BINUS UNIVERSITY DOCTORATE PROGRAM
Doctor of Computer Science


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Lightweight Advanced Encryption Standard (AES) Model to Secure Data Transfer in Industrial Control Systems for Smart Factory in Manufacturing Industry

Background

- ✓ Security threats in OT systems are a recent trend in ICS, Industrial Control Systems (Stouffer et al., 2023; Jayalaxmi et al., 2021).
- ✓ The IT/OT convergence introduces security risks to OT systems (Cyber attack), including PLCs, the core controller in ICS (Wu H, Geng Y, Liu K, Liu W., 2019)
- ✓ Lack of encryption in industrial protocols. A secure communication between IoT devices to protect the data is essential [Jayalaxmi, P. et al. (2021)]
- ✓ PLC has been the core automation in Industrial Automation and the manufacturing industry since the beginning of Industry 3.0 (Yadav R, Namekar S., 2020)
- ✓ Symmetric scheme is computationally inexpensive compared to the Asymmetric [Maqsood, F. *et al.* (2017)], suitable for ICS (low resource requirements).
- ✓ In 2000, NIST announced the selection of the Rijndael block cipher family for the AES for Symmetric Encryption [Morris J. Dworkin, 2023]
- ✓ For the security aspect and implementation complexity, AES is considered as one of the strongest and most efficient algorithms [John, S. k (2023)]
- ✓ Modifying the existing algorithm: AES for lightweight applications is possible [John, S. k (2023)]
- ✓ The Lightweight AES (LAES) algorithm increased higher than AES by 4.2969% in terms of avalanche effect, meaning increased security [Salman, R.S., Farhan, A.K. and Shakir, A. (2022); Acla, H.B., and Gerardo, B.D. (2019)]

In Industrial Control Systems (ICS) within Industry 4.0, lightweight cryptography (LWC) is crucial for securing the Internet of Things (IoT)/Industrial IoT (IIoT). IoT devices have limited resources (memory, CPU, and battery) and thus require light techniques for securing communications. LWC is a collection of solutions for encryption techniques that feature devices with low computational complexity. It aims to expand the applications of cryptography to limited-resource devices while providing a high level of security (Mammeri, 2024, p. 194).

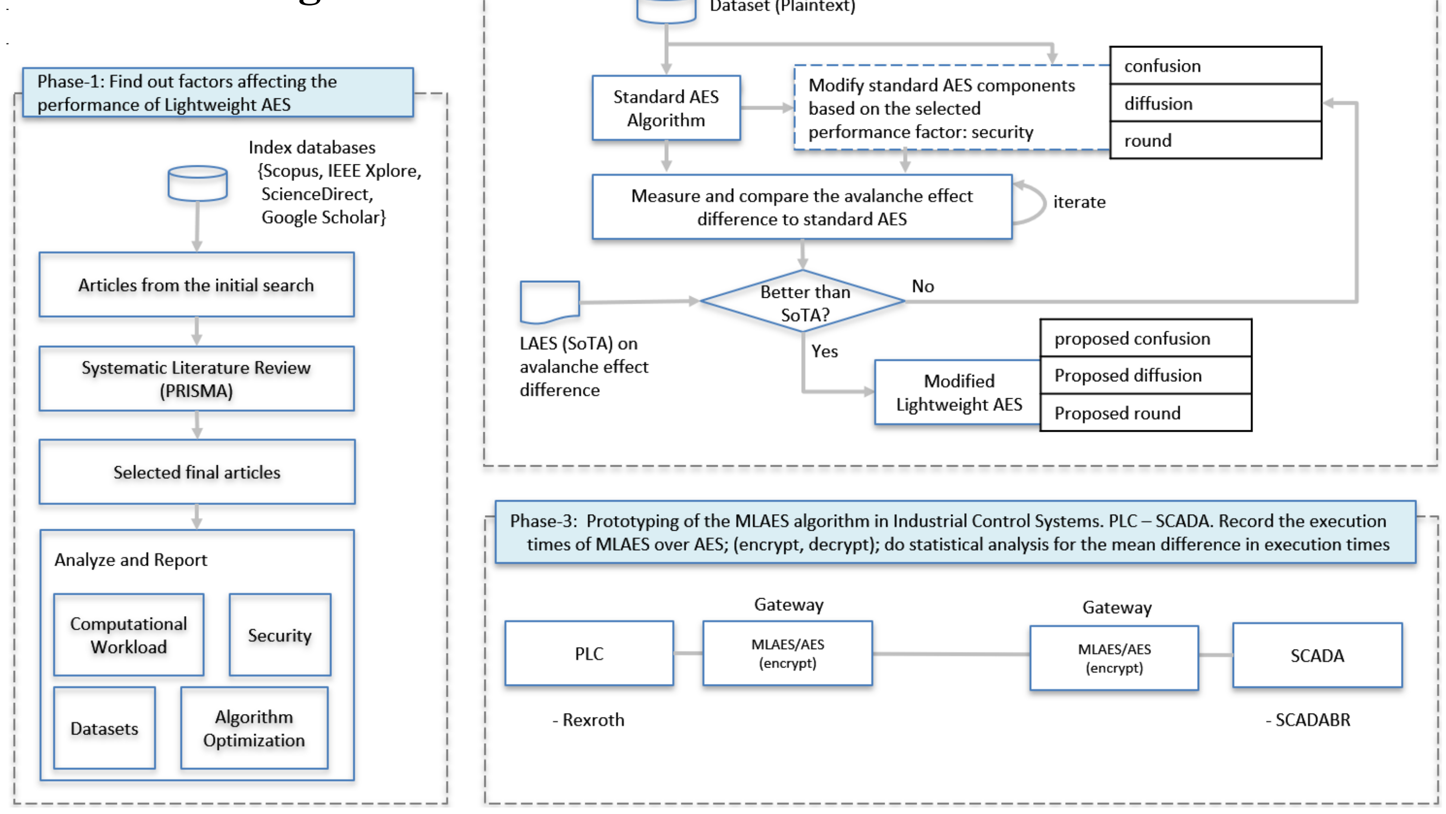
Research Objectives

Securing data exchange in ICS through the modification of the symmetric-based encryption algorithm, based on the AES, Advanced Encryption Standard, for lightweight applications.

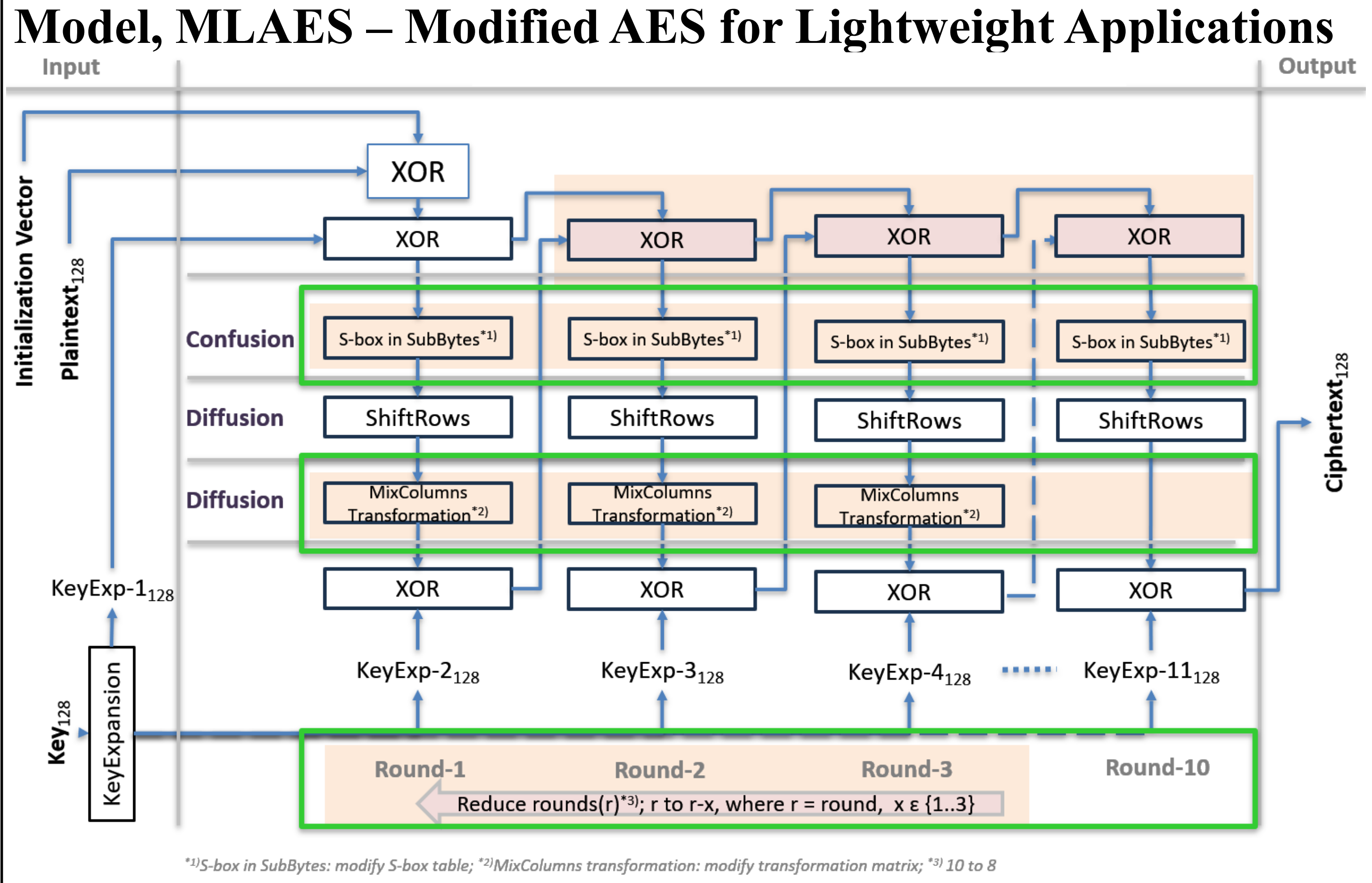
Research Questions

RQ-1: What factors that affect the performance of the lightweight Advanced Encryption Standard (AES) algorithm?
RQ-2: How to obtain an improved version of the AES algorithm that runs faster but utilizes fewer resources?

Research Design



Model, MLAES – Modified AES for Lightweight Applications



[*1] S-box in SubBytes: modify S-box table; [*2] MixColumns transformation: modify transformation matrix; [*3] 10 to 8

Conclusion

MLAES algorithm is based on the AES algorithm with the purpose to obtain an improved version that runs faster while utilizing fewer resources while providing secure data exchange within ICS environment. MLAES enables a more efficient, secure data exchange among connected systems in ICS that have been designed with no security as their priority, vulnerable to cyber attack towards Industry 4.0. In terms of execution time performance during prototyping, MLAES is faster than AES (statistically significant), while still maintaining the security performance.

Implication

The average avalanche effect of MLAES is 0.6250% higher than the state-of-the-art (53.0469%). A better result, on average, in terms of avalanche effect, although statistically insignificant, indicates a qualitatively better security. MLAES provides lightweight security to improve computation time for low-resource devices such as IoT within ICS in the Manufacturing Industry. MLAES will provide less latency in an FPGA-based hardware implementation compared to a software implementation, such as PLC firmware or a Node-RED application, in an edge computing gateway.

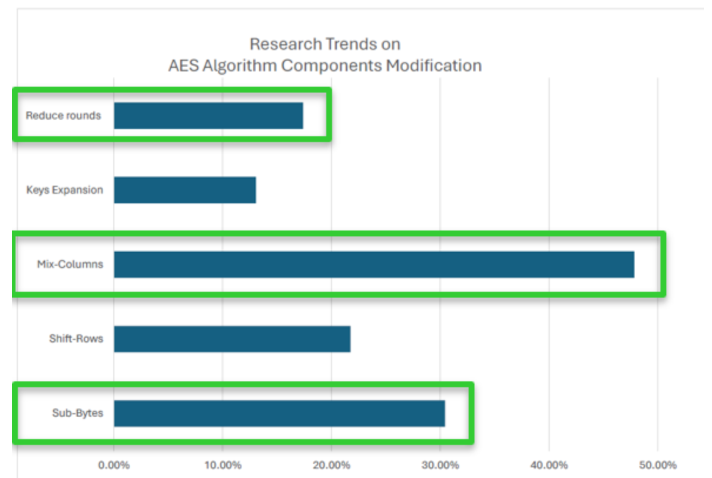
Limitations

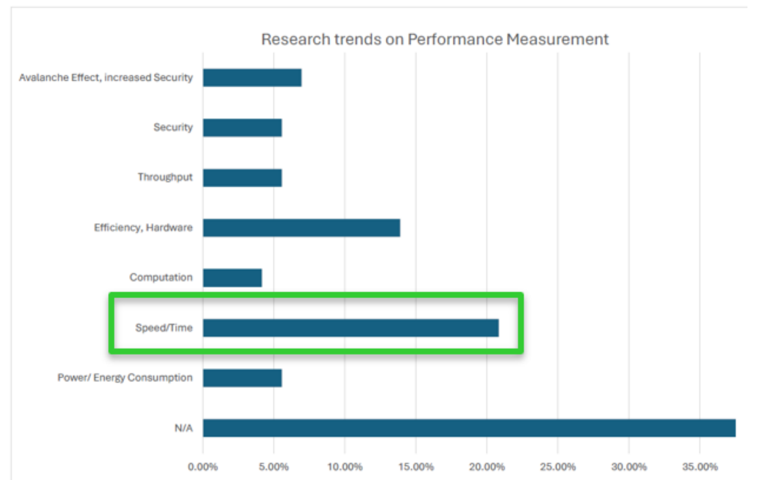
The results for the average avalanche effects of MLAES and AES algorithms with the SoTA+ dataset show insignificant results on the Mann-Whitney test statistics. Although qualitatively, MLAES is better than AES.

Suggestion/Future Work

Future theoretical contributions could enhance the algorithm by further exploring the transformation into an S-box table within the SubBytes operation, modifying the ShiftRows and MixColumns algorithms, and considering the use of lightweight computing power and limited resources in embedded systems.
Future research on practical implementation may include implementing the MLAES algorithm on PLC by integrating it into the firmware or FPGA, within the PLC that supports Node-RED, edge computing, or IoT devices within Industrial Control Systems, where processing speed is a priority.

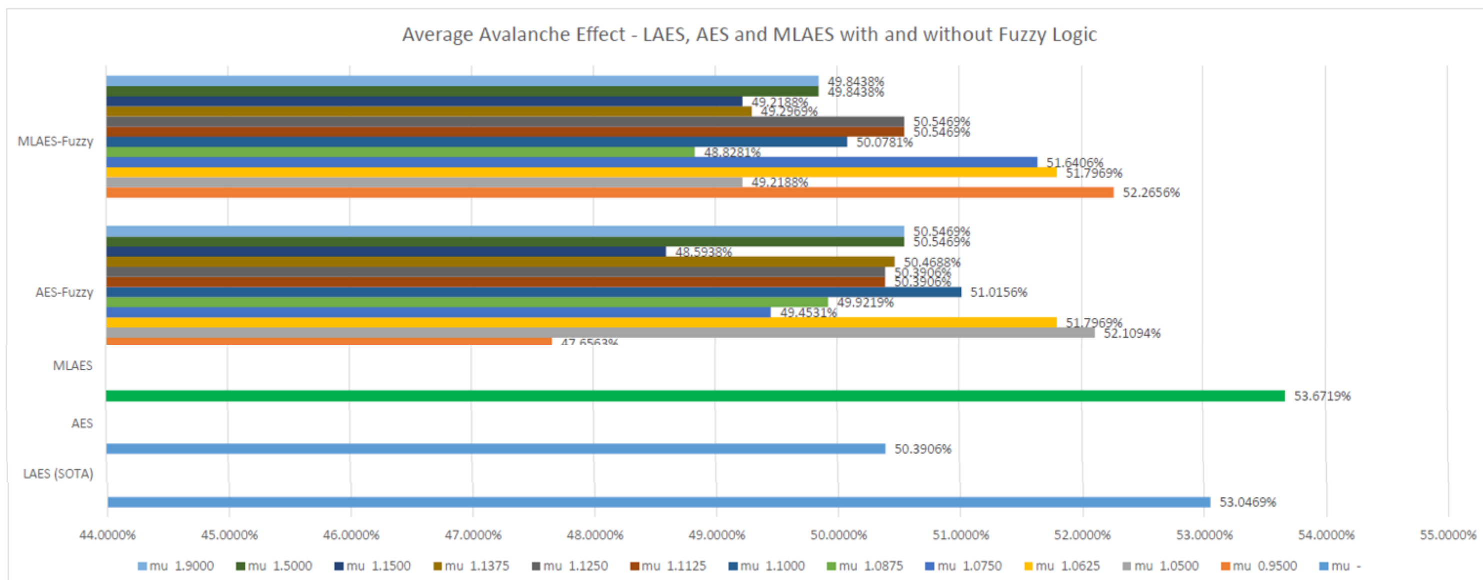
Research Results (Phase-1), Findings for RQ1



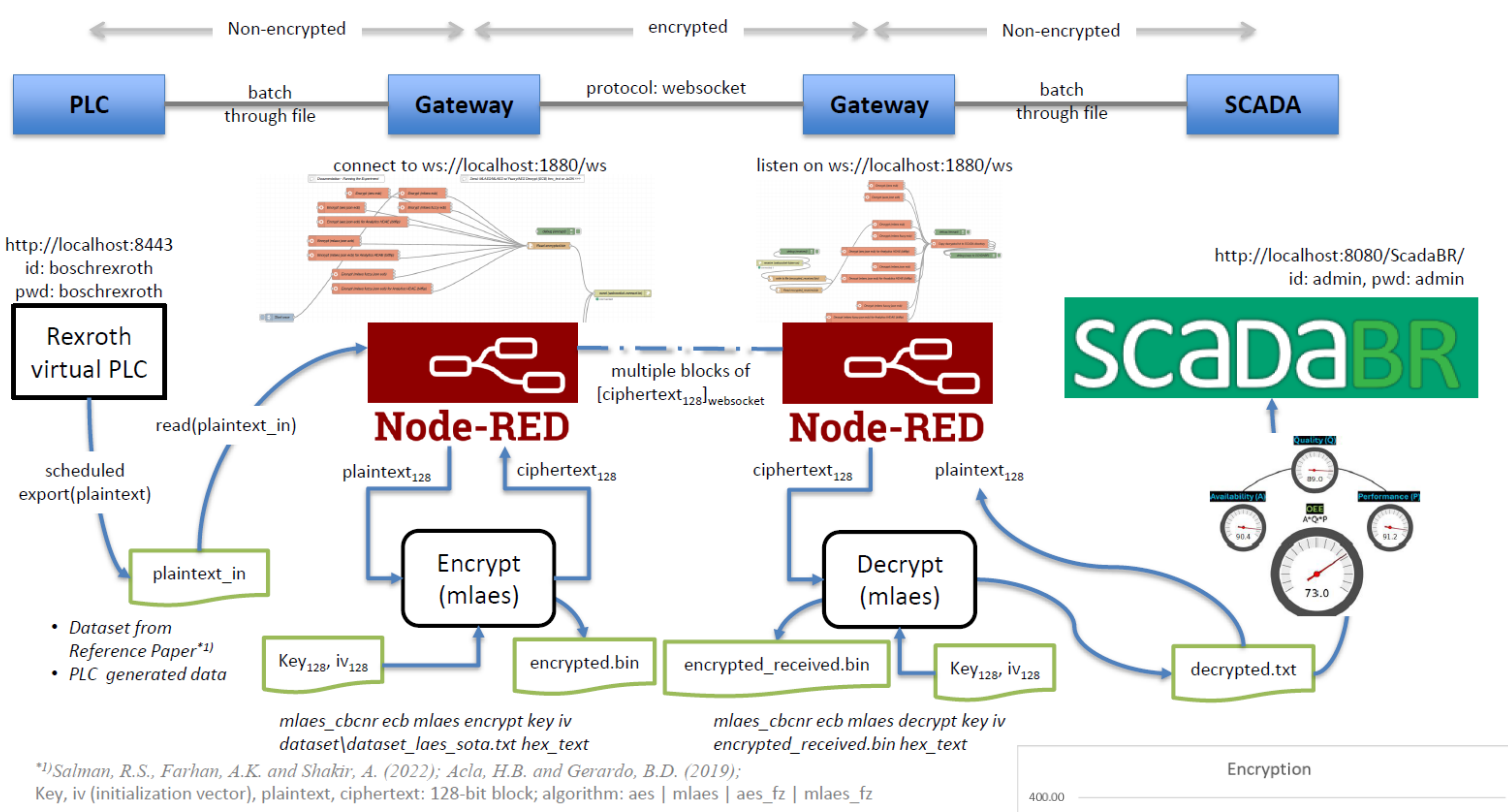


Research Results (Phase-2), Experiments

With SoTA dataset, the state-of-the-Art dataset from the reference paper (Acla and Gerardo, 2019; Salman, Farhan, and Shakir, 2022), the Modified Lightweight AES (MLAES) achieved **53.6719%** in average avalanche effect without fuzzy logic. MLAES is **1.5625%**, **1.4063%**, and **0.6250%** higher than AES with fuzzy logic (**52.1094%** with mu=1.0500), MLAES with fuzzy logic (52.2656% with mu=0.9500), and the state-of-the-art Lightweight AES, LAES (**53.0469%**). Fuzzy logic uses a tent chaotic map for the inference rule and a center-of-gravity method for defuzzification. Despite insignificant statistical performance improvement (average avalanche effect) following the five times increased of the dataset (SoTA+) with Mann-Whitney statistical test, MLAES has qualitatively better average avalanche effect than the standard (AES), LAES, and MLAES with Fuzzy Logic (significance level α=0.05).

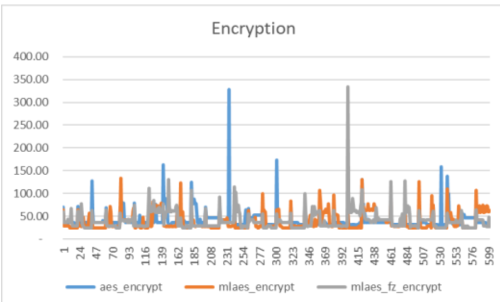


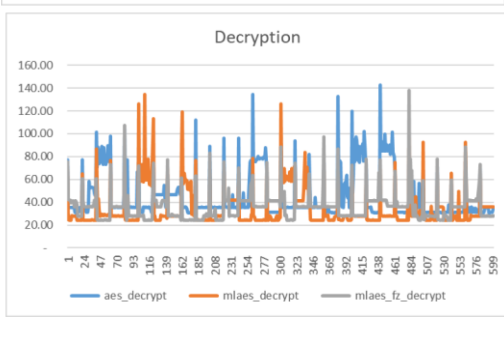
Research Results (Phase-3), Findings for RQ2



[*1] Salman, R.S., Farhan, A.K. and Shakir, A. (2022); Acla, H.B. and Gerardo, B.D. (2019);
Key, iv (initialization vector), plaintext, ciphertext: 128-bit block; algorithm: aes | mlaes | aes_fz | mlaes_fz

In the prototyping (SoTA dataset, N=600 for each algorithm (MLAES, AES) and mode of operations (encrypt, decrypt), α=0.01), there is a **statistically significant mean difference** in the **execution time** for the **encryption** and **decryption operations** between the **MLAES** and **AES** algorithms, validated by t-test statistics for two independent samples.
In terms of execution time, MLAES is faster than AES, by utilizing fewer resources (decreasing the original AES rounds from 10 to 8).





Publications

- Conference, Procedia Computer Science, 2023, Indexed, Acquiring Automation and Control Data in The Manufacturing Industry: A Systematic Review (citation: 4)
- Conference, ICICyTA, 2023, Indexed, Implementation of Lightweight PRNG on PLC for Industrial Control Systems
- Conference for RSCH9016 Publication I (ICCTech, 2024, Indexed), Random Number Generator for Securing Data Exchange in Smart Factory - Recent Trends and Best Practices
- Journal for RSCH9018 Publication II (IJSSE, 2024, Indexed), Lightweight Pseudo Random Number Generator for Embedded Systems
- Journal for RSCH9020 Publication III (IJSSE, 2025, Indexed), Modified Lightweight Advanced Encryption Standard for Lightweight Applications