Side-Channel and Fault Attacks in Modern Lattice-Based Cryptography

Mündliche Prüfung – Julius Hermelink

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Prüfer:	Prof. Dr. Christof Paar	(MPI-SP)
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The Quantum Threat

Quantum computers threaten currently used asymmetric cryptography.

We have to assume that:

- Large-scale quantum computer break commonly used asymmetric schemes.
- Adversaries: harvest now, decrypt later.

Therefore, we need:

- Post-quantum asymmetric cryptography.
- Most pressingly key exchanges.

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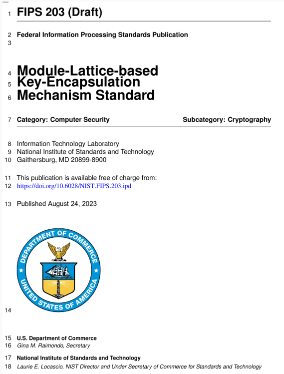

FIPS 203 (Draft)

Federal Information Processing Standards Publication

Module-Lattice-based Key-Encapsulation Mechanism Standard

Category: Computer Security **Subcategory: Cryptography**

Information Technology Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899-8900

This publication is available free of charge from:
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Published August 24, 2023

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NIST started a standardization process in 2016.

- Fourth round ongoing.
- Four candidates already selected.
- Three are lattice-based.
- Kyber selected as KEM (Kyber $\mapsto$ ML-KEM).

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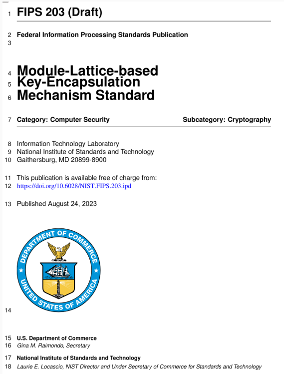
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ML-KEM used in Signal, Chrome, iMessage, ...

NIST draft standard, `https://nvlpubs.nist.gov/nistpubs/FIPS/NIST.FIPS.203.ipd.pdf`, accessed 16/02/2024; applications: see [Aut23, Kre23, EA24].

Attacks on Embedded Devices

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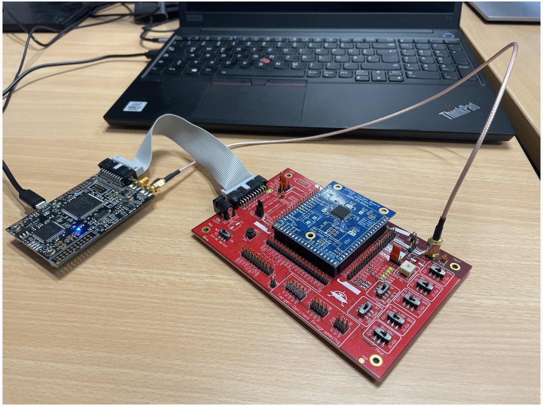

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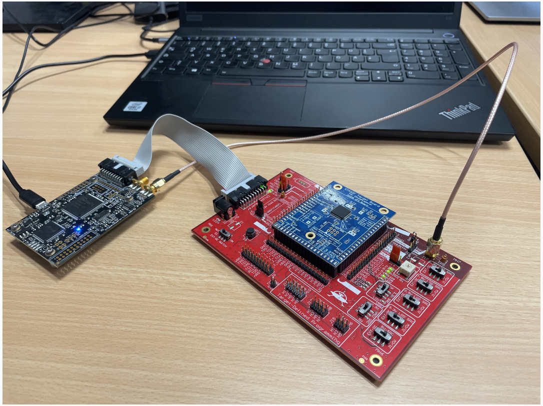

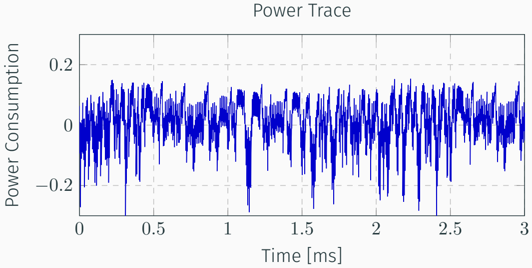

Research Objective

Lattice-Based Cryptography uses different building blocks.

- Different underlying hard problems.
- Different multiplications (e.g., using number theoretic transforms).
- Error correction to recover message from noisy coefficients.
- Construction from PKE using FO-transforms to achieve IND-CCA security.
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Research Question 1

The number theoretic transform (NTT):

- Enables fast multiplication in several lattice-based schemes.
- Used at multiple points in all routines of ML-KEM.
- Inverse NTT processes data depending on the secret key during decryption.
- Previous work established (inverse) NTT as target for side-channel attacks.
- However, required noise levels limit attacks when targeting secret key.

RQ: To what extent is the number theoretic transform vulnerable to side-channel analysis.

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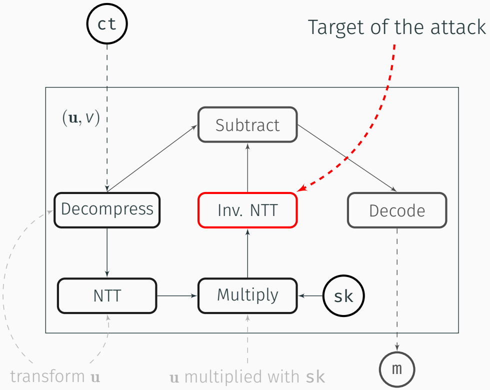
Chosen-Ciphertext k-Trace Attacks – Idea



Previous work [PPM17, PP19]:

- Template attack on inv. NTT; then belief propagation.
- However, cannot target secret key with high noise tolerance.

Decryption as shown on the left:

- Ciphertext components are decompressed.
- Component is multiplied with secret.
- Results fed into the inv. number theoretic transform.

Attack strategy: Reduce entropy using compressible NTT-sparse chosen ciphertext.

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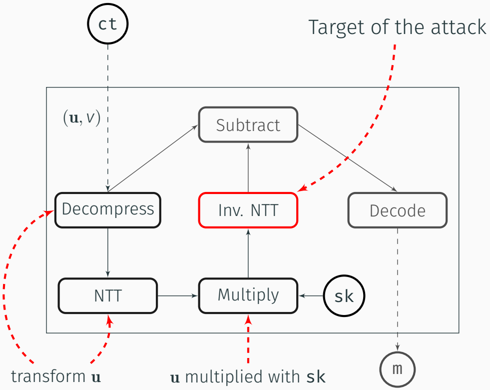

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Chosen-Ciphertext k-Trace Attacks

Our attack strategy for increased noise tolerance:

For targeted subkeys:

- Formulate as lattice problem.
- Run lattice reduction.
- Obtain compressible NTT-sparse `ct`.

For each `ct`:

- Record trace for `ct`.
- Obtain distributions for intermediates.
- Run belief propagation; obtain subkeys.

Using the subkeys:

- Formulate key recovery using subkeys as lattice problem.
- Run lattice reduction.
- Obtain full key.

Lattice reduction is computationally expensive and slow but done offline.

Mike Hamburg, **Julius Hermelink**, Robert Primas, Simona Samardjiska, Thomas Schamberger, Silvan Streit, Emanuele Strieder, and Christine van Vredendaal. "Chosen Ciphertext k-Trace Attacks on Masked CCA2 Secure Kyber". In: *IACR Transactions on Cryptographic Hardware and Embedded Systems* 2021.4 (2021), pp. 88–113

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Adapting Belief Propagation to Counter Shuffling of NTTs

Real-world attacks have to take countermeasures into account.

Important classes of countermeasures:

- Masking circumvented.
- Hiding prevents these attacks.

Ravi et al. [RPBC20] (ascending security):

- Fine shuffling
- Coarse block shuffling
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We propose two techniques against hiding:

- Fine shuffling: Shuffle node adapts factor depending on processed information.
- Coarse shuffling: Extended attacker model and matching algorithm.

Adaptation to hiding countermeasures for belief-propagation-based attacks.

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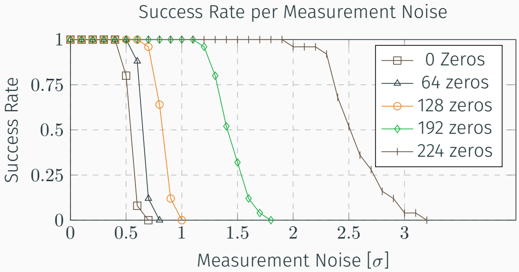
Evaluation in the leakage models provided by previous work [PPM17, PP19].



Attack	Secret Key	Noise Tolerance	Traces	Hiding considered
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This work	Yes	$\sigma \leq 1.7$ (3.1)	1-8	Yes

Noise tolerance increased from $\sigma \leq 0.6$ to $\sigma \leq 1.7$ ($\sigma \leq 3.1$).

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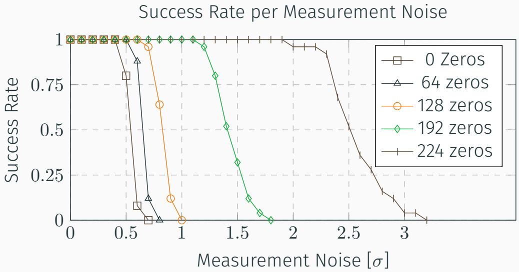

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Learning with errors schemes recover the message from noisy coefficients:

- Observation whether introduced error causes failure: leaks information.
- Fujisaki-Okamoto (FO) transform achieves IND-CCA2 security.

Previous attacks:

- CCA to potentially cause failure; observe using SCA on comparison [GJN20, BDH+21].
- Or use fault against decoder to potentially cause failure and observe outcome [PP21].
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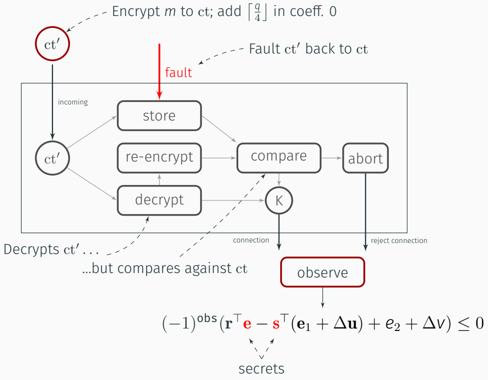
Introduce error through chosen ciphertext, then correct with fault.



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- Allows for unreliable fault; attack surface over most of the execution time; may only target public data.

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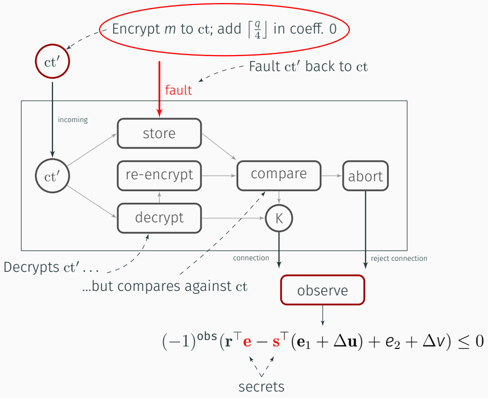

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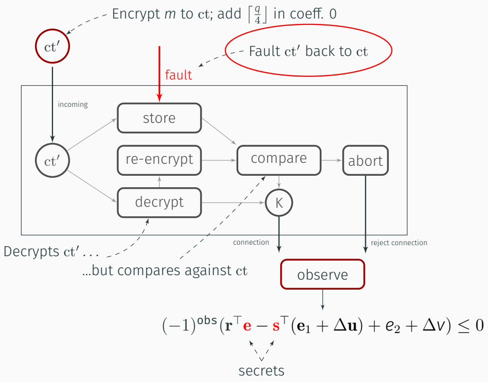

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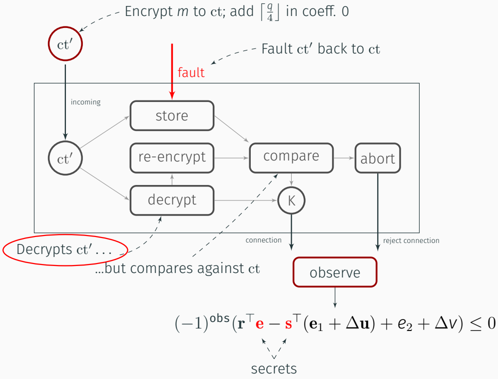

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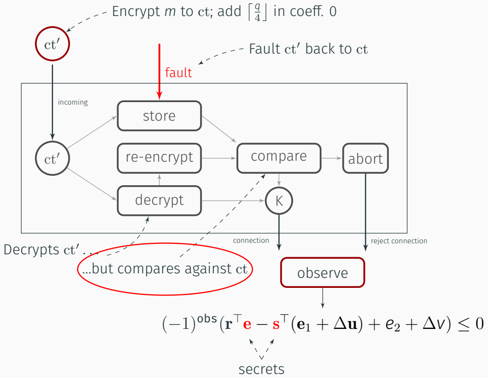

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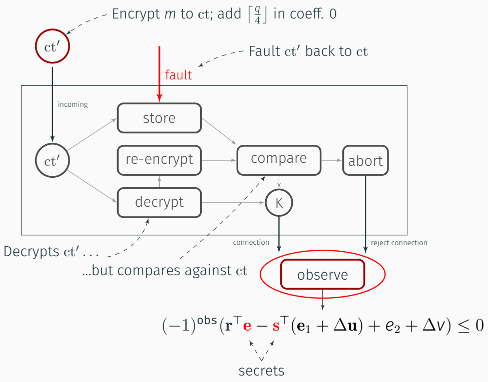

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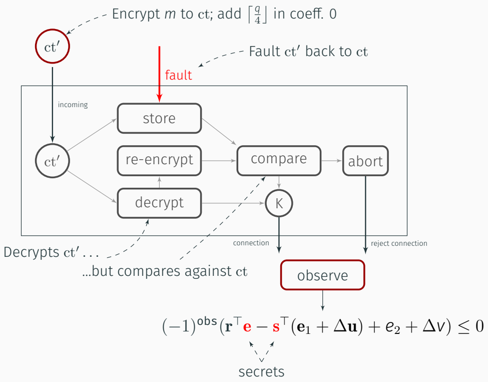

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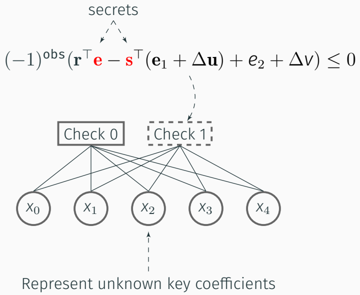
Fault-Enabled Chosen-Ciphertext Attacks – BP

We propose solving decryption failure inequalities using belief propagation.



Belief propagation inspired by [PP21]:

- Check nodes represent inequalities.
- Variable nodes represent unknown coefficients.
- Priors are binomial distributions of secrets.

Requires fewer inequalities while being more computationally efficient.

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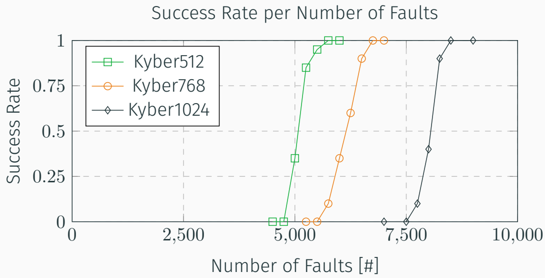

Attack	Type	Point of Attack	Requirement/Robustness
[GJN20]	Timing	Comparison	Non-constant time
[BDH+21]	SCA	Comparison	Leaking comparison
[PP21]	Fault	Decoding	Unprotected decoding
[DHP+22]	SCA	Comparison	Max. first order protection
[Del22]	Fault	Multiple	Unreliable/Imprecise fault
[Wei22]	SCA/ML	Multiple	Defeats 1th order masking
[FKK+22]	Rowhammer	Key Generation	KeyGen Failure Boosting
This work [HPP21]	Fault	Multiple	Unreliable fault

Allows for very unreliable fault, enlarges attack surface, only targets public data.

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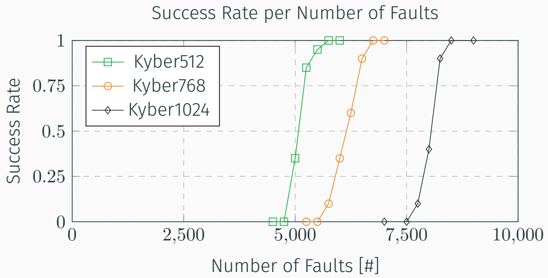

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[GJN20]	**Timing**	**Comparison**	**Non-constant time**
[BDH+21]	**SCA**	**Comparison**	**Leaking comparison**
[PP21]	**Fault**	**Decoding**	**Unprotected decoding**
[DHP+22]	SCA	Comparison	Max. first order protection
[Del22]	Fault	Multiple	Unreliable/Imprecise fault
[Wei22]	SCA/ML	Multiple	Defeats 1th order masking
[FKK+22]	Rowhammer	Key Generation	KeyGen Failure Boosting
This work [HPP21]	Fault	Multiple	Unreliable fault

Allows for very unreliable fault, enlarges attack surface, only targets public data.

Julius Hermelink, Peter Pessl, and Thomas Pöppelmann. "Fault-Enabled Chosen-Ciphertext Attacks on Kyber". In: *Progress in Cryptology - INDOCRYPT 2021 - 22nd International Conference on Cryptology in India, Jaipur, India, December 12-15 , 2021, Proceedings*. Ed. by Avishek Adhikari, Ralf Küsters, and Bart Preneel. Vol. 13143. Lecture Notes in Computer Science. Springer, 2021, pp. 311–334

Research Question 3

Decryption failures leak information in form of inequalities:

- Exploited in wide variety of attacks including ours.
- Particularly hard to mitigate.
- Our attack strategy improved by [Del22], further enlarged attack surface.

Attacks require recovery method to solve for secret key:

- Partial information not considered; no security estimates.
- Error resistance increases #inequalities.
- General problem: combine belief propagation and algebraic methods?

RQ: Which techniques allow for key recovery from partially leaked decryption failure information?

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Security Estimates for Error-Tolerant Key Recovery

Decryption failures in LWE leak information in form of inequalities.

Several methods to obtain secret from inequalities exist:

Method	Inequalities	Error Resistant	Estimates
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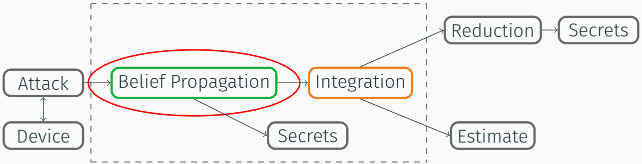

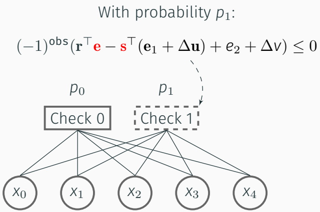

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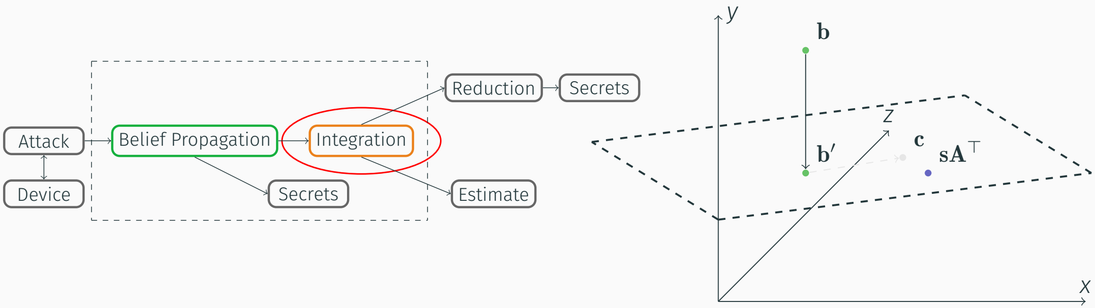

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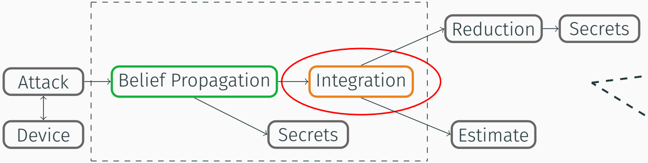

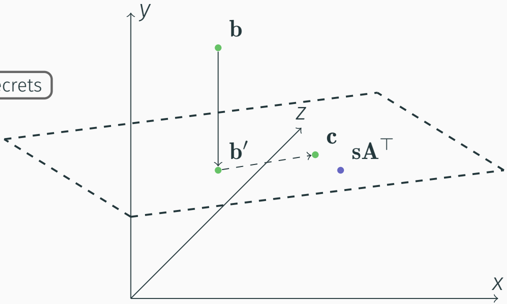

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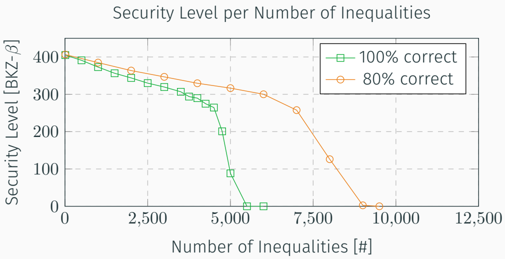

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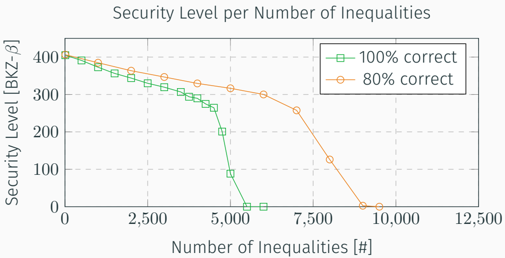

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Contributions

NIST is standardizing ML-KEM – a lattice-based scheme.

Our work provides:

- Improvement on the state of the art in side-channel and fault attacks on lattice-based schemes.
- Attack strategies against lattice-based schemes enabling future attacks (e.g., [Del22]).
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- Extended assessment on vulnerabilities of major building blocks of modern lattice-based key encapsulation mechanisms.

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Publications

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Adapting Belief Propagation – Results

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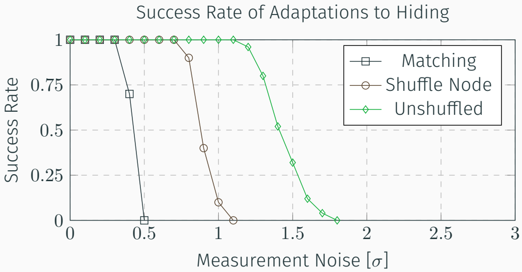

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- Attacks not fully prevented by hiding countermeasures.
- However, noise tolerance reduced.
- Strongest from of shuffling protects requires vast computational resources.
- Large-scale adversaries might even circumvent coarse full shuffling.

Several hiding countermeasures can be circumvented; protected NTT still vulnerable.

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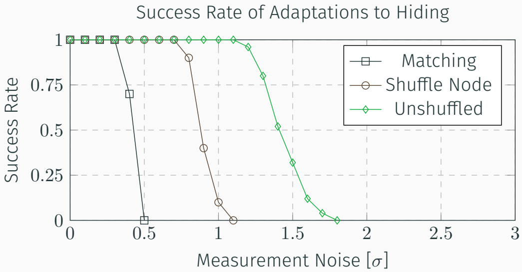

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