

Round5: merge of Round2 and HILA5

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Round5

Round5 is a merger of the Round2 [1] and HILA5 [3] submissions. Basically, Round5 is Round2 combined with the error-correction code defined in HILA5.

This document summarizes which elements of Round2 and HILA5 are combined in Round5. It also describes the official comments on Round2, HILA5, and Round5 on the NIST PQC forum, and how they have been addressed. It further summarizes changes done over time.

1 2nd Round Submission

1.1 Changes in Round5 compared to Round2 and HILA5

- **Error correction:** Round5 incorporates an error correction code, called XEf and based on that of HILA5, into the INDCCA-PKE scheme defined in Round2. The goal is to achieve the same target failure probability as Round2, but using smaller configuration parameters that lead to better performance. Direct application of HILA5' error correction in Round2 does not work well, as the decoder is confronted with correlated errors. These correlations are caused by the usage of a prime cyclotomic polynomial as reduction polynomial. Securely applying HILA5's code to Round2 requires performing operations on \mathbf{v} in the NTRU ring and using balanced secrets. These are not major changes since Round2 – internally – already performs all operations on \mathbf{v} in the NTRU ring, and Round2's implementation also uses balanced secrets.

The XEf error correction code avoids table look-ups and conditions altogether and it is, therefore, resistant to timing attacks.

- **Security targets:** Security targets in Round5 for NIST security levels I, III, and V are such that breaking Round5 requires a classical effort of at least 128, 192, and 256 bits, respectively. Similarly, the quantum-effort to break Round5 is bigger than $128 - \text{MAXDEPTH}$, $192 - \text{MAXDEPTH}$, and $256 - \text{MAXDEPTH}$, respectively. Round5 encapsulates 128-, 192-, and 256-bit long keys in NIST security levels I, III, and V.
- **Parameter sets:** Round5 defines 21 parameter sets.
 - Six ring-based parameter sets (three each for INDCCA-KEM and INDCCA-PKE, each for NIST security levels I, III, and V) with a code XEf capable of five error correction. Using XEf requires the reduction polynomial to be $\xi(x) = x^{n+1} - 1$ and that the sparse ternary secrets are balanced. These parameter sets are based on the merge of HILA5 with Round2 and show that the usage of error correction leads to the smallest public key and ciphertext sizes.
 - Six ring-based parameter sets (as above, three each for KEM and PKE, corresponding to NIST security levels I, III, and V) without error correction. These parameter choices can be considered more conservative than the previous ones, as they do not employ error correction and therefore are only based on the Round2 design that has received public review since its submission. However, since no error correction is applied, bandwidth requirements are around 33% higher than the previous parameters based on the merge of Round2 and HILA5 using error correction.
 - Six non-ring-based parameter sets (as above, three each for KEM and PKE, corresponding to NIST security levels I, III, and V) without

error correction. These parameter choices rely on same design choices as the original Round2 submission.

- Three application-tailored parameter sets.
 - * A ring-based KEM parameter set addressing Internet of Things applications that achieves even smaller bandwidth (736 Bytes in total) at the price of lower security and higher failure probability.
 - * A ring-based KEM NIST level 1 parameter set in which the encapsulated key is 192-bit long instead of just 128-bit long so that the difficulty of attacking the encapsulated key (by Grover) equals the difficulty of quantum lattice attack to Round5.
 - * A non-ring-based PKE NIST Level III parameter set with a ciphertext size of only 988 Bytes, with very fast encryption and decryption, by taking $\overline{m} = 1$, at the cost of a larger public key. This configuration makes unstructured lattice configurations feasible in applications in which the public-key can remain static for a long time, e.g., email encryption.
- **Rounding constants:** In contrast to Round2, Round5 defines the rounding operation in terms of flooring and rounding constants. Round5 does so to make the INDCCA security proof work.
- **Power-of-two moduli:** All moduli in Round5 are powers of two. This allows for easy-to-implement modular arithmetic, and avoids the generation of random uniform noise otherwise required to guarantee uniform symbols in public keys and ciphertexts. Thus, Round5 does not provide support for NTT speed-ups that were applicable with both Round2 and HILA5.
- **Improved description:** Round5 specification is based on Round2 documentation to make it easier to identify changes with regard to the original submission. The specification is improved by including a broader security analysis and a more detailed technical specification. Moreover, it reports simulation results that support the independence assumption in the analysis of the failure probability in case that error correction is used.

1.2 PQC comments

- **Constant time sorting in Round2:** On December 27, 2017, Daniel J. Bernstein addressed the constant-time generation of ternary secrets. Round5 addresses this by not requiring sorting in the generation of ternary secrets and using simple rejection sampling. Rejection sampling is not constant-time, but it is not related to the secret itself.
- **INDCCA security in HILA5:** On December 28, 2017, Lorenz Panny pointed out an error in HILA5's description that claimed IND-CCA security. Round5 addresses this by using the Fujisaki - Okamoto transformation proposed in Round2.

- **INDCPA-PKE proof in Round2:** On January 12, 2018, Jan-Pieter D’Anvers pointed out that the IND-CPA security proof of Round2 should be corrected using rounding constants. Round5 addresses this issue in the way suggested by D’Anvers.
- **Security levels:** On January 13, 2018, Michael Hamburg pointed out that the Round2 security levels did not match NIST definition. Round5 uses correct NIST security levels.
- **Correlated errors in prime cyclotomic polynomial:** On August 4th, 2018, Léo Ducas pointed out potential issues in the independence assumption in the failure probability analysis of the initial Round5 description.

In a subsequent comment on August 24, 2018, Michael Hamburg discussed the correlation of failures in the prime cyclotomic ring. He concluded that it does not affect the original Round2 design, but it frustrates the direct application of XEf on Round2. In the same comment, Hamburg also describes a ring switching trick, developed by himself and three members of the Round2 team, which addresses this issue and is used to securely apply Xef error correction to Round5. The Round5 specification also reports on simulation results that support the independence assumption in the analysis of the failure probability in case that error correction is used.

2 Round5 update during 2nd Round

2.1 Team extension

The Round5 team has been extended with new members who have contributed to Round5: Jung Hee Cheon and Yongha Son from SNU (Republic of Korea) and Paul Gorissen from Philips (Netherlands).

2.2 Updates in the specification

The following changes have been made in the specification.

- Round5's internal IND-CCA KEM is exposed explicitly, since some applications might benefit of an IND-CCA KEM. This does not require any changes in parameters or change in the specification. However, since after this change Round5 has two available KEMs, 2nd Round parameter sets are renamed from $R5N^*_{*}\{KEM/PKE\}_{*}d$ into $R5N^*_{*}\{CPA/CCA\}_{*}d$. An IND-CPA parameter set can be used in combination with Round5's IND-CPA KEM. Round5's IND-CCA KEM and PKE require IND-CCA parameter sets.
- The specification now includes the enumeration method used to obtain concrete enumeration-based security estimates.
- Section 2.7.6 on the hybrid attack now contains the state-of-the-art analysis due to Wunderer [4]. This has led to a slight increase/decrease in the concrete classical/quantum security estimates.
- Section 2.7.7, formerly called "Attacks against Sparse Secrets", contains a more detailed study of the guessing + dual attack. This has led to a slight reduction in the concrete security estimates.
- The analysis of the failure probability of Round5 in Section 2.8 now takes into account that secrets are balanced, i.e., contain equally many ones as minus ones. This results in slightly smaller failure probabilities.
- The concrete security number in the tables for the different parameter sets are those obtained from the tighter security and failure probability analysis in Section 2.7.6, 2.7.7 and 2.8.
- According to [2, Sec.4], lattice-based schemes in which the public parameter \mathbf{A} is not sent over explicitly, but is obtained from applying a function to a transmitted seed σ , can only claim IND-CPA security in their core IND-CPA secure public-key encryption scheme in the random oracle model. Thus, the IND-CPA-proof for Round5 in Appendix A has been updated accordingly; specifically, the previous section Appendix A.1 has been removed. In the new section 2.7.10, we argue why the (default) instantiation of the function for generating \mathbf{A} from σ and of the secret generation makes it unlikely that there are attack avenues to that exploit the assumptions made about them.

- The new Section 2.9.4 describes the multiple options for side-channel countermeasures that are applicable to different types of platforms. Appendix B shows how a parameter pertaining to these implementations is computed. Performance numbers for these implementations are included in Section 2.9.8.
- The algorithm to generate the secrets is slightly modified so that if a Round5 secret has more than one vector, then the pseudorandom data required for each of the secret vectors is independent of each other. This allows for interoperability independently of the side-channel countermeasures used in an implementation. The algorithm is described in 2.11.6, functions `create_S_T` and `create_R_T`.
- Updated performance numbers including performance numbers for the different side-channel countermeasures included in the implementation, AVX2-optimized code for ring parameters, and performance numbers when a Hardware-Software codesign is applied.

2.3 Updates in implementations

The optimized implementation is extended as follows:

- Included `CM_CT` option for a fully constant-time implementation in the generation of a ternary secret and ring multiplication routines.
- Modification in generation of Round5 secret keys containing multiple secret key vectors so that the pseudorandom data required to sample each of those vectors is independent of each other. This allows for interoperability in implementations using different types of side-channel countermeasures in the secret-key generation routine.
- The `r5_cca_kem` algorithm is accessible and it can be used with IND-CCA parameter sets.
- Renaming of the parameter sets to enable the previous change. `R5N*_KEM_*d` into `R5N*_CPA_*d` and `R5N*_PKE_*d` into `R5N*_CCA_*d`.
- The optimized library includes a standalone library implementing SHA-3, SHA-3 Extendable-Output Functions and cSHAKE. Thus, `r5_cpa_kem` and `r5_cca_kem` algorithms can be used without external libraries.
- We have applied AVX2 instructions to improve the performance of the ring multiplication routine.

2.4 Updates in scripts

- Extension of the scripts used for parameter search to perform a wider-search.

- Improvements in the routines used to compute the failure probability to take into account the usage of balanced secrets.
- Update of the code to include the tighter security analysis for the Guessing+Dual attack and the hybrid attack.

References

- [1] Hayo Baan, Sauvik Bhattacharya, Oscar Garcia-Morchon, Ronald Rietman, Ludo Tolhuizen, Jose-Luis Torre-Arce, and Zhenfei Zhang. Round2: KEM and PKE based on GLWR. Technical report, National Institute of Standards and Technology, November 2017. Available at <https://csrc.nist.gov/projects/post-quantum-cryptography/round-1-submissions>.
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- [3] Markku-Juhani O. Saarinen. HILA5: Key Encapsulation Mechanism (KEM) and Public Key Encryption Algorithm. Technical report, National Institute of Standards and Technology, November 2017. Available at <https://csrc.nist.gov/projects/post-quantum-cryptography/round-1-submissions>.
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