

Contents

1	Abstract and Organization	4
2	Introduction and Preliminaries	9
2.1	Introduction	9
2.2	Cryptography	10
2.2.1	Encryption	12
2.2.2	Diffie-Hellman Key Exchange	14
2.2.3	From Key Exchange to Encryption: the ElGamal Cryptosystem	15
2.2.4	Semantic Security	17
2.2.5	From Encryption to Key Exchange: Key Encapsulation Mechanism	20
2.2.6	Digital Signature	21
2.2.7	Basic Security Notions for Signatures	22
2.2.8	Identification Schemes	24
2.2.9	From Identification to Signatures: The Schnorr Signature	25
2.3	Post-Quantum Cryptography	28
2.3.1	Lattices	30
2.3.2	Hard Problems on Lattices	31
2.3.3	SIS, LWE and their Algebraically Structured Variants	32
2.3.4	NIST Standardization Process	35
3	Efficient KEMs Implementations on Embedded Devices	38
3.1	Preamble	38
3.2	Introduction	39
3.3	Polynomial Multiplication	39
3.3.1	NTT-based Multiplication	40
3.3.2	Fast Fourier Transform Algorithms	40
3.4	Lattice-Based Key Exchange/Key Encapsulation	45
3.4.1	NewHope	46
3.4.2	Kyber	50
3.5	Fast NTT for Fast Implementations of NewHope and Kyber on Cortex-M4	52
3.5.1	Efficient Reduction Algorithms	52
3.5.2	Cortex-M4	54
3.5.3	SIMD and Useful Instructions	54
3.6	Original NewHope NTT	56
3.6.1	Optimized Assembly Code on Cortex-M4	57
3.7	Cortex-M4 Optimizations for $\{R,M\}$ LWE Schemes (EPRINT 2020)	62
3.7.1	Polynomial Multiplication in Kyber	63
3.7.2	NewHope-Compact	63

3.7.3	Speed Optimizations of Polynomial Multiplication	64
3.7.4	Optimization of NewHope and NewHope-Compact for Stack Usage	67
3.7.5	Tradeoffs Between Secret Key Size and Speed	68
3.7.6	Results and Comparison	69
3.7.7	Speed Comparison	69
3.7.8	Dominance of Hashing	70
3.7.9	Comparing Polynomial Multiplications	71
3.8	Conclusion	72
3.9	Thoughts and Future Works	73
4	Protecting Lattice-based Cryptography Against Physical Attacks	76
4.1	Preamble	76
4.2	Introduction	76
4.3	Power analysis attacks	77
4.3.1	Correlation Power Analysis	77
4.4	Concrete attack: Breaking Kalyna ! (SPACE 2016)	78
4.4.1	Encryption Algorithm	79
4.4.2	Key Scheduling	79
4.4.3	Side-Channel Attacks on Kalyna	80
4.4.4	Experiments	81
4.5	Masking	84
4.6	Lattice-Based Signatures	85
4.6.1	GLP	85
4.6.2	A Scheme from Bai and Galbraith	89
4.6.3	qTESLA	90
4.7	Masking qTESLA at any Order (CARDIS 2019)	93
4.7.1	Masking-Friendly Design	95
4.7.2	Existing Gadgets	96
4.7.3	New Gadgets	97
4.7.4	Masked Scheme	101
4.7.5	Proof of Masking	103
4.7.6	Practical Aspects and Implementation Details	107
4.8	Conclusion	109
4.9	Thoughts and Future Works	110
5	Efficient Design for Lattice-Based Cryptography	113
5.1	Preamble	113
5.2	Introduction	113
5.3	Signcryption	114
5.4	Security model for signcryption	116
5.5	Zheng’s Scheme	117
5.5.1	Schnorr Variant	118
5.6	Reconciliation Mechanism	119
5.7	SETLA: Signature and Encryption from Lattices (CANS 2018)	120
5.7.1	SETLA-KEX Signcryption	120
5.7.2	SETLA-KEM Signcryption	123
5.8	Security Arguments	125