Doctoral Thesis

Efficient Software Implementation of Pairing-Based Cryptographic Primitives for High-level Security for IoT

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Declaration of Authorship

This dissertation and the work presented here for doctoral studies were conducted under the supervision of Professor Yasuyuki Nogami. I, Md. Al-Amin KHANDAKER, declare that this thesis titled, "Efficient Software Implementation of Pairing-Based Cryptographic Primitives for High-level Security for IoT" and the work presented in it are my own. I confirm that:

- The work presented in this thesis is the result of original research carried out by myself, in collaboration with others, while enrolled in the Faculty of Engineering at Okayama University as a candidate for the degree of Doctor of Philosophy in Engineering.
- This work has not been submitted for a degree or any other qualification at this University or any other institution.
- Some of the previously published works presented in this dissertation listed in "Research Activity". .
- The published work of others cited in this thesis is clearly attributed. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help to pursue this work.
- In all works my coauthors contribution is acknowledged.
- The experiments and results presented in this thesis and in the articles where I am the first author were conducted by the myself.

Signed:

Date:

"*If we knew what it was we were doing, it would not be called research, would it? "*

Albert Einstein

Abstract

Md. Al-Amin Khandaker

Efficient Software Implementation of Pairing-Based Cryptographic Primitives for High-level Security for IoT

Pairing-based cryptography over the elliptic curves is a relative new paradigm in public key cryptography(PKC). In general, pairing calculation involves certain elliptic curve named pairing-friendly curve defined over finite extension of prime field. It is typically defined as bilinear map from rational points of two additive groups to a multiplicative group. Two mathematical tool named as Miller's algorithm and final exponentiation is mostly involved in pairing calculation. However, most protocols also requires two more operation in pairing groups named scalar multiplication and exponentiation in multiplicative group. The above mentioned mathematical tools are the major bottleneck for the efficiency of pairing-based protocols.

Since, the inception at the advent of this century pairing-based cryptography brings monumental amount of research. The results of this vast amount of research brought some novel cryptographic application which was not possible before pairing-based cryptography. However, computation speed of pairing was very slow to consider them as a practical option. Years of research from the mathematicians, cryptographers and computer scientists improves the efficiency of pairing.

The security of pairing-based cryptography is not only rely on the intractability of elliptic curve discrete logarithm problem (ECDLP) of additive elliptic curve group but also discrete logarithm problem (DLP) on multiplicative group. It is known that key size in cryptography based of ECDLP requires fewer bits than cryptography based on DLP. Therefore, it is a crucial to maintain a balance in parameter sizes for both additive and multiplicative groups in pairing-based cryptography. In CRYPTO 2016, Kim and Barbulescu showed a more efficient version of number field sieve algorithm to solve DLP. This new attack makes all previous parameter settings to update.

This thesis presents several improvement technics for pairing-based cryptography over two ordinary pairing-friendly curves named KSS-16 and KSS-18. The motivation behind to work on these curves is, they not widely studied in literature compared to other pairing-friendly curves. After the extNFS algorithm, the security level of widely used pairing-friendly curves were challenged. The technics can also be applied on the ordinary pairing-friendly curves. We also present several improvements in extension field arithmetic operation. We implement the proposed improvements in for experimental purpose. All the sources are bundled in an installable library.

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Notation	Description
p	$p > 3$ is an odd prime integer in this thesis.
$x \bmod p$	Modulo operation. the least nonnegative residue of x modulo p.
$\mathbb{F}_p$	Prime field. The field of integers mod p.
$\mathbb{F}_p^*$	The multiplicative group of the field $\mathbb{F}_p$. In other words, $\mathbb{F}_p^* = \{x \mid x \in \mathbb{F}_p \text{ and } x \neq 0\}$.
$\lfloor \cdot \rfloor$	The floor of $\cdot$ is the greatest integer less than or equal to $\cdot$. For example, $\lfloor 1 \rfloor = 1$ and $\lfloor 6.3 \rfloor = 6$.

Dedicated to the people I owe most. To my parents who brought me to this world and to my wife who sacrificed the most during my Ph.D. journey.

Research Activities

- Peer-Reviewed Journal Papers (First author)

  1. **Md. Al-Amin Khandaker** and Yasuyuki Nogami. "An Improvement of Scalar Multiplication by Skew Frobenius Map with Multi-Scalar Multiplication for KSS Curve". In: *IEICE Transactions* 100-A.9 (2017), pp. 1838-1845. DOI: 10.1587/transfun.E100.A.1838.

  2. **Md. Al-Amin Khandaker**, Taehwan Park, Yasuyuki Nogami, and Howon Kim. "A Comparative Study of Twist Property in KSS Curves of Embedding Degree 16 and 18 from the Implementation Perspective". In: *J. Inform. and Commun. Convergence Engineering* 15.2 (2017), pp. 97-103. DOI: 10.6109/jicce.2017.15.2.97.

- Peer-Reviewed International Conference Papers (First author)

  LNCS Proceedings:

  1. **Md. Al-Amin Khandaker**, Yuki Nanjo, Loubna Ghammam, Sylvain Duquesne, Yasuyuki Nogami, and Yuta Kodera. "Efficient Optimal Ate Pairing at 128-Bit Security Level". In: *INDOCRYPT 2017*. Ed. by Arpita Patra and Nigel P. Smart. Vol. 10698. LNCS. Springer, Heidelberg, Dec. 2017, pp. 186–205. DOI: 10.1007/978-3-319-71667-1_10.

  2. **Md. Al-Amin Khandaker**, Hirotaka Ono, Yasuyuki Nogami, Masaaki Shirase, and Sylvain Duquesne. "An Improvement of Optimal Ate Pairing on KSS Curve with Pseudo 12-Sparse Multiplication". In: *ICISC 2016*. Ed. by Seokhie Hong and Jong Hwan Park. Vol. 10157. LNCS. Springer, Heidelberg, 2017, pp. 208–219. DOI: 10.1007/978-3-319-53177-9_11.

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  5. **Md. Al-Amin Khandaker** and Yasuyuki Nogami. "Isomorphic Mapping for Ate-Based Pairing over KSS Curve of Embedding Degree 18". In: *Fourth International Symposium on Computing and Networking, CANDAR 2016*, Hiroshima, Japan, November 22-25, 2016. 2016, pp. 629–634. DOI: 10.1109/CANDAR.2016.0113.

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  2. Takuya Kusaka, Sho Joichi, Ken Ikuta, **Md. Al-Amin Khandaker**, Yasuyuki Nogami, Satoshi Uehara, Nariyoshi Yamai, and Sylvain Duquesne. "Solving 114-Bit ECDLP for a Barreto-Naehrig Curve". In: *ICISC 2017*. Ed. by Howon Kim and Dong-Chan Kim. Vol. 10779. LNCS. Springer, Heidelberg, Oct. 2017, pp. 231–244. DOI: 10.1007/978-3-319-78556-1_13.

  3. Taehwan Park, Hwajeong Seo, Garam Lee, **Md. Al-Amin Khandaker**, Yasuyuki Nogami, and Howon Kim. "Parallel Implementations of SIMON and SPECK, Revisited". In: *WISA 2017*. Ed. by Brent ByungHoon Kang and Taesoo Kim. Vol. 10763. LNCS. Springer, Heidelberg, Aug. 2017, pp. 283–294. DOI: 10.1007/978-3-319-93563-8_24.

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2. **Md. Al-Amin Khandaker** and Yasuyuki Nogami. "Efficient Scalar Multiplication by Skew Frobenius Map with Multi-Scalar Multiplication for KSS Curve". In: *Symposium on Cryptography and Information Security (SCIS), 2017*, CD-ROM (B1-3).

- Domestic conferences (Co-author)

1. Yuki Nanjo, **Md. Al-Amin Khandaker**, Takuya Kusaka, Yasuyuki Nogami. "A Study on a Construction Method of Degree 18 Extension Field for Efficient Pairing over KSS Curves". In: *Computer Security Symposium (CSS), 2018*, CD-ROM (??).
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[Kha+17b] Md. Al-Amin Khandaker, Yuki Nanjo, Loubna Ghammam, Sylvain Duquesne, Yasuyuki Nogami, and Yuta Kodera. "Efficient Optimal Ate Pairing at 128-Bit Security Level". In: *INDOCRYPT 2017*. Ed. by Arpita Patra and Nigel P. Smart. Vol. 10698. LNCS. Springer, Heidelberg, Dec. 2017, pp. 186–205. DOI: 10.1007/978-3-319-71667-1_10.

[Par+17] Taehwan Park, Hwajeong Seo, Garam Lee, Md. Al-Amin Khandaker, Yasuyuki Nogami, and Howon Kim. "Parallel Implementations of SIMON and SPECK, Revisited". In: *WISA 17*. Ed. by Brent ByungHoon Kang and Taesoo Kim. Vol. 10763. LNCS. Springer, Heidelberg, Aug. 2017, pp. 283–294. DOI: 10.1007/978-3-319-93563-8_24.

Biography

Md. Al-Amin Khandaker was born on September 11, 1990, in a beautiful village of Bangladesh. He completed his high school in 2007 and in 2008, admitted to Jahangirnagar University, Bangladesh. In 2012, he graduated majoring in Computer Science and Engineering. After that, he joined in a Holland-based off-shore software development company in Dhaka. In 2015 he awarded Japan Govt. Scholarship (MEXT) to pursue Doctor's course in the field of cryptography in Okayama University under the supervision of Professor Yasuyuki NOGAMI. His main fields of research are optimization and efficient implementation techniques for the elliptic curve, pairing-based cryptography and it's application for IoT security. He is a graduate student member of IEEE.