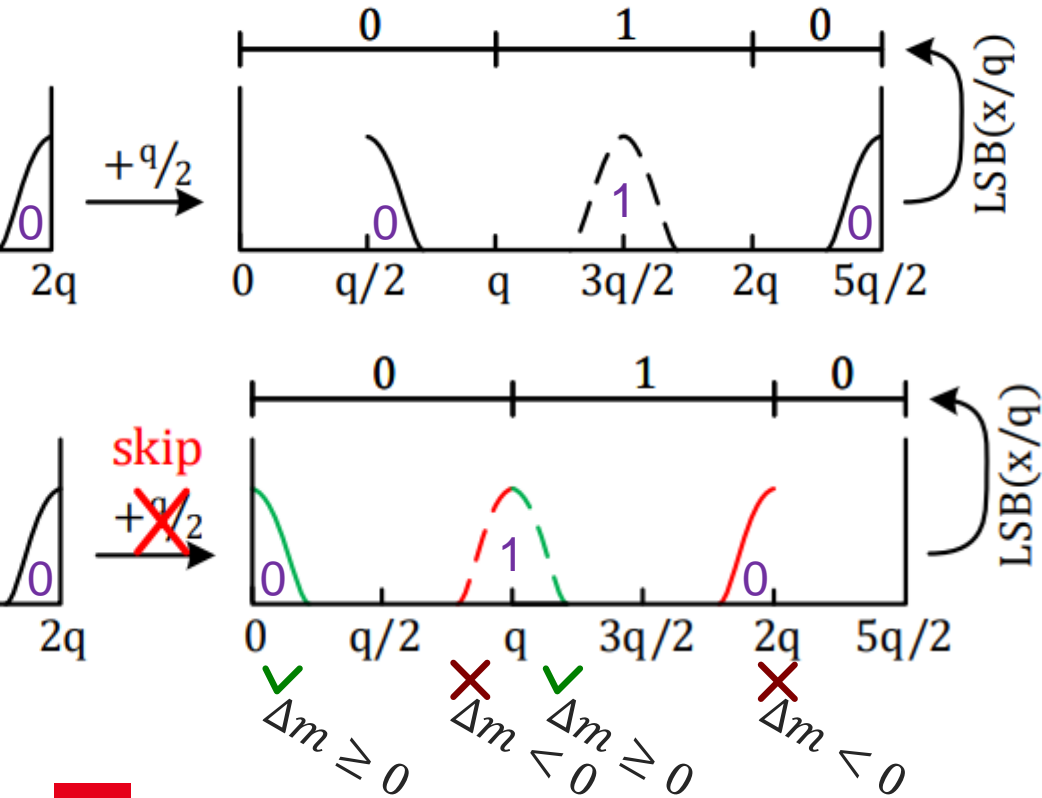
Decrypt, Fault injection attack



Prokop, Lukas, and Peter Peßl. "Fault attacks on CCA-secure lattice KEMs." *IACR Transactions on Cryptographic Hardware and Embedded Systems 2021.2* (2021): 37-60.
 Target = STM32F405, FI = CW Clock glitch.

Decrypt, Fault injection attack

$$\Delta m = e^T \odot r + e_2 + \Delta v - s^T \odot e_1 - s^T \odot \Delta u$$



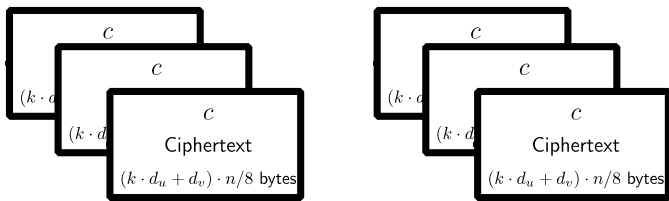
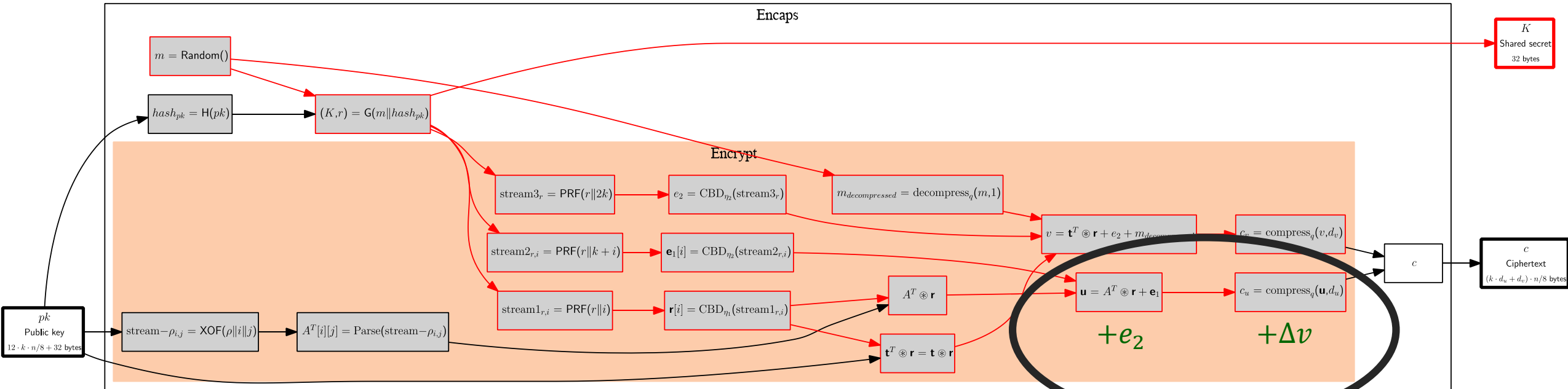
- ✓ Expected K :
→ Ineffective fault → $\Delta m \geq 0$
- ✗ Unexpected K:
→ Effective fault → $\Delta m < 0$

Prokop, Lukas, and Peter Peßl. "Fault attacks on CCA-secure lattice KEMs." IACR Transactions on Cryptographic Hardware and Embedded Systems 2021.2 (2021): 37-60. Target = STM32F405, FI = CW Clock glitch.

Decrypt, Fault injection attack



Generate valid ciphertexts with $|e_2 - \Delta v| < 10$

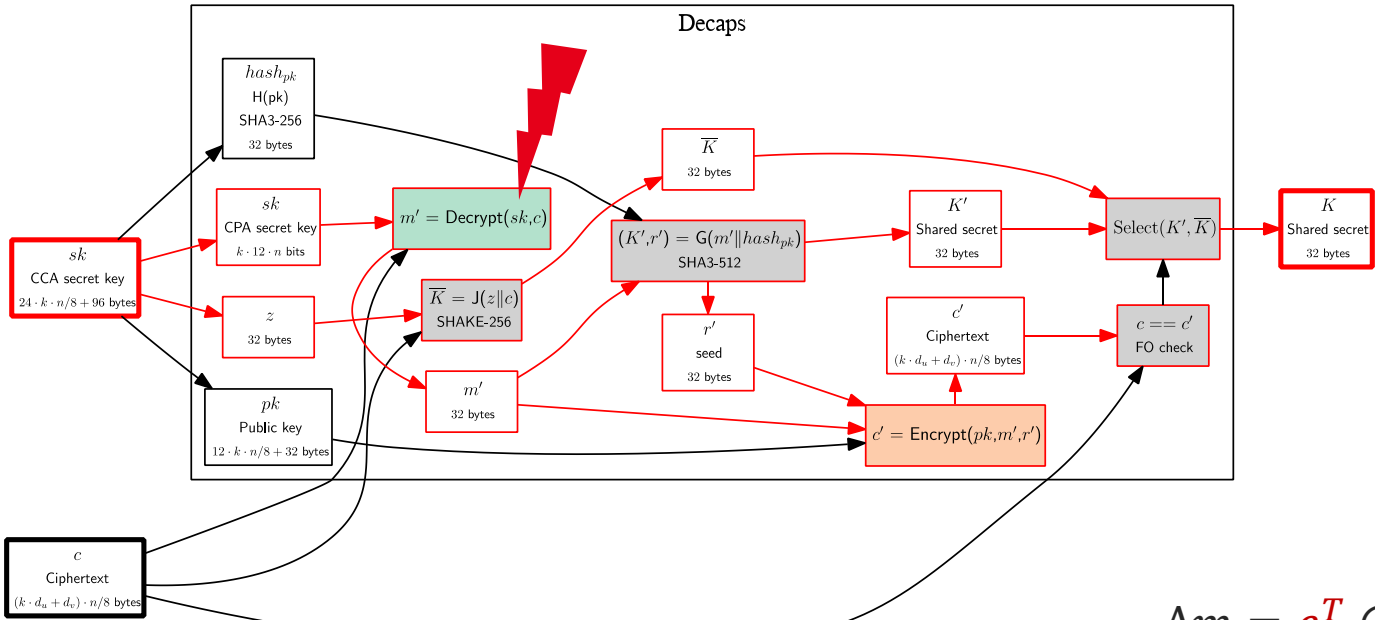
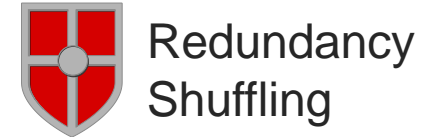


$$\Delta m = e^T \otimes r - s^T \otimes (e_1 - \Delta u) + (e_2 + \Delta v)$$

Small \Rightarrow More information about s and e in inequalities $\Delta m < 0$

Prokop, Lukas, and Peter Peßl. "Fault attacks on CCA-secure lattice KEMs." IACR Transactions on Cryptographic Hardware and Embedded Systems 2021.2 (2021): 37-60. Target = STM32F405, FI = CW Clock glitch.

Decrypt, Fault injection attack



$$\Delta m = e^T \circledast r - s^T \circledast (e_1 - \Delta u) + e_2 + \Delta v$$

✓ Expected K :

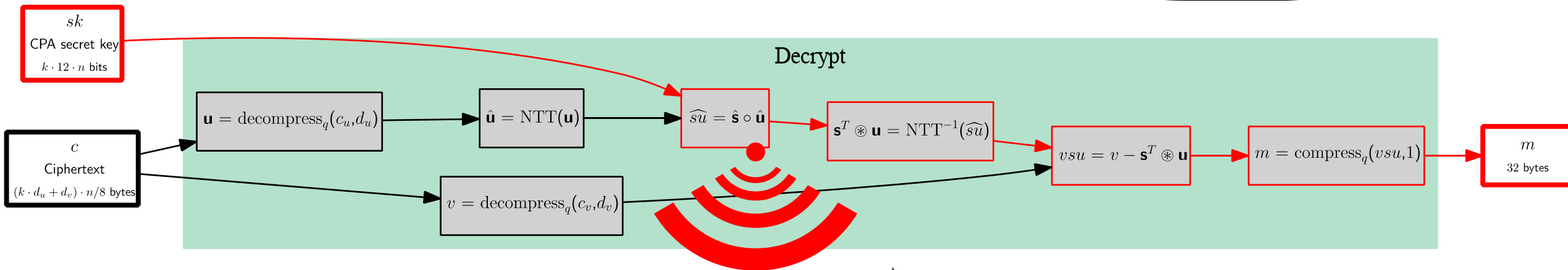
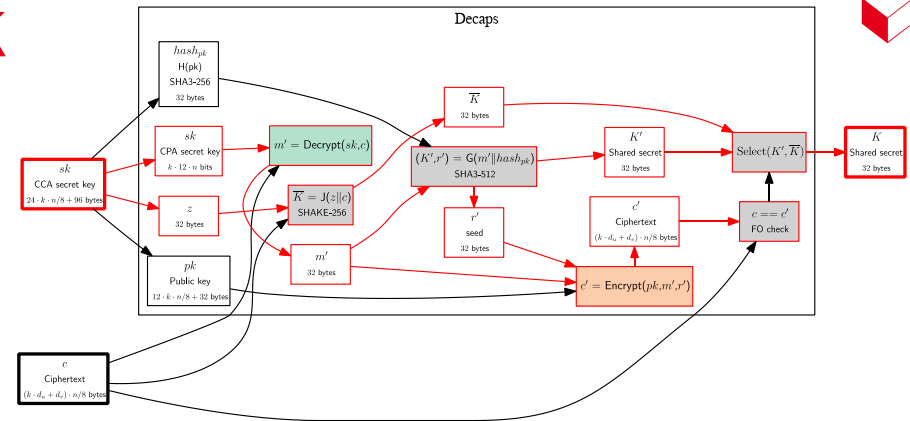
→ Ineffective fault → $\Delta m \geq 0$ → Filter these inequalities that could be unsuccessful fault injection.

✗ Unexpected K:

→ Effective fault → $\Delta m < 0$ → Solve the system of linear inequalities with belief-propagation techniques (60k or 125k Kyber512 decapsulations to recover s and e).

Prokop, Lukas, and Peter Peßl. "Fault attacks on CCA-secure lattice KEMs." IACR Transactions on Cryptographic Hardware and Embedded Systems 2021.2 (2021): 37-60. Target = STM32F405, FI = CW Clock glitch.

Decrypt, CPA side-channel attack



Leakage on \hat{s} \Rightarrow Correlation Power Analysis (CPA) attack
200 traces to recover \hat{s}

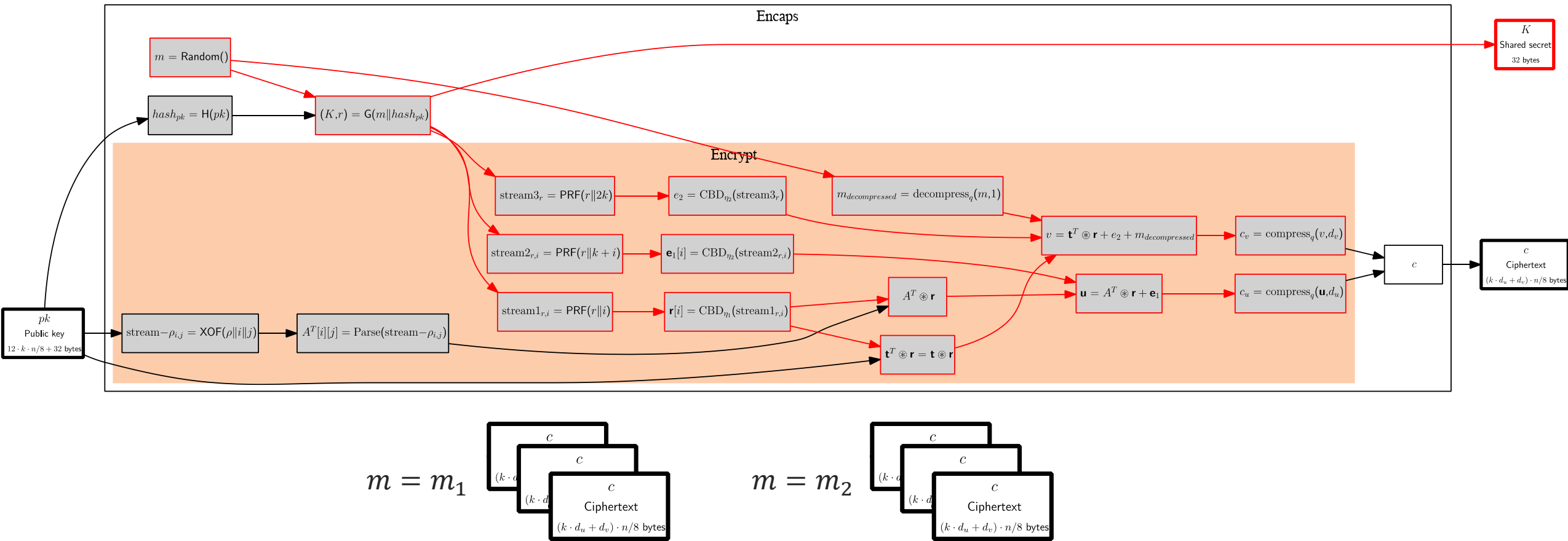


Mujdei, Catinca, et al. "Side-channel analysis of lattice-based post-quantum cryptography: Exploiting polynomial multiplication." ACM Transactions on Embedded Computing Systems 23.2 (2024): 1-23.
Target = STM32F415, SCA = CW Power CPA.

FO-Transform, Template side-channel attack

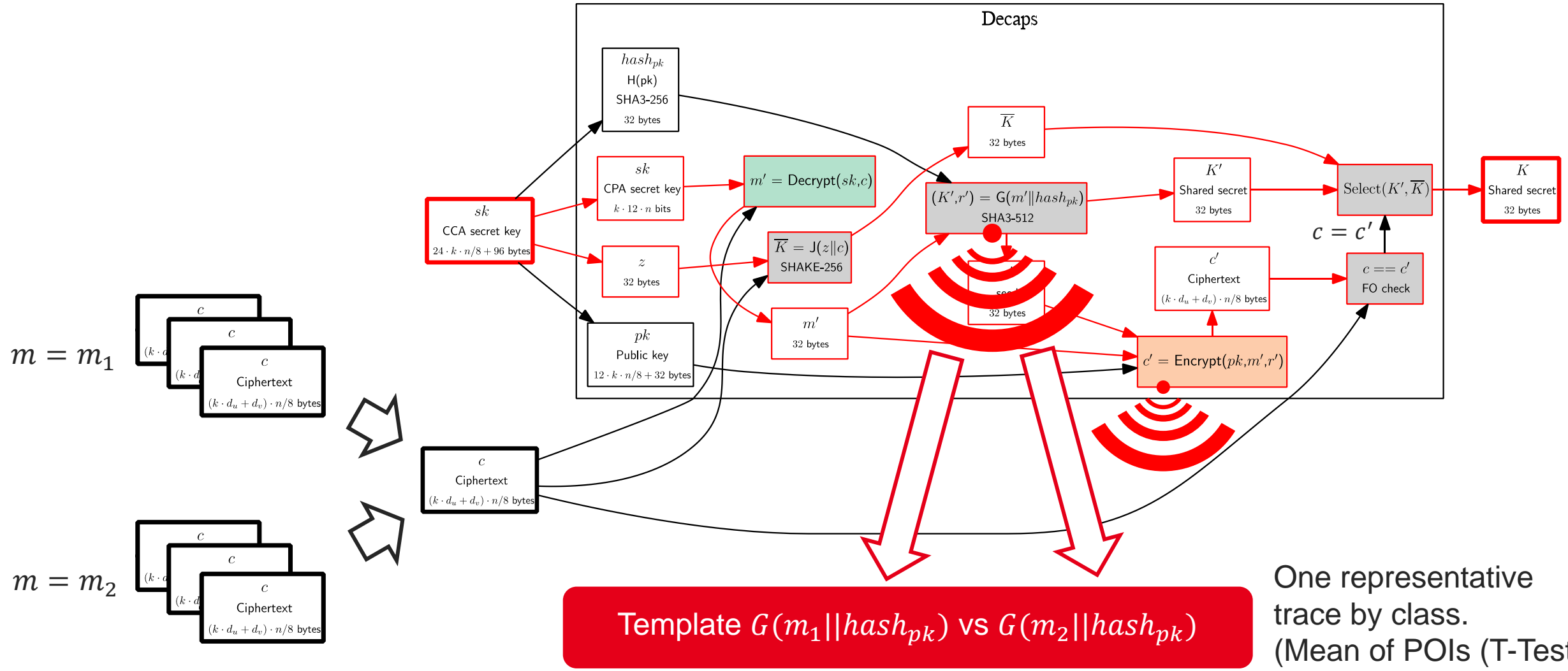


Build two classes of valid ciphertexts ($m = m_1, m = m_2$)



Ravi, Prasanna, et al. "Generic side-channel attacks on CCA-secure lattice-based PKE and KEMs." IACR transactions on cryptographic hardware and embedded systems (2020): 307-335.
Target = STM32F407, SCA = EM CPA.

FO-Transform, Template side-channel attack



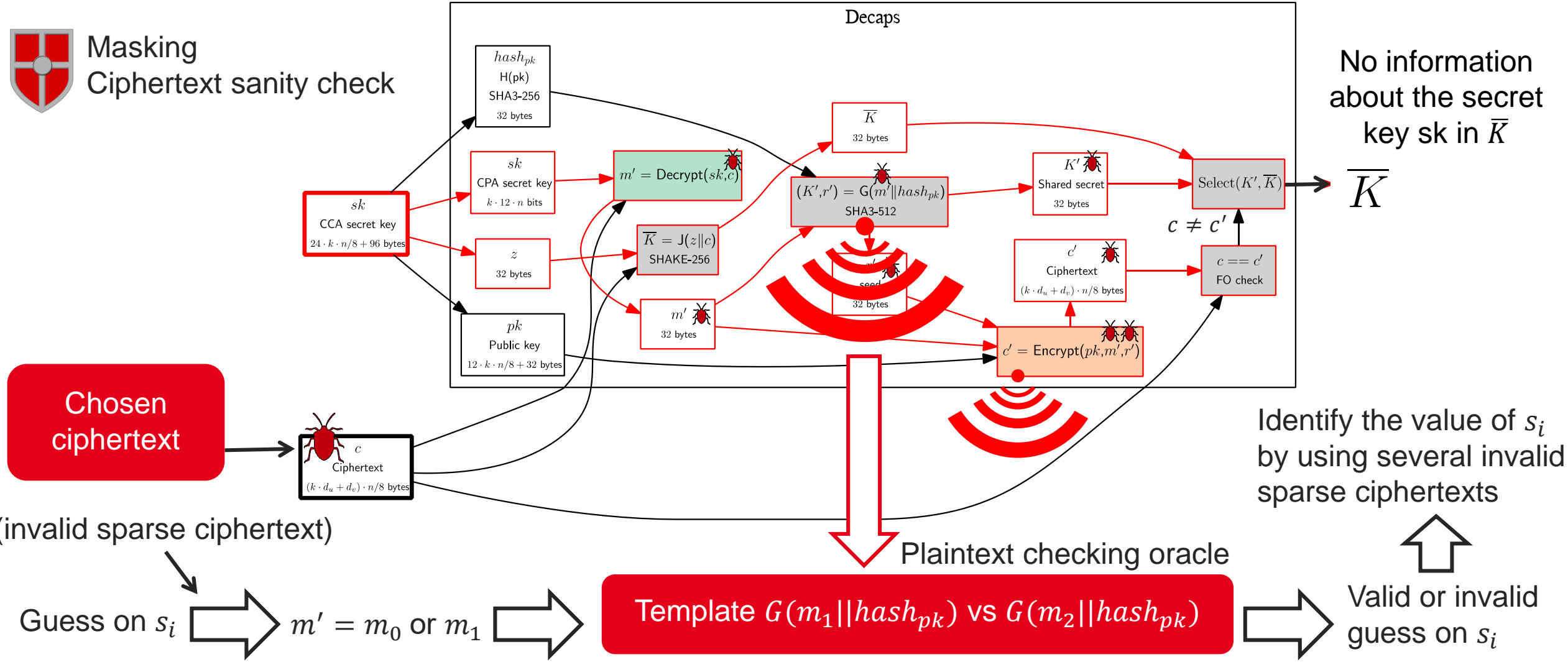
One representative trace by class. (Mean of POIs (T-Test))

Ravi, Prasanna, et al. "Generic side-channel attacks on CCA-secure lattice-based PKE and KEMs." IACR transactions on cryptographic hardware and embedded systems (2020): 307-335. Target = STM32F407, SCA = EM CPA.

FO-Transform, Template side-channel attack



Masking
Ciphertext sanity check



No information about the secret key sk in \bar{K}

\bar{K}

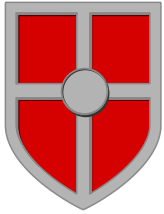
Identify the value of s_i by using several invalid sparse ciphertexts

Valid or invalid guess on s_i

Ravi, Prasanna, et al. "Generic side-channel attacks on CCA-secure lattice-based PKE and KEMs." IACR transactions on cryptographic hardware and embedded systems (2020): 307-335. Target = STM32F407, SCA = EM CPA.

Conclusion

- Countermeasures must be combined to design secure ML-KEM implementation:



- Masking
- Shuffling
- Redundancy
- Sanity checks

- This overview is an introduction to some existing SCA and FI attacks on ML-KEM implementations:

- Warning: this overview is not an exhaustive one

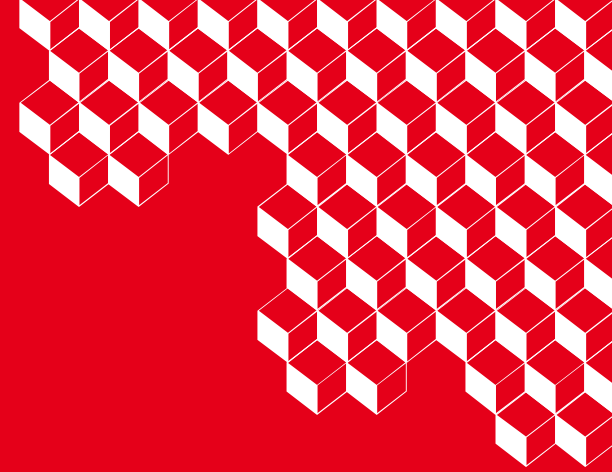
Examples:

- *Hermelink, Julius, Peter Pessl, and Thomas Pöppelmann. "Fault-enabled chosen-ciphertext attacks on Kyber." Progress in Cryptology–INDOCRYPT 2021: 22nd International Conference on Cryptology in India, Jaipur, India, December 12–15, 2021, Proceedings 22. Springer International Publishing, 2021.*
- *Ravi, Prasanna, et al. "Fiddling the twiddle constants-fault injection analysis of the number theoretic transform." IACR Transactions on Cryptographic Hardware and Embedded Systems (2023)*
- ...

- Warning: there are attacks against implementation with countermeasures

Examples:

- **Soft-Analytical Side Channel Attack on NTT to recover secret from masked ML-KEM implementations**
Pessl, Peter, and Robert Primas. "More practical single-trace attacks on the number theoretic transform." Progress in Cryptology–LATINCRYPT 2019: 6th International Conference on Cryptology and Information Security in Latin America, Santiago de Chile, Chile, October 2–4, 2019, Proceedings 6. Springer International Publishing, 2019.
- *Qiao, Zehua, et al. "When NTT Meets SIS: Efficient Side-channel Attacks on Dilithium and Kyber." Cryptology ePrint Archive (2023).*
- ...



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