Decryption Errors and Implementation Attacks on Kyber

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Short CV:

- PhD Student at UniBw M (supervisors: Gabi Dreo, Mark Manulis at UniBw, Thomas Pöppelmann, Peter Pessl at Infineon).
- Until 03/2023 in cooperation with Infineon.
- Master's in Mathematics from LMU.
- Working student at Infineon since 2014.

Research interests:

- Implementation attacks on lattice-based schemes.
- Adapting attacks to/circumventing countermeasures.
- Key recovery methods using statistical and algebraic approaches.
- In the future: Improve SASCA using neural networks.

The Quantum Threat

Quantum computers threaten current cryptography.

- RSA
- Diffie-Hellman
- ECDSA
- ...

- Keccak/SHA-3
- SHA-2
- AES
- ...

The Quantum Threat

NIST selected algorithms for standardization in 2022.

- Several selected schemes are based on *learning with errors* (lattice-based).
- Main candidate for key exchanges, Kyber, is (module) learning with errors based.
- Kyber is comparably performant with small key sizes.
- Thus, especially suited for embedded devices.

Decryption Errors

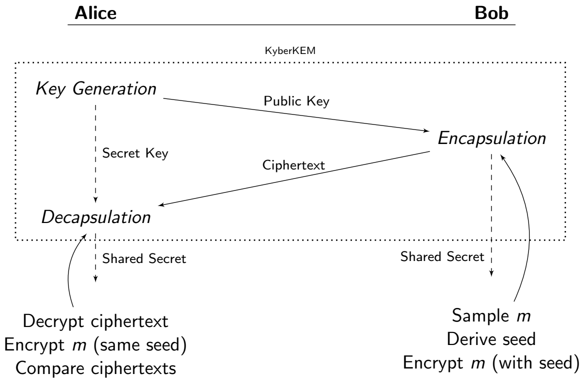
In LWE schemes, decryption errors leak information about the secret key.

- Encryption: Message bits are mapped to coefficients in $\mathbb{F}_q$.
- Decryption: Retrieves noisy version of message coefficients.
- If noise too large, decryption fails.
- Attacker can add to noise using chosen-ciphertext or fault.
- If they can observe decryption errors: Learns if noise term positive.

Probability for decryption errors without manipulation very low.

Key Encapsulation - CCA Security

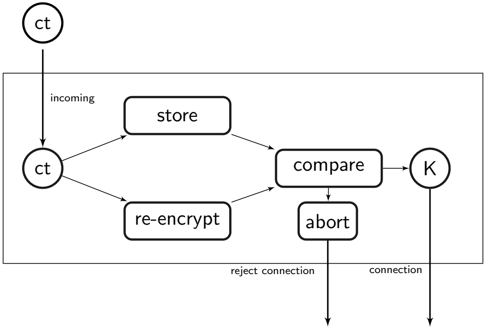
KyberKEM is build from KyberPKE using an FO-Transform.



- Re-encrypt and compare: Chosen-ciphertext causes decapsulation error.
- No information leaked when using chosen-ciphertext.

FO-Transform

An incoming ciphertext is re-encrypted and compared against the re-encrypted result:



An manipulated ciphertext leads to a decapsultation error without revealing potential decryption errors.

Decryption Errors and Decapsulation Errors

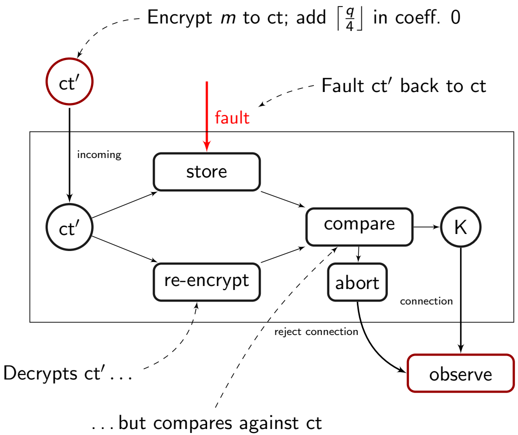
Decryption errors:

- Observing if added noise causes decryption errors leaks information on noise term.
- Error term contains information about secret.
- Attacker can derive inequality involving secret key.

Decapsulation errors:

- Decapsulation errors always occur when ciphertext manipulated.
- Decapsulation thereby hides decryption errors when using chosen-ciphertext.

Fault-Enabled Chosen-Ciphertext Attacks



- m is encrypted to ct; ct′ has $\lceil \frac{q}{4} \rfloor$ error.
- Fault changes ct′ to ct.
- Device decrypts ct′ but compares against ct.
- Depending on error term, $\lceil \frac{q}{4} \rfloor$ causes decryption error.

1. Decryption error: ct′ decrypts to $m' \neq m$, comparison fails $\rightarrow$ decapsulation error.
2. Decryption success: ct′ decrypts to $m' = m$, comparison succeeds $\rightarrow$ decapsulation success.

$\rightarrow$ We can observe decryption errors as decapsulation errors.

[HPP21] **Hermelink, J.**, Pessl, P. and Pöppelmann, T., 2021. 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 22 (pp. 311-334). Springer International Publishing.

Decryption Errors and Implementation Attacks

Several other attacks exploit decryption errors:

- Pessl and Prokop [PP21] use a fault applied to the decoding method,
- Bhasin et al. [BDH+21] and D'Anvers et al. [DHP+22] exploited EM-leakage,
- Hermelink et al. [HPP21] and Delvaux [Del22] used a fault to turn FO into a decryption error oracle,
- and Fahr et al. [FKK+22] present a failure boosting attack on FrodoKEM.

Whenever side-channel allows observing comparison, attack as in [BDH+21, DHP+22] possible.

Recovering the Secret Key

Inequalities contain information about the secret key, but how to recover?

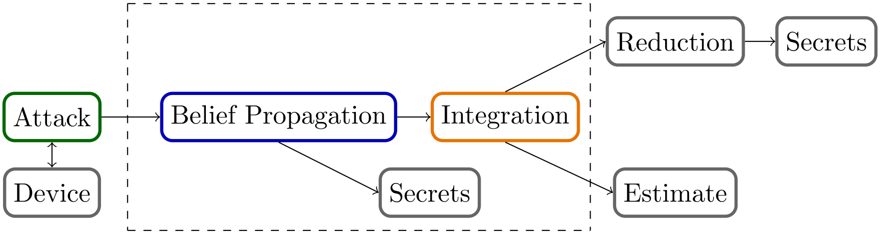
Several methods to obtain secret from inequalities exist:

Method	Inequalities	Error Resistant	Practical[1]	Estimates
Pessl and Prokop [PP21]	8000	No	Yes	No
Hermelink et al. [HPP21]	5750	No	Yes	No
Delvaux [Del22]	9000	Yes	Yes	No
Dachman-Soled et al. [DDHG20]	≥ 10000	No	No	Yes
Dachman-Soled et al. [DGH+22]	n.a.	No	No	Yes

[1] Successfully used in a practical attack for full key recovery from this kind of inequalities.

Combining BP and lattice reduction

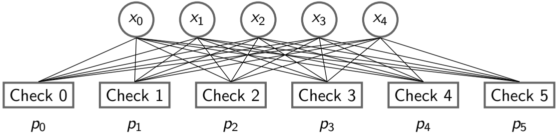
General problem: How to combine statistical method with lattice reduction?



Belief propagation output can be integrated into a lattice problem.

Error Tolerant BP

Belief Propagation (BP) can solve inequalities which are incorrect with probability p_i:



- BP is message passing algorithm.

- Variable nodes: Unknowns coefficients.

- Factor nodes: Inequalities.

- Messages represent belief.

- Initial: Sampling distribution.

- Factors update according to inequality.

- Variables combine incoming information.

- Incorrectness probability: Integrated in Bayesian update process in factors.

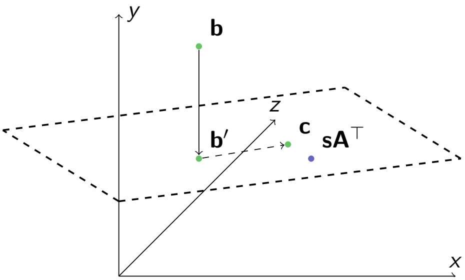
Integrate Statistical Information

Integration of belief propagation works in two steps:

Two steps of integrating information:

1. Reduce dimension with recovered coefficients.
2. Find closer vector with remaining information.

First step works directly on LWE equation, $\mathbf{s}\mathbf{A}^\top + \mathbf{e} \equiv \mathbf{b} \mod q$ instead of CVP/SVP; this enables the second step.



Our Method

We modified the belief propagation to be error resistant and explained how to integrate into lattice problem.

Method	Inequalities	Error Resistant	Practical[1]	Estimates
Pessl and Prokop [PP21]	8000	No	Yes	No
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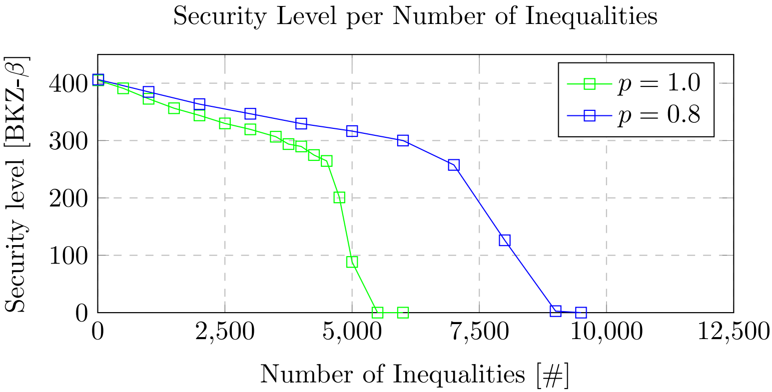
Dachman-Soled et al. [DDHG20]	≥ 10000	No	No	Yes
Dachman-Soled et al. [DGH+22]	n.a.	No	No	Yes
Hermelink et al. [HMS+23]	5500	Yes	Yes	Yes

[1] Successfully used in a practical attack for full key recovery from this kind of inequalities.

Results



Optimal code with optimal decoding would require $\sim$ 2,500 inequalities.

Conclusion

The occurance of decryption errors can be exploited for implementation attacks:

- Decryption errors allow for powerful implementation attacks.
- Large attack surface and securing comparison not sufficient.
- Recovering the secret by combining belief propagation and lattice reduction.
- Combination of belief propagation and lattice reduction likely useful in other attacks (e.g. [PP19, HHP21+, HSST23]).

Open Question and Future Work

Several questions open:

- How to (optimally) solve inequalities where coefficients correlated (occuring in [FKK+22], solved in [DGHK22])?
- Compare to/unify with/improve using the method of [DGHK22]?
- How to better model belief propagation with regards to coding theory?
- Threat of neural networks learning decryption failure from traces (as e.g. in [Weik22])?
- Generally applicable countermeasures apart from shutting device down after n decryption errors?

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