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

Julius Hermelink

Max Planck Institute for Security and Privacy

Years at Infineon

It has been more than 10 years since I started at Infineon ☺

- 2014-2020: Studying mathematics.
- 2014: Started at Infineon at DES.
- 2018: Switched to CCS/Thomas Pöppelmann.
- 2020: Begin of PhD in cooperation with UniBW M.
- 2023: Started at MPI-SP in Bochum
- 2024: Finished PhD

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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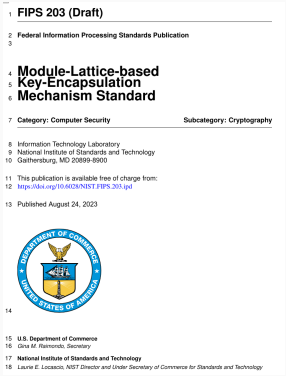
The NIST Standardization Process

NIST is in the process of standardizing post-quantum cryptography.



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

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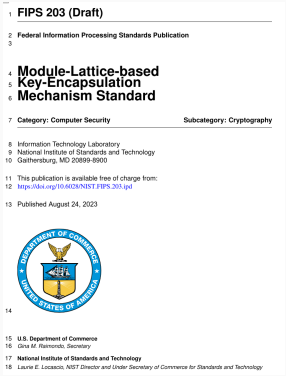

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ML-KEM used in Signal, Chrome, iMessage, ...

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Attacks on Embedded Devices

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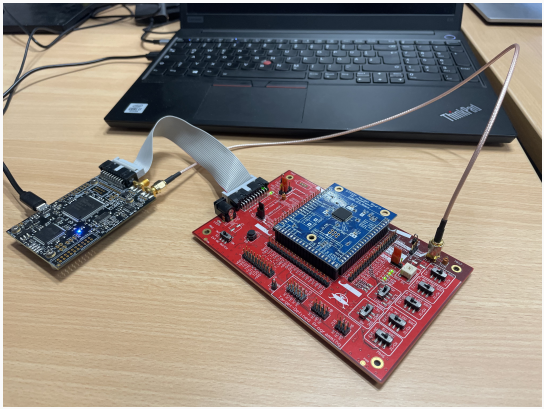

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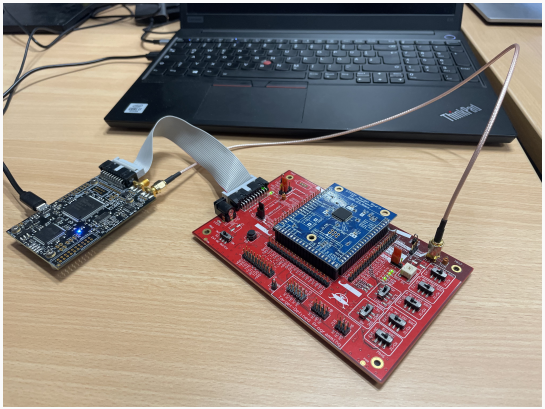

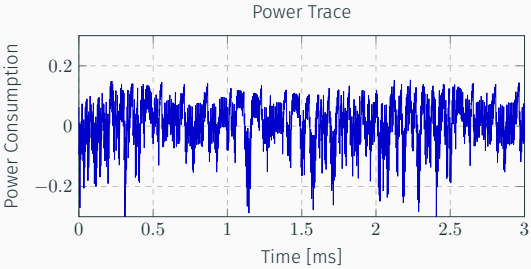

Side-Channel Attacks on LBC

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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Which new vulnerabilities in regard to side-channel and fault attacks does this open up?

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The NTT

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.
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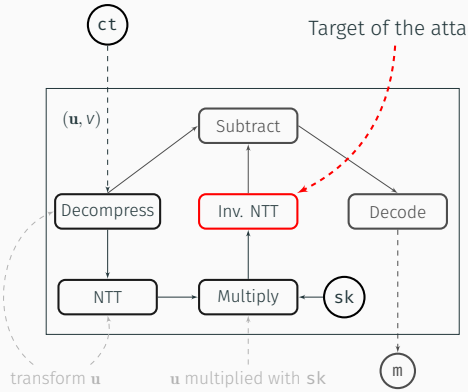
Chosen-Ciphertext k-Trace Attacks – Idea



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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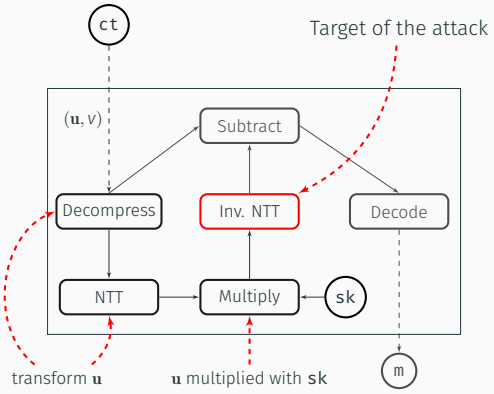

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Our attack strategy for increased noise tolerance:

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
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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.

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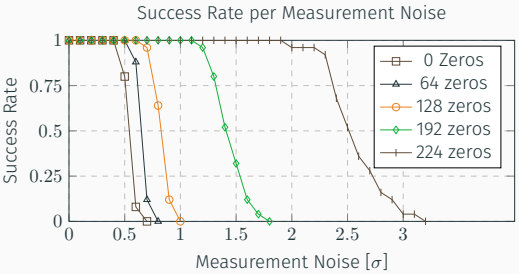

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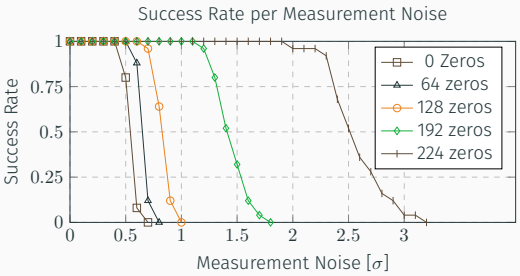

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Targeting the FO-Transform

Learning with errors schemes recover the message from noisy coefficients:

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Previous attacks:

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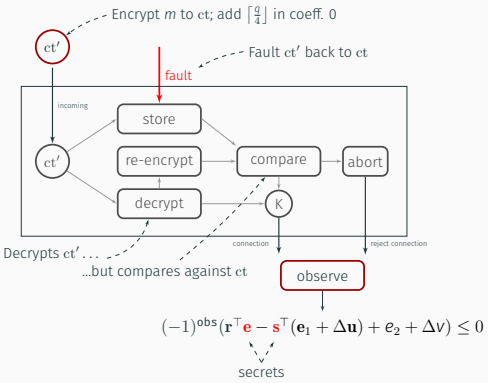

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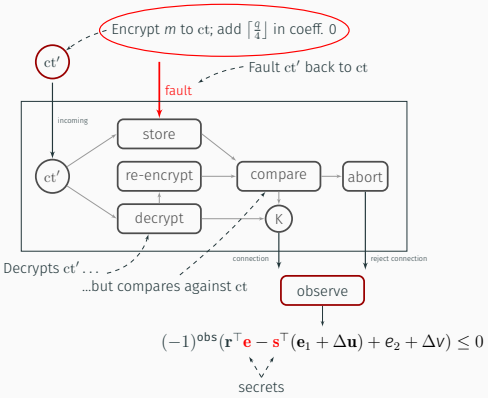

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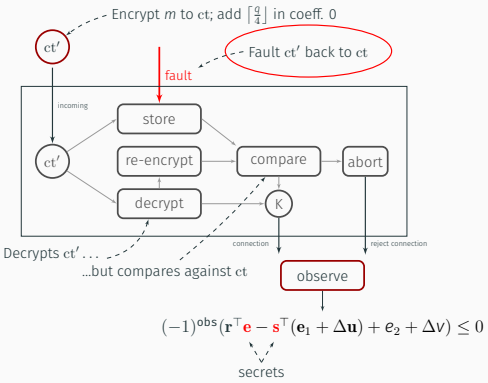

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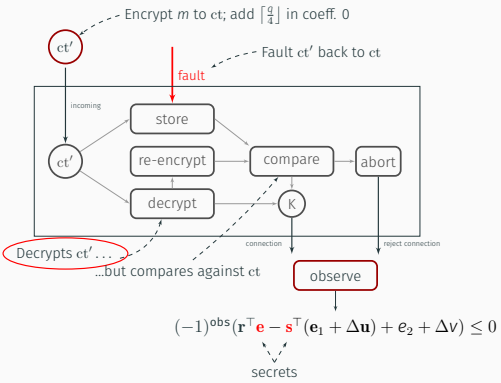

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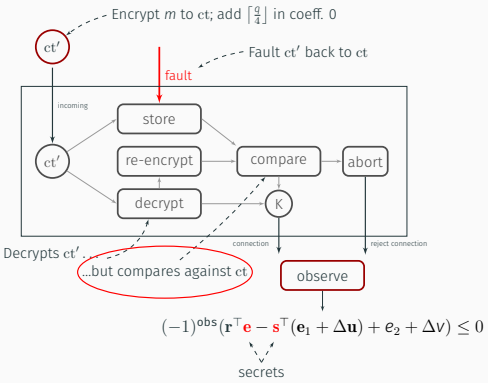

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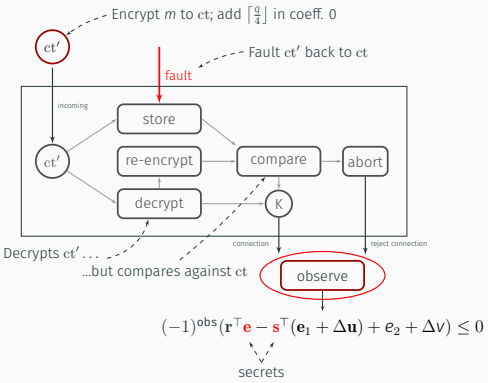

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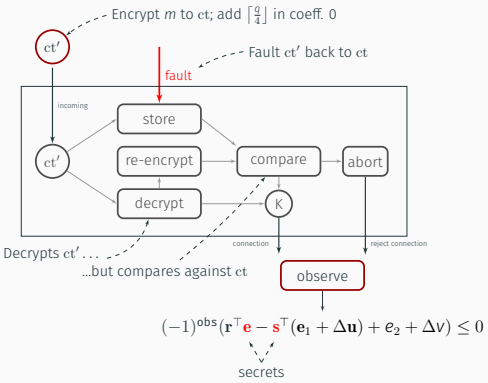

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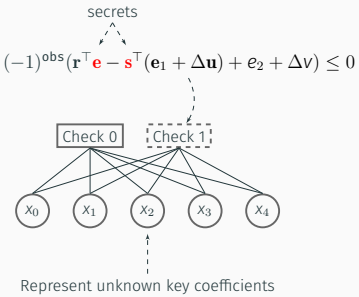
Fault-Enabled Chosen-Ciphertext Attacks – BP

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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Fault-Enabled Chosen-Ciphertext Attacks – Results

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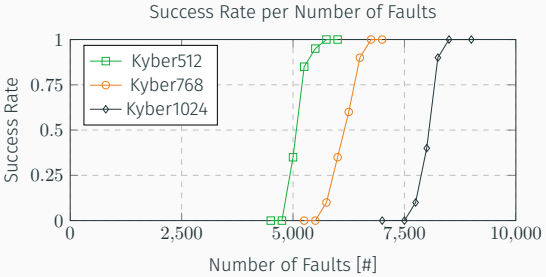

Attack	Type	Point of Attack	Requirement/Robustness
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[BDH+21]	SCA	Comparison	Leaking comparison
[PP21]	Fault	Decoding	Unprotected decoding
[DHP+22]	SCA	Comparison	Max. first order protection
[Del22]	Fault	Multiple	Unreliable/Imprecise fault
[Wei22]	SCA/ML	Multiple	Defeats 1th order masking
[FKK+22]	Rowhammer	Key Generation	KeyGen Failure Boosting
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Allows for very unreliable fault, enlarges attack surface, only targets public data.

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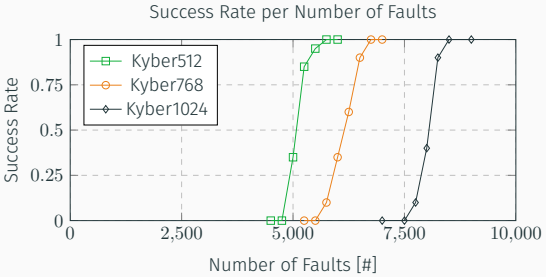

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Key Recovery from Decryption Failure Inequalities

Decryption failures leak information in form of inequalities:

- Exploited in wide variety of attacks including ours.
- Particularly hard to mitigate.
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Attacks require recovery method to solve for secret key:

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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
Pessl and Prokop [PP21]	8000	No	No
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How can we combine the advantages of previous methods?

[1] Used for key recovery from such decryption failure information on widely available hardware in a concrete attack.

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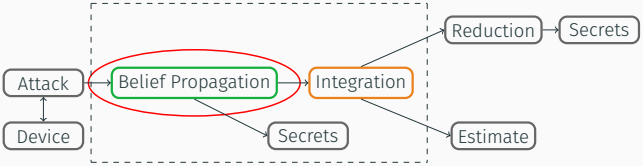
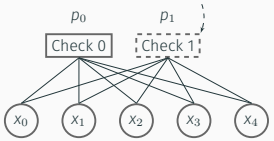
New error-tolerant belief propagation with two-step lattice integration:



With probability p_1:

$$(-1)^{\mathsf{obs}}(\mathbf{r}^\top \mathbf{e} - \mathbf{s}^\top(\mathbf{e}_1 + \Delta\mathbf{u}) + e_2 + \Delta v) \leq 0$$



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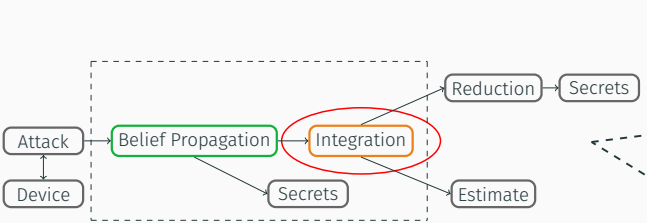

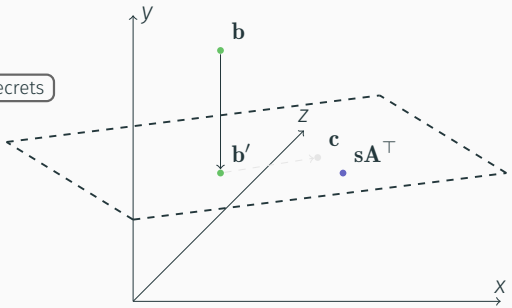

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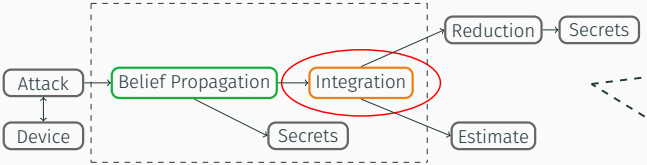

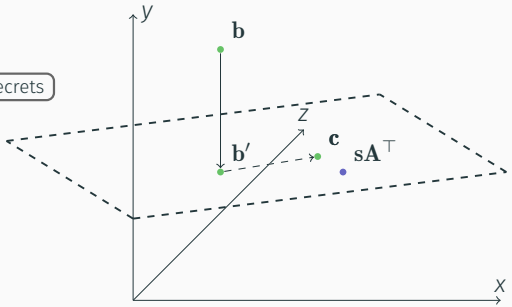

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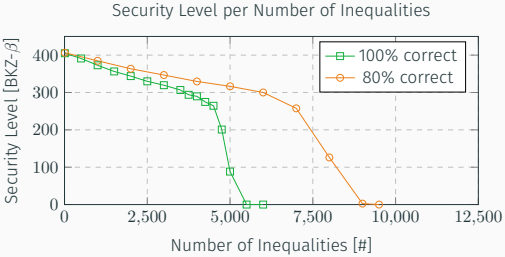

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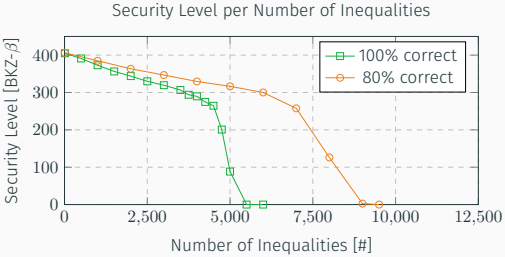

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Contributions

NIST has standardized 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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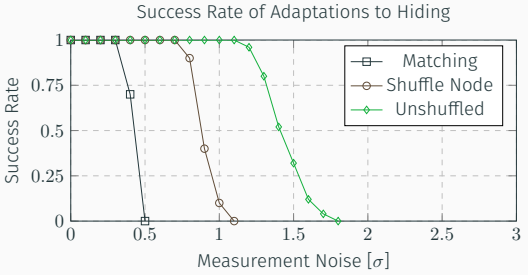
Adapting Belief Propagation – Results

Real-world attacks have to take countermeasures into account.



Our results show that

- 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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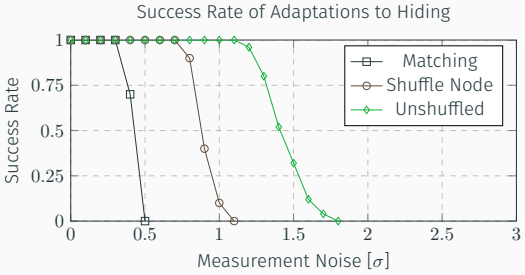

Our results show that

- 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.

Julius Hermelink, Silvan Streit, Emanuele Strieder, and Katharina Thieme. "Adapting Belief Propagation to Counter Shuffling of NTTs". In: *IACR Transactions on Cryptographic Hardware and Embedded Systems* 2023.1 (2023), pp. 60–88