Research Article

Energy Consumption Analysis of Lightweight Cryptographic Algorithms That Can Be Used in the Security of Internet of Things Applications

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The Internet of Things (IoT) has begun to acquire place in our lives quietly and gradually thanks to the presence of wireless communication systems. An increasing number of M2M applications, such as smart meters, healthcare monitoring, transportation and packaging, or asset tracking, make a significant contribution to the growth of devices and connections. Within such a large and uncontrollable ecosystem, IoT poses several new problems. Security and privacy are among the most important of these problems. Lightweight cryptography can be used more effectively for small size, low energy, and small footprint such as RFID tags, sensors, and contactless smart cards. Therefore, it can be used to ensure security and privacy in the IoT applications. In this study, PRESENT, CLEFIA, PICCOLO, PRINCE, and LBLOCK lightweight cryptographic algorithms, which can be used to secure data in IoT applications, were analyzed in a test environment. As a result of the tests, the energy consumption of the algorithms, current measurement, active mode working time, and active mode energy consumption were identified and based on this, some inferences have been made.

1. Introduction

ARPANET, which was originally created in 1969 based on the idea that only a few systems are connected, has become an immense separate world where billions of computers and systems come together. Internet speed, capacity, and traffic have increased exponentially and extend into the future. The mobile devices that almost everyone has in their pockets today have superior capabilities than the super computers 20 years ago. Now, human beings can make almost all devices smart thanks to microsensors and smart chips. Smart phones, cars, and heating systems have become easily controllable and programmable.

In the last decade, the IoT has begun to take place in our lives quietly and gradually thanks to the presence of wireless communication systems. On a global scale, the number of objects that can be described as devices and connections is growing faster than the human population. Therefore, this situation accelerates the increase in the average number of devices and connections per household and per person. Every year, new devices in different forms with increasing talent and intelligence are introduced and adopted. An increasing number of M2M applications, such as smart meters, healthcare monitoring, transportation and packaging, or asset tracking, make a significant contribution to the growth of devices and connections.

In this context, various definitions used in the literature on the concept of IoT are given as follows:

(i) It is the network of systems created by connecting devices, vehicles, and living things to each other or other systems [1]
(ii) It is a system of devices that share information and network by connecting to each other thanks to various communication protocols [2]
(iii) It is the application area where different technologies integrated with each other are used in social life [3]

(iv) These are systems where devices connected to the Internet share data over the Internet to meet the needs of people without the need for human intervention [4]

(v) It is a system that enables critical and effective use of services such as critical infrastructure, education, health, security, and transportation related to a settlement by using information and communication technologies [5]

(vi) It is a community and marketplace made up of smart devices that communicate with each other using various communication protocols, produce information, and exchange information with their surroundings thanks to the network they create [6]

The concept of the IoT was first mentioned in a presentation prepared by Kevin Ashton in 1999 for the company Procter and Gamble. In fact, in his presentation, Ashton listed the benefits of the company with the use of RFID (Radio Frequency Identification) technology. However, Ashton may have led the concept of the IoT that attracts attention and many products in this direction by putting forward the idea of connecting all devices to each other. With the "ITU Internet report 2005: Internet of Things" report published by the International Telecommunication Union (ITU) in 2005, the IoT concept was officially announced [7]. Then, in 2009, a report titled "Internet of Things—Action Plan for Europe" was published by the European Commission [8]. Similarly, in the European Union report published in 2013, it was emphasized that the findings of the public survey conducted in 2012 show that the IoT technologies will facilitate the lives of individuals in areas such as health, social life, transportation, environment, and energy [9].

According to the report published by Cisco in 2011, in 2003, 500 million devices were connected to the Internet and the number of devices per person was 0.08. In 2010, the number of devices increased to 12.5 billion and the number of devices per person increased to 1.84. By 2020, it is estimated that the world population will be 7.6 billion and the number of devices connected to the Internet will be 50 billion [10]. According to Cisco Annual Internet Report (2018–2023), it is estimated that approximately two-thirds of the world’s population will have Internet access by 2023. In addition, by 2023, it is predicted that the number of devices to be connected to the network by obtaining an IP address will be more than three times the global population. Thus, the number of devices connected to the network in 2018 is expected to increase from 18.4 billion to 29.3 billion in 2023. Within such a large and uncontrollable ecosystem, IoT poses several new problems. These problems that the new IT world has to deal with are listed and briefly explained as follows [11].

(i) Security issues: as people, businesses, and countries have increased loyalty to IoT, hackers and malicious people also have a desire to access and steal data. Therefore, security is the biggest problem that IoT has to overcome.

(ii) Privacy issues: most IoT apps collect and process information to make people's daily lives easier. Since most of this data can be described as personal data, privacy problems arise. Such questions require careful analysis and risk-reducing solutions, especially from a legal perspective.

(iii) Interoperability and standards-related problems: although IoT applications work with the Internet TCP/IP infrastructure and server/client architecture, many nonstandard protocols have been developed to allow objects with low processing capacities to communicate better and to operate data transfers effectively. This diversity raises interoperability problems.

(iv) Legal problems: legislation has recently been on the agenda for the solution of the problems experienced by the ownership of the data collected by IoT applications. The national level studies on this issue may be insufficient for global IoT practices.

(v) Economic development problems: IoT applications and developed technologies significantly change the economy. It is thought that dark factories and unmanned transportation vehicles can cause serious development problems. These technologies make it possible to decrease the workforce based on manpower, that is, to increase unemployment or open new business areas. It is argued that developed countries can overcome these problems partially, but developing or underdeveloped countries are expected to experience serious crises.

2. IoT and Security

Devices manufactured for IoT applications provide many advantages, as well as many disadvantages inherently. These disadvantages and the wide ecosystem are of particular interest to attackers. Below are some of the reasons why these devices were chosen as targets by attackers:

(i) Excessive number of devices: as mentioned at the beginning of the study, the number of devices used in the IoT area is quite above the number of laptops or desktop computers. The large surface area is interesting for attackers, because, from the point of view of the attacker, the more the devices there are, the more the entry points that can be captured.

(ii) Resource use is limited: devices used in the IoT are manufactured only to use resources to the extent that they perform their tasks. Therefore, it is not
possible to apply various security measures such as firewall, antivirus software on computers to such devices. This situation predicts that these devices can be easily targeted by attackers.

(iii) Producers’ ability of preventing operability: companies producing devices within the scope of the IoT are primarily aimed at operating the system in a healthy way. These manufacturers often try to create new products as security problems arise. First products are offered to the market with weak security measures due to the target of being the first and most used product in the market.

(iv) Collection of personal information: IoT products, especially the ones for the end user, collect and save a great deal of personal information. For example, health practices, home automation systems can be counted in this category. Certainly, storing the private information of individuals in a system attracts the attention of the attackers and increases the attacks on this subject.

(v) Software updates that are not delivered on time: manufacturers only release updates when there is a problem or when there is a high level of innovation. However, delays in situations where these updates cannot be applied to all systems, or not applied at all, and instead encouraging the consumer to buy new products create particular security problems.

(vi) Manufacturer’s back door release: manufacturer companies use various access methods, known as back doors, to interfere with the devices remotely. If this method is detected by attackers, all devices can remain vulnerable.

(vii) Default usernames and passwords: most devices are launched with the default username and password provided at the factory during initial setup to connect to the admin interface. In this way, the devices used without changing the default settings can be easily captured.

The devices used in the IoT are in cyber space, and the components that make up cyber space are not inherently safe. At the heart of the problem lies the lack of security in the TCP/IP communication protocol. The data in IP packets is readable with simple software that most people can use, which proves the insecurity of cyber space.

In the informatics world, security is the provision of three main principles in general. These three principles are as follows [11]:

(i) Confidentiality: only authorized users can see the information.
(ii) Integrity: only authorized users can change the information.
(iii) Availability: information is always available when authorized users request it.

The most important problem for data transfer systems is privacy. In the IT world, confidentiality means protecting data from anyone except those who have an access right. The most important and functional technical data is encrypted by using cryptographic algorithms to ensure confidentiality. According to the Unit42 report, 98% of the IoT device traffic is transmitted on the network unencrypted. In addition, 57% of these devices are vulnerable to medium or high severity attacks [12]. This means that personal or corporate data transmitted by IoT applications are insecure. Therefore, data transmission must be encrypted.

Encryption algorithms are divided into two groups, symmetric and asymmetric algorithms. Symmetric algorithms use the same key (secret key) for encryption and decryption. Asymmetric encryption algorithms, on the other hand, use a public key for encryption, while using a secret key for decryption. Symmetric encryption algorithms work fast compared to asymmetric encryption algorithms. In these algorithms, plain text is encrypted using a secret key and transmitted to the other party. The encrypted text is decrypted again using the same secret key. Symmetric encryption algorithms can be examined in 2 categories: block ciphers and stream ciphers. Block ciphers cryptographic algorithms process open text in bit groups called fixed-length blocks. The encrypted text is revealed by decrypting the blocks with a key. In the deciphering process, the encrypted text is turned into plain text with the help of the same key. When the literature is analyzed, it is seen that block ciphers are used in IoT applications.

3. Lightweight Cryptographic Algorithms

Cryptographic algorithm solutions to be used in the IoT should be designed and implemented in accordance with the limited resources of the devices used in IoT applications. This necessity has created a new encryption area under the name of lightweight cryptography, which can be used more effectively for small size, low energy, and small footprint such as RFID tags, sensors, and contactless smart cards. In the world of data transmission, AES [13] is generally used as it is a secure standard. Although AES is a safe standard, it is not suitable for hardware restricted devices. It is known that a new solution other than AES is needed especially for applications that need to work with low power. Because in the 16 years since the adoption of AES, many technological innovations have emerged. On the other hand, [14] state that 2000 GE area is reasonable for RFID and similar devices and also integrated circuits for this should be produced. However, AES implementations have a 2400 GE area in the best conditions [15].

The purpose of lightweight cryptography is to provide algorithms that provide information security by using limited resources such as space, power consumption, and energy consumption. Many lightweight algorithms have been produced to achieve this goal. The majority of algorithms developed are block encryption algorithms. Throughout the study, PRESENT [16], CLEFIA [17], PICOLO [18], PRINCE [19], and LBLOCK [20] lightweight
cryptographic algorithms were analyzed. The reason for choosing these algorithms can be explained as follows. PRESENT and CLEFIA are standardized as lightweight block cipher algorithm with the document ISO/IEC 29192-2: 2012 [21] which specifies the requirements for lightweight cryptography. On the other hand, PICCOLO, PRINCE, and LBLOCK are still in use for IoT applications. Also, all of these algorithms are suitable for hardware applications.

General information for analyzed algorithms is given in Table 1 and in this section some detailed information is summarized about the structures of algorithms.

3.1. PRESENT. PRESENT [16] is a block cipher developed by Orange Labs, Ruhr University Bochum, and Technical University of Denmark in 2007. With the document ISO/IEC 29192-2: 2012 [21], it is standardized as lightweight block cipher algorithm. It is the most known and used lightweight encryption algorithm. It supports 64- or 128-bit key options, having a 64-bit block length. The algorithm is designed with SPN architecture and consists of 31 rounds. The round structure of the PRESENT encryption algorithm is given in Figures 1 and 2. Each round consists of key addition, nonlinear S-Box layers, and linear bitwise permutation layers.

Round key \((K_i = k_{i-3}, \ldots, k_0)\) and round input bits \((b_{63}, \ldots, b_0)\) are entered into the XOR operation as follows, with \(1 \leq i \leq 32\) in the key insertion phase. Here, 32 XOR process is used for final bleaching. In the nonlinear displacement process, the following S-box defined as 4-bit \(S: \mathcal{F}_4^2 \rightarrow \mathcal{F}_4^2\) is used.

\[
|x| \quad 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7 \quad 8 \quad 9 \quad A \quad B \quad C \quad D \quad E \quad F
\]
\[
S(x) \quad C \quad 5 \quad 6 \quad B \quad 9 \quad 0 \quad A \quad D \quad 3 \quad E \quad F \quad 8 \quad 4 \quad 7 \quad 1 \quad 2
\]

Linear bitwise permutation process was performed according to the following table. Accordingly, the bit in position \(i\) is transferred to position \(P(i)\).

\[
|i| \quad 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7 \quad 8 \quad 9 \quad 10 \quad 11 \quad 12 \quad 13 \quad 14 \quad 15
\]
\[
P(i) \quad |0| \quad 16 \quad 32 \quad 48 \quad 1 \quad 17 \quad 33 \quad 49 \quad 2 \quad 18 \quad 34 \quad 50 \quad 3 \quad 19 \quad 35 \quad 51
\]
\[
|i| \quad 16 \quad 17 \quad 18 \quad 19 \quad 20 \quad 21 \quad 22 \quad 23 \quad 24 \quad 25 \quad 26 \quad 27 \quad 28 \quad 29 \quad 30 \quad 31
\]
\[
P(i) \quad 4 \quad 20 \quad 36 \quad 52 \quad 5 \quad 21 \quad 37 \quad 53 \quad 6 \quad 22 \quad 38 \quad 54 \quad 7 \quad 23 \quad 39 \quad 55
\]
\[
|i| \quad 32 \quad 33 \quad 34 \quad 35 \quad 36 \quad 37 \quad 38 \quad 39 \quad 40 \quad 41 \quad 42 \quad 43 \quad 44 \quad 45 \quad 46 \quad 47
\]
\[
P(i) \quad 8 \quad 24 \quad 40 \quad 56 \quad 9 \quad 25 \quad 41 \quad 57 \quad 10 \quad 26 \quad 42 \quad 58 \quad 11 \quad 27 \quad 43 \quad 59
\]
\[
|i| \quad 48 \quad 49 \quad 50 \quad 51 \quad 52 \quad 53 \quad 54 \quad 55 \quad 56 \quad 57 \quad 58 \quad 59 \quad 60 \quad 61 \quad 62 \quad 63
\]
\[
P(i) \quad 12 \quad 28 \quad 44 \quad 60 \quad 13 \quad 29 \quad 45 \quad 61 \quad 14 \quad 30 \quad 46 \quad 62 \quad 15 \quad 31 \quad 47 \quad 63
\]

As in [22–25], there are successful attacks to reduced-round of PRESENT. However, there is no successful attack published in the literature for full-round PRESENT.

3.2. CLEFIA. CLEFIA [17] is an algorithm developed by Sony Corporation that encrypts 128-bit data blocks with 128-, 192-, and 256-bit key options. It has been standardized as a lightweight block cipher algorithm with ISO/IEC 29192-2: 2012 [21] document like PRESENT. The algorithm using the Feistel architecture encrypts at 18 rounds for 128-bit key length, while it is encrypting at 22 and 26 rounds for 192- and 256-bit key lengths, respectively. Each round consists of 4 buses and two 32-bit F functions. CLEFIA round structure is given in Figure 3. In the encryption process, \(P, C \in \{0, 1\}^{128}\), with \(P\) plain text and \(C\) encrypted text.

In addition, 4 pieces in the form of \(P = P_0|P_1|P_2|P_3\), with \(P, C \in \{0, 1\}^{128}\), are processed in the data paths to obtain \(C = C_0|C_1|C_2|C_3\) which is a C encrypted text. In the first and last round, \(WK_0, WK_1, WK_2, WK_3 \in \{0, 1\}^{32}\) is used for key whitening. Round keys from the key generation phase are specified as \(RK_i \in \{0, 1\}^{32}\) \((0 \leq i < 2r)\), with \(r\) being the number of rounds. As a first step, \(P_1\) and \(P_3\) of the open text are taken to XOR with \(WK_0\) and \(WK_1\).

Then, \(P_0\) block is taken to the function \(F_0\) with the key \(RK_2\) and \(F_0(WK_2, P_0)\) being performed. The result is taken to the XOR transaction with the result of the \(P_0 \oplus WK_0\) transaction. Likewise, the \(P_2\) block is taken to the \(F_1\) function with the \(RK_1\) key and the result obtained by performing the \(F_1(WK_1, P_2)\) operation is taken to the XOR operation with the result of the \(P_2 \oplus WK_1\) operation. By changing the \(P_0 \oplus P_1 \oplus P_2 \oplus P_3\) block formed at the end of the round to
$P_0 \rightarrow P_3, P_1 \rightarrow P_0, P_2 \rightarrow P_1, P_3 \rightarrow P_2$, the next round is passed. The $P_1$ and $P_3$ parts of the function outputs of the last round are taken to XOR with $WK_2$ and $WK_3$.

$F_0$ and $F_1$ functions enable $F_0$, $F_1 : (RK, x) \rightarrow y$ in the encryption process. The diagrams of the functions are given in Figure 4. $S_0$ and $S_1$ which are specified in the functions are nonlinear 8-bit S-boxes. The order of use of S-boxes in $F_0$ and $F_1$ functions is different. The $M_0$ and $M_1$ matrices used in functions are $4 \times 4$ in Hadamard form and are defined by the object formed by the $x^3 + x^4 + x^3 + x^2 + 1$ irreducible polynomial in $GF(2^8)$ as a result of matrix multiplications.

The designers of CLEFIA consider that any attack does not threaten full-round CLEFIA. They analyzed against the differential cryptanalysis, linear cryptanalysis, impossible differential cryptanalysis, and square attack. In [26–31], there are some successful attacks to reduced-round of CLEFIA. However, there is no successful attack published in the literature for full-round CLEFIA.

### 3.3. PICCOLO

PICCOLO [18] is an algorithm that encrypts 64-bit data blocks, optimized for devices with extremely limited capacity by Sony, such as CLEFIA, with 80- and 128-bit key options. The designers of the algorithm are Kyoji Shibutani et al., Takanori Isobe, Harunaga Hiwatari, Atsushi Mitsuda, Toru Akishita, and Taizo Shirai. The algorithm using Feistel architecture encrypts at 25 rounds for 80-bit key length, while it is encrypting at 31 rounds for 128-bit key

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**Table 1: General information for analyzed algorithms.**

| Encryption algorithm | Year | Block size | Key size | Number of rounds | Architecture | Application area |
|----------------------|------|------------|----------|------------------|--------------|-----------------|
| PRESENT              | 2007 | 64         | 80, 128  | 31               | SPN          | Hardware        |
| CLEFIA               | 2007 | 128        | 128, 192, 256 | 18, 22, 26 | Feistel      | Software, hardware |
| PICCOLO              | 2011 | 64         | 80, 128  | 25, 31           | Feistel      | Hardware        |
| PRINCE               | 2012 | 64         | 128      | 12               | SPN          | Hardware        |
| LBLOCK               | 2011 | 64         | 80       | 32               | Feistel      | Software, hardware |

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**Figure 1: PRESENT encryption algorithm diagram.**

**Figure 2: PRESENT encryption round structure.**
lengths. In the encryption phase, 64-bit open text is divided into 4 16-bit pieces. After the 1st and 3rd parts whitening switch is put into XOR operation with $w_k_0$ and $w_k_1$, the results are processed with the F function. The function output is subjected to XOR operation with the round switches $r_k_0$ and $r_k_1$. Before the results are transferred to the next round, they are taken to the permutation process with the RP layer. The round structure of the PICCOLO encryption process is given in Figure 5.

The F function defined as $F: \{0, 1\}^{16} \rightarrow \{0, 1\}^{16}$ used in the rounds in the PICCOLO algorithm is given in Figure 6. Accordingly, the 16-bit input value passes primarily through the 4-bit S-boxes as follows:

$$ (x_0, x_1, x_2, x_3) \longmapsto (S(x_0), S(x_1), S(x_2), S(x_3)). $$

The S-box used at this stage is as follows.

| $x$ | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | A | B | C | D | E | F |
|-----|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $S(x)$ | E | 4 | B | 2 | 3 | 8 | 0 | 9 | 1 | A | 7 | F | 6 | C | 5 | D |
3.4. PRINCE. PRINCE [19] is an algorithm that encrypts 64-bit data blocks with a 128-bit key. Hardware optimized PRINCE was designed by Borghoff et al. presented in Asiacrypt 2012. The algorithm, which has a structure called FX, performs the encryption by using a different key. According to the designers’ suggestion, the algorithm that encrypts in 12 steps divides the 128-bit key into two 64-bit pieces as \( k = k_0 k_1 \). Then, \( k_0 k_0' k_1 k_1' \) conversion is performed so that 192 bits are expanded to \( k_0' = (k_0 \gg 1) \oplus (k_0 \gg 63) \).

3.5. LBLOCK. LBLOCK [20] is an algorithm that encrypts 64-bit data blocks proposed by Wu and Zhang with an 80-bit key. It is designed to be efficient and safe on equipment that works with limited resources. The algorithm that uses Feistel architecture completes the encryption process in 32 rounds. In encryption process, 64-bit \( M \) open text is divided into two 32-bit pieces as \( M = X_1 | X_0 \). Then, \( X_1 \) and \( K_1 \) round keys are taken to the \( F \) round function, and XOR operation is taken with the result of \( X_0 \oplus 8 \), which cyclically shifted 8 bits to the left. The result is saved as the \( X_5 \) value of the next round. At the end of 32 rounds, \( M \) open text is encrypted as \( C = X_{32} | X_{33} \). The LBLOCK round structure is given in Figure 9.

The \( F \) round function, which takes place in the LBLOCK encryption algorithm, includes the steps of passing the input values to the XOR through the S-boxes and then applying the diffusion process. The expression of the \( F \) round function is as follows. The diagram is given in Figure 10:

\[
F: \{0,1\}^{32} \times \{0,1\}^{32} \rightarrow \{0,1\}^{32},
\]

\[
(X, K_i) \rightarrow U = P(S(X \oplus K_i)).
\]

8 different 4-bit S-boxes are used in the \( F \) round function. Accordingly, by XORing with \( K_i \) round key, 32-bit \( X \) value is divided into 8 pieces of 4 bits in the form of \( X = X_7 | X_6 | X_5 | X_4 | X_3 | X_2 | X_1 | X_0 \) and \( s_7, s_6, s_5, s_4, s_3, s_2, s_1, s_0 \) is passed through S-boxes and transferred to diffusion layer. The \( X \) value passing through the S-boxes in the \( F \) round function is taken to diffusion. The diffusion process for the LBLOCK algorithm is designed as a permutation of 8 values of 4 bits. Accordingly, the \( X_7 | X_6 | X_5 | X_4 | X_3 | X_2 | X_1 | X_0 \) entries coming to the diffusion stage are listed as \( X_7 | X_6 | X_5 | X_4 | X_3 | X_2 | X_1 | X_0 \).

As in [43–48], there are some successful attacks to reduced-round of LBLOCK. However, there is no successful attack published in the literature for full-round LBLOCK.

4. Test Environment and Results

In this study, MSP-EXP430FR5994 LaunchPad Development Kit [49] is selected from MSP430 family, which is the product of Texas Instruments (TI) firm used in the industry
has low power consumption and is very efficient thanks to its new technology Low-Energy Accelerator (LEA). It can process analog data in real time. It has built-in eZ-FET debugging feature. With the help of this feature, the performance of the encryption code can be tested and analyzed regardless of any device. Eclipse based Code Composer Studio (CCS) [50], which can be used in devices manufactured by TI, has been used as a development environment. All lightweight encryption algorithms were compiled with C code in CCS and transferred to MSP430FR5994 device. Energy, power, and current measurements of the algorithms were carried out through EnergyTrace software [51]. EnergyTrace technology is an energy-based code analysis tool that measures and displays the energy profile of the application and also helps optimize for ultra-low power consumption. It works integrated within Code Composer Studio. It has two modes, EnergyTrace and EnergyTrace++. Basic energy measurements can be made with the EnergyTrace mode. The supply voltage in the microcontroller is sampled continuously to measure energy and power. This mode can be used to verify the application’s energy consumption without accessing the debugger. EnergyTrace++ mode provides basic energy measurements as well as information about the internal status of the microcontroller such as RAM usage and energy modes. MSP430FR5994 used in the test environment is given in Figure 11.

For a secure communication environment, the task of edge devices such as MSP430 can be summarized as encrypting the data they receive from the sensors, transmitting them to cloud, server or broker role devices, and deciphering and processing data from such devices. In other words, usually these devices only encrypt or decrypt data. For this reason, encryption and decryption are considered separately for each algorithm in the scenario used in the test environment. Since the energy consumption of data transmission differs according to communication technologies such as Bluetooth, Wi-Fi, Zigbee, Z-Wave, 6LoWPAN,
The eZ-Fet on-board debug probe enables debugging/programming as well as communication back to the PC. The eZ-Fet can also provide power to the target MCU.

Energy trace technology Real-time power consumption readings & state updates from the MSP430FR5994 MCU, including CPU and peripheral state are viewable through the Energy Trace GUI

Jumpers to isolate debug problem from target MCU

Figure 11: MSP430FR5994 overview.

The test scenario

| Data encryption or decryption | Sleep mode |
|-------------------------------|------------|
| Active mode (AM)              | Low power mode (LPM) |

Start
Energy trace™

0 1 2 3 4 5 6 7 8 9 10
Time (seconds)

Stop
Energy trace™

Figure 12: The timing diagram of test scenario.

Relative power

| Relative power (mW) |
|---------------------|
| 1.8                 |
| 1.7                 |
| 1.6                 |
| 1.5                 |
| 1.4                 |
| 1.3                 |
| 1.2                 |
| 1.1                 |
| 1.0                 |
| 0.9                 |
| 0.8                 |
| 0.7                 |
| 0.6                 |
| 0.5                 |
| 0.4                 |
| 0.3                 |
| 0.2                 |
| 0.1                 |
| 0                  |

0 1 2 3 4 5 6 7 8 9 10
Time (s)

Figure 13: PRESENT encryption power consumption.
Figure 14: PRESENT decryption power consumption.

Figure 15: AM-LPM transitions for PRESENT encryption (a) and decryption (b).

Figure 16: LBLOCK encryption power consumption.
Figure 17: LBLOCK decryption power consumption.

Figure 18: AM-LPM transitions for LBLOCK encryption (a) and decryption (b).

Table 2: Energy consumption of the analyzed algorithms.

| Cipher  | Architecture | Block length | Key length | Number of rounds | Procedure | Energy (mJ) |
|---------|--------------|--------------|------------|------------------|-----------|-------------|
| PRESENT | SPN          | 64           | 80         | 31               | Encryption | 9.523       |
|         |              |              |            |                  | Decryption | 9.573       |
|         |              | 128          |            |                  | Encryption | 9.128       |
|         |              |              |            |                  | Decryption | 9.128       |
|         |              | 128          | 192        | 22               | Encryption | 9.452       |
|         |              |              |            |                  | Decryption | 9.494       |
|         |              | 128          | 256        | 26               | Encryption | 9.452       |
|         |              |              |            |                  | Decryption | 9.575       |
| CLEFIA  | Feistel      | 128          |            |                  | Encryption | 8.487       |
|         |              |              |            |                  | Decryption | 8.490       |
|         |              | 128          | 256        | 25               | Encryption | 8.533       |
|         |              |              |            |                  | Decryption | 8.547       |
| PICCOLO | Feistel      | 64           | 80         | 25               | Encryption | 7.513       |
|         |              |              | 128        | 31               | Decryption | 7.549       |
| PRINCE  | SPN          | 64           | 128        | 12               | Encryption | 5.812       |
|         |              |              |            |                  | Decryption | 5.924       |
| LBLOCK  | Feistel      | 64           | 80         | 32               | Encryption |             |
|         |              |              |            |                  | Decryption |             |
Table 3: Power consumption of the analyzed algorithms.

| Cipher   | Key length | Number of rounds | Procedure   | Power (mW) Max | Power (mW) Avg |
|----------|------------|------------------|-------------|---------------|---------------|
| PRESENT  | 80         | 31               | Encryption  | 1.6383        | 0.9548        |
|          |            |                  | Decryption  | 1.6374        | 0.9591        |
| CLEFIA   | 128        | 18               | Encryption  | 1.6036        | 0.9186        |
|          | 192        | 22               | Encryption  | 1.6123        | 0.9187        |
|          | 256        | 26               | Encryption  | 1.6040        | 0.9482        |
| PICCOLO  | 80         | 25               | Encryption  | 1.1419        | 0.8439        |
|          | 128        | 31               | Encryption  | 1.1768        | 0.8449        |
|          |            |                  | Decryption  | 1.1886        | 0.8495        |
| PRINCE   | 128        | 12               | Encryption  | 1.1694        | 0.7578        |
|          |            |                  | Decryption  | 1.2797        | 0.7621        |
| LBLOCK   | 80         | 32               | Encryption  | 0.8295        | 0.5799        |
|          |            |                  | Decryption  | 0.8605        | 0.5894        |

Table 4: Current measurements of the analyzed algorithms.

| Cipher   | Key length | Number of rounds | Procedure   | Current (mA) Max | Current (mA) Avg |
|----------|------------|------------------|-------------|-----------------|-----------------|
| PRESENT  | 80         | 31               | Encryption  | 0.4982          | 0.2905          |
|          |            |                  | Decryption  | 0.4980          | 0.2918          |
| CLEFIA   | 128        | 18               | Encryption  | 0.4877          | 0.2795          |
|          | 192        | 22               | Encryption  | 0.4905          | 0.2795          |
|          | 256        | 26               | Encryption  | 0.4877          | 0.2885          |
| PICCOLO  | 80         | 25               | Encryption  | 0.3472          | 0.2568          |
|          | 128        | 31               | Encryption  | 0.3579          | 0.2570          |
|          |            |                  | Decryption  | 0.3614          | 0.2585          |
| PRINCE   | 128        | 12               | Encryption  | 0.3863          | 0.2306          |
|          |            |                  | Decryption  | 0.3892          | 0.2319          |
| LBLOCK   | 80         | 32               | Encryption  | 0.2522          | 0.1764          |
|          |            |                  | Decryption  | 0.2617          | 0.1793          |

Table 5: Estimated battery life for the analyzed algorithms.

| Cipher   | Key length | Number of rounds | Procedure   | Battery life (2 × AA batteries) |
|----------|------------|------------------|-------------|---------------------------------|
| PRESENT  | 80         | 31               | Encryption  | 9 months and 21 days            |
|          |            |                  | Decryption  | 9 months and 19 days            |
| CLEFIA   | 128        | 18               | Encryption  | 10 months and 2 days            |
|          | 192        | 22               | Encryption  | 10 months and 3 days            |
|          | 256        | 26               | Encryption  | 10 months and 23 days           |
|          |            |                  | Decryption  | 9 months and 22 days            |
|          |            |                  | Encryption  | 9 months and 23 days            |
|          |            |                  | Decryption  | 9 months and 19 days            |
| PICCOLO  | 80         | 25               | Encryption  | 10 months and 27 days           |
|          | 128        | 31               | Encryption  | 10 months and 26 days           |
|          |            |                  | Decryption  | 10 months and 25 days           |
|          |            |                  | Encryption  | 10 months and 24 days           |
| PRINCE   | 128        | 12               | Encryption  | 1 year and 9 days               |
|          |            |                  | Decryption  | 1 year and 7 days               |
| LBLOCK   | 80         | 32               | Encryption  | 1 year and 3 months             |
|          |            |                  | Decryption  | 1 year and 3 months             |
and LoRaWAN, it is not considered in this scenario. According to the scenario determined in the test environment, after running MSP430FR5994, it will switch to active mode (AM) in every second, it will perform the encryption or decryption process, and then it will go into the power saving mode LPM (Low Power Mode). The timing diagram of test scenario is shown in Figure 12. Energy, power, and current data of algorithms were measured with EnergyTrace software by operating the device for 10 seconds in this way. The energy consumption of the tested algorithms was determined by compiling the obtained results.

Considering the PRESENT algorithm, the encryption process worked on MSP430FR5994 for 10 seconds, consuming 9.523 mJ of energy. As seen in Figure 13, on average, it consumed 0.9548 mW and at most 1.6383 mW. An average of 0.2905 mA and a maximum of 0.4982 mA current were drawn. In this way, the device can work with 2 AA batteries for 9 months and 21 days.

MSP430FR5994 completed the PRESENT encryption process in active mode at 15.5% of the 10 seconds of its operating time and the rest in the LPM mode at 84.5%. This situation can be seen in Figure 15. The device spent only 23% of its total energy consumption when encrypting in active mode. Similar results were obtained in the deciphering process.

Energy measurements of the algorithms examined throughout the study are given in Table 2, power measurements are given in Table 3, current measurements are given in Table 4, estimated battery life is given in Table 5, and operating time and active mode rates according to the energy consumed are given in Table 6.

| Cipher | Key length | Number of rounds | Procedure | Active mode (time) | Active mode (energy) |
|--------|------------|-----------------|-----------|-------------------|---------------------|
| PRESENT | 80         | 31              | Encryption | %15.5             | %23.0               |
|         |            |                 | Decryption | %15.8             | %23.0               |
|         | 128        | 18              | Encryption | %9.9              | %14.7               |
|         |            |                 | Decryption | %10.0             | %14.8               |
|         | 192        | 22              | Encryption | %14.0             | %20.4               |
|         |            |                 | Decryption | %14.0             | %20.3               |
|         | 256        | 26              | Encryption | %15.4             | %22.1               |
|         |            |                 | Decryption | %15.4             | %22.1               |
| CLEFIA  | 80         | 25              | Encryption | %1.8              | %2.9                |
|         | 128        | 22              | Encryption | %1.9              | %3.1                |
|         | 192        | 26              | Encryption | %1.8              | %2.9                |
|         | 256        | 26              | Encryption | %1.9              | %3.1                |
| PICCOLO | 80         | 25              | Encryption | %26.8             | %38.8               |
|         | 128        | 31              | Encryption | %26.9             | %39.0               |
| PRINCE  | 128        | 12              | Encryption | %2.2              | %3.9                |
|         |            |                 | Decryption | %2.2              | %3.8                |
| LBLOCK  | 80         | 32              | Encryption | %2.2              | %3.9                |
|         |            |                 | Decryption | %2.2              | %3.8                |

5. Conclusions

The role of energy consumption is emphasized in this study, which was conducted to guide future studies. Access to devices can be difficult, depending on the usage areas of IoT applications. For this reason, parameters such as energy consumption and battery life should be considered when preparing secure communication applications. As mentioned earlier, communication of IoT applications is mostly unsafe. The safest and cheapest method to ensure security is data encryption.

In this study, PRESENT, CLEFIA, PICCOLO, PRINCE, and LBLOCK lightweight cryptographic algorithms, which can be used to secure data in IoT applications, were analyzed in a test environment in terms of energy consumption. The test devices were chosen from the edge devices used in the industry.
PRESENT and CLAFIA algorithms are standardized as lightweight block cipher algorithm with ISO/IEC 29192-2: 2012 document. However, these algorithms emerged at the time when Internet applications of objects had just become widespread. As a result of the tests, the energy consumption of the algorithms, current measurement, active mode working time, and active mode energy consumption were identified. The results are listed in Tables 2–6.

Accordingly, LBLOCK, which encrypts the minimum energy 64-bit block length with an 80 bit key, is used by CLEFIA, which decrypts the 128-bit block length with a 256-bit key. While the LBLOCK algorithm was first in power consumption, other algorithms gave similar values. LBLOCK takes first place in current measurement. Considering the active mode times of the device in encryption and decryption processes, PICCOLO and LBLOCK went ahead, while the PRINCE algorithm had quite bad results. Finally, when active mode energy ratios are examined, it is seen that PICCOLO and LBLOCK algorithms take the first place.

When the results obtained in the study are examined, it can be said that the number of loops and block size of the algorithms make a difference in terms of energy consumption, current measurement, active mode working time, and active mode energy consumption. CLEFIA is the encryption algorithm that has the largest block length among the algorithms examined with 128-bit block length, while, in other algorithms, 64-bit is preferred as block length. This is inherently important for devices operating in the Internet applications of low-capacity objects. It is more efficient to encrypt small size blocks. Also, those that give good results from the studied algorithms use Feistel architecture. On the other hand, increased key size decreases energy efficiency. Of course, the larger the key size is, the better the security is provided. However, in the IoT applications, the keys between 80 bits and 128 bits can be considered ideal. Selecting the structures in the algorithms in a simple way that does not consume too much energy increases efficiency. Energy consuming structures such as reduction processes and mixed bumps used in CLEFIA and PICCOLO algorithms prove this situation. It can be concluded that the reason for the LBLOCK algorithm to come first in these measurements is due to simple operations such as XOR and S-boxes in its structure.

There is no AES-like standard in the industry of IoT for lightweight algorithms. For this reason, it is possible to encounter new encryption algorithms for many new IoT in the near future. Secure data transmission is essential in the field of IoT. However, besides the security, an efficient application is also very important. Therefore, parameters like energy consumption should also be considered for the design of lightweight cryptographic algorithms to be developed in the future.

Data Availability

Data are available upon request to the corresponding author.

Conflicts of Interest

The authors declare no conflicts of interest.

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