LoRCA: Lightweight round block and stream cipher algorithms for IoV systems

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***Abstract*—The Internet of Vehicles (IoV) is a disruptive technology that has a great impact on people's lifestyle and activities. Fully autonomous vehicles are the next generation of connected cars. However, IoV systems suffer from several security threats that could offset the intended advantages. To address the security and privacy issues, several cryptographic and non-cryptographic security solutions should be adopted. However, traditional security solutions might burden the IoV network with further complexity and computational overhead. This would translate into additional performance issues in a network already suffering from big data and large-scale challenges. In this context, lightweight security solutions are needed to reduce the required resources in terms of computations, power and memory, and to optimize the network performance in terms of latency and bandwidth. In this paper, we propose a new lightweight cipher scheme, LoRCA, with dynamic key-dependent structure to provide data confidentiality with minimum resources' requirements. To validate our solution's robustness and efficiency within the IoV context, several performance and security tests were performed. The results show that the proposed solution strikes a good balance between the security level and performance. The proposed LoRCA ciphers achieve a high throughput with an enhancement of at least 100% improvement as compared to the Advanced Encryption Standard (AES), 358% compared to Simon, 388 % improvement for Speck and 24% improvement compared to our previous one round cipher scheme.**

***Index Terms*—Lightweight encryption; dynamic encryption; key-dependent primitives; security analysis; performance analysis.**

I. Introduction

The Internet of Vehicles (IoV) is emerging as an extension of the Internet of Things (IoT) paradigm to interconnect all types of vehicles and to allow online access. This results into a large-scale network with a heterogeneous set of inter-connected devices, while enabling innovative applications to benefit from the huge amount of collected data. However, this will burden the network with new QoS challenges and security issues. In addition to the threats associated with traditional networks, IoV systems gave rise to new types of threats that could have a drastic impact on the privacy and security of data and systems. The security threats affect the different types of security services such as confidentiality, integrity, authentication, and availability (see Figure 1-a). To defend against these security threats, there are some existing solutions that can be divided into two types: cryptographic and non-cryptographic, as shown in Figure 1-b.

Devices with good computational resources and reasonable memory capacity rely on traditional cryptographic algorithms to ensure the required security services. Specifically, data confidentiality and user privacy are essential requirements of any communication system such as IoV. Typically, data confidentiality is ensured by applying encryption, while user privacy can be achieved by using data minimization and pseudonymity features [1]–[5]. In general, data confidentiality is based on Symmetric Key Cryptography (SKC) since it is more efficient than Asymmetric Key Cryptography (AKC) (see Figure 2). The SKC Algorithms [6], [7] are based on a secret key shared between two entities.

Moreover, encryption algorithms can be performed at the block level or in stream mode. In stream cipher mode, the data is mixed (xor-ed) with a pseudo-random stream called "key-stream", usually at the byte level; for every byte of data, a random byte is generated and then, both bytes are xor-ed, and the output byte is transmitted as the cipher-byte. However, in the case of block cipher, the data is divided into blocks of fixed size, usually 128 bits. Then, a block cipher employs a reversible round function that is iterated r times on each block [8]. The round function should ensure two essential cryptographic properties according to the famous information theorist "Claude Shannon" [9]. These properties are:

- **Confusion:** It obscures the relationship between the secret key and cipher-text. Typically, the confusion property is satisfied by employing a substitution table, also called S-box or through the use of a nonlinear transformation.

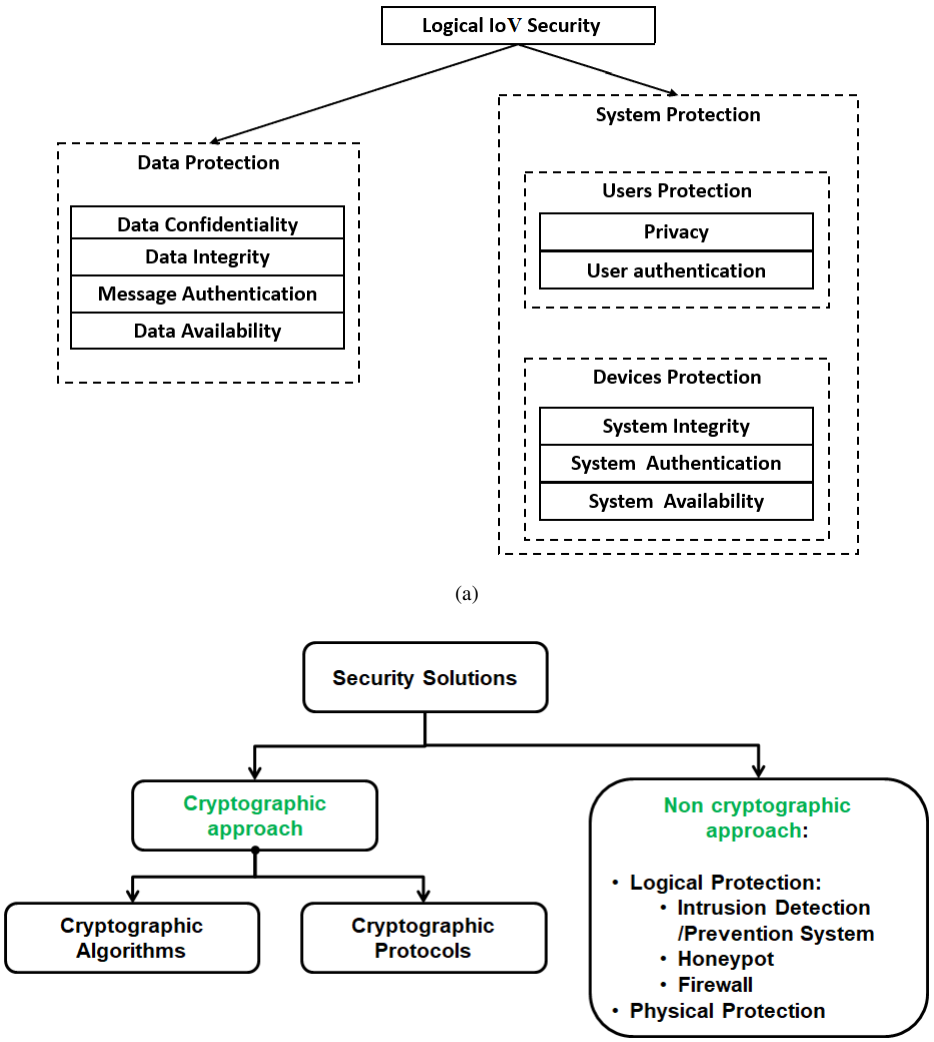


Figure 1: Classification of IoV security services (a) and how can be achieved (b)

- **Diffusion:** It ensures that the influence of one plain-text symbol impacts many cipher-text symbols, with the goal of hiding the statistical properties of the plain-text. The diffusion property can be ensured by using a Permutation table (P-box) such as the case of the Data Encryption Standard (DES) or by using an invertible diffusion matrix such as the " Matrix Distance Separate (MDS)" [10], that is adopted in AES in the "Mix-Column" operation.

The diffusion operation is a linear transformation, while the substitution operation provides a local avalanche effect at the byte (or word) level. Furthermore, the diffusion operation combined with substitution ensure the global avalanche effect after several iterations.

Additionally, a block cipher can be used as a stream cipher when the block cipher is employed to produce a key-stream sequence, which is the case of Output Feed-Back (OFB) and Counter (CTR) operation modes [11]. The security of a stream cipher is based on different metrics that depend on the quality of the produced key-stream sequences, which should exhibit high non-linearity, long periodicity, high level of randomness, and high uniformity degree.

Furthermore, a message authentication algorithm is necessary to guard against threats related to data integrity and source authentication. Message authentication algorithms can be based on a keyed hash function such as HMAC [12] or a block cipher with authentication

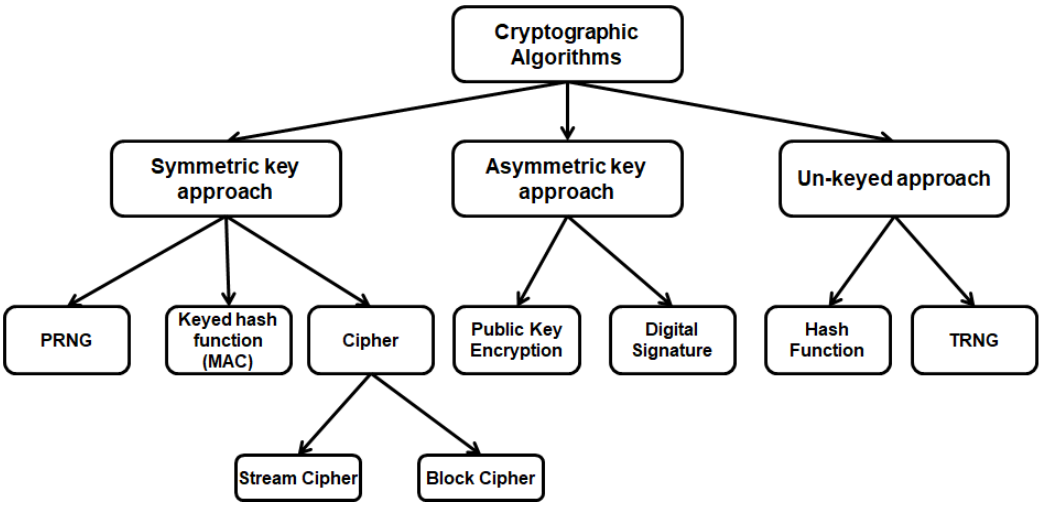


Figure 2: Classification of existing cryptographic algorithms

operation mode, such as CMAC and GMAC [7]. Note that in some cases, data secrecy reinforces privacy since encrypted surveillance videos, for example, may prevent attackers from identifying people.

Due to the fact that traditional SKC algorithms follow a static structure, the substitution and diffusion primitives should be chosen according to their maximum cryptographic performance. For example, the static AES S-box was designed to provide minimum differential probability (to defend against differential attacks) and minimum linear probability (to defend against linear attacks). Also, SKC algorithms use static diffusion operation with a high linear branch number, and a low number of fixed points.

A. Problem Formulation

Many IoV systems and applications are based on sensitive information that must be protected through the adoption of best practices in terms of data confidentiality. However, most of the existing encryption algorithms, as indicated previously, are computationally expensive (r rounds and multi-operations per round) and hence, they are not appropriate for IoV real-time applications and for in-vehicle constrained devices (e.g., micro-controllers).

Even though the existing symmetric ciphers, which are based on a static structure, have shown resistance against linear and differential cryptanalysis attacks, such fixed structures lend themselves to future potential attacks [13], [14]. These attacks would target their fixed structure to recover the secret key. In this case, these existing solutions would have to increase the number of rounds leading to even higher latency and resources overhead. This would reduce further their performance and makes them not suitable for some future systems and applications such as IoV ones.

Accordingly, it is important to design secure and efficient cryptographic algorithms that optimize the trade-off between the security level and the performance overhead. One possible way to achieve this target is to modify the existing SKC structure by using the dynamic key-dependent approach to achieve higher efficiency and robustness against powerful future attacks.

B. Motivation

As shown in Figure 3, an IoV network consists of IoV devices that are connected to a data center (or application servers) through a gateway. The communication between IoV devices and the gateway is wireless. The IoV devices can be interconnected through several gateways. Therefore, a secure end-to-end encryption should be put in place between the IoV devices and the data center or applications servers.

In this context, this paper proposes a new cipher scheme that is suitable for constrained IoV devices, exhibiting the minimum possible amount of computations and latency, while maintaining the required security level. The proposed cipher ensures the data confidentiality security service. Furthermore, the structure of the proposed LoRCA block and stream ciphers consist of iterating two functions (round and update functions) for one round to generate a key-stream block. These functions consist of simple, yet efficient operations allowing them to achieve the needed cryptographic properties. The dynamic key approach is adopted in a way that a

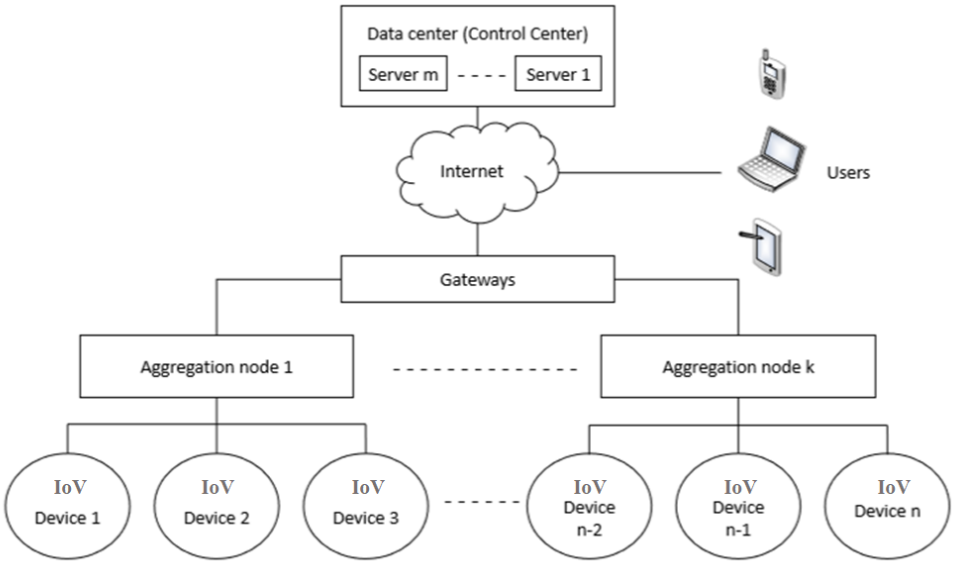


Figure 3: Example of an IoV system with n IoV devices, k aggregation nodes and m servers

different dynamic key is generated and used for each input message (audio, video or image).

C. Contributions

In previous works, we proposed cipher schemes based on the dynamic key approach and with a low number of rounds [15]–[18]. In this paper, the novelty of the proposed cipher schemes lies in the ability to achieve an excellent balance between performance and security for IoV devices, with the main advantages as listed below:

1) Minimum error propagation rate: compared to [18], LoRCA is applied at the block level, which reduces the error propagation rate.
2) Minimum overhead: LoRCA requires a small number of operations. Moreover, no block permutation operation is required, which minimizes delay and memory consumption. Also, compared to [15]–[17], LoRCA reduces the computational complexity by avoiding diffusion/chaining operations.
3) Easier implementation: the solution presented in [18] cannot be deployed on small devices such as Arduino boards or resource-restricted devices since it requires double the memory overhead.
4) Dynamic cipher primitives: LoRCA updates two cryptographic primitives (X and RM that are defined in Section III) after each encrypted/decrypted block. This operation is designed to consume a low overhead in terms of computational resources and latency, yet it offers a high security level.

On the other hand, the contributions of the proposed cipher solution in terms of robustness and efficiency are summarized as follows:

Performance Contributions:

- **Efficiency**: LoRCA avoids diffusion and requires a low number of operations to reduce both resources usage and computational complexity.
- **Flexibility:** LoRCA handles dynamic block lengths (N bytes), where N can be configured depending on the application and device constraints.
- **Simple hardware/software implementations:** HardWare (HW) and SoftWare (SW) implementations of LoRCA are simple and efficient with the use of "Exclusive-OR" logical operation and look-up substitution and permutation operations.
- **Error Tolerance**: Compared to [15], [18], [19], LoRCA provides better resistance to channel errors. Each byte error in any encrypted block affects only the byte itself and does not propagate to other bytes in the corresponding block. In general, the proposed cipher variant is well suited for noisy communication channels since it exhibits low error propagation rate when compared to existing standard block ciphers such as the Advanced Encryption Standard (AES).

Security Contributions:

- **Dynamic Key-Dependent Approach:** Being a dynamic key-dependent cipher scheme, LoRCA re-

lies on cryptographic primitives that change in a pseudo-random manner for every input message. This hardens the statistical/implementation attacks, especially with the use of dynamic encryption keys [15], [19]–[21].

- **Dynamic Cipher Primitives**: Traditional block ciphers use static cipher primitives, which are the same for all input blocks, whereas LoRCA uses dynamic pseudo-random blocks (X and RM). This ensures that the relation among the encrypted blocks is more complex and random, which guarantees its immunity against different analytic attacks since for each input message block, the encryption/decryption is dynamic and variable.

D. Organization

This paper is organized as follows. In Section II, we review the exiting lightweight stream and block cipher schemes along with their limitations. Section III describes the generation of the dynamic key and the associated cryptographic primitives. The variants of LoRCA (stream cipher and block cipher) are detailed in Section IV. Extensive security analysis is presented in Section V to prove that the proposed cipher variants exhibit the desired cryptographic properties. Section VI assesses the robustness of the proposed cipher variants against various types of attacks, while the effectiveness of LoRCA is presented in section VII. Finally, this work is concluded in section VIII with directions for future work.

II. Related Work

As indicated previously, most of the traditional block cipher methods exhibit a high overhead in terms of computations, memory, and power consumption. For example, AES [22] with counter mode requires a relatively large number of rounds with diffusion operations within the round function [18]. Considering other traditional block ciphers, such as the Hummingbird2 cipher [18], the minimum number of required rounds is 4. Therefore, within the IoV context, the traditional cryptographic algorithms lead to poor performance [18]. On the other hand, the scientific interest towards lower overhead cryptography is not only confined to the IoV domain as indicated in [23].

In the ongoing effort to address the computational complexity issue, several lightweight ciphers have been proposed such as LED (PHOTON family) [24], [25], ITUbee [26], RECTANGLE (Substitution–Permutation Network (SPN) based) [27], AKF (Feistel based) [28], Simon and Speck [29]. The Speck algorithm exhibits a lower overhead than the Simon's algorithm, making it more suitable for tiny devices. However, a multi-round structure is still being used by Speck, but with a simple round function. SIMECK, a combination of Speck and Simon, was proposed in [30]. In [31], SIMECK was proven to be vulnerable to bit-flip and random-byte attacks. More recently, other lightweight block ciphers were proposed including LiCi (SPN based) [32], BORON [33], PRESENT [34], GIFT [35], and CHAM [36].

Researchers also used elliptic curve to design lightweight cipher schemes [37]. A primary work, TWINE, was presented in [38], [39]. By combining SPN and the Feistel Network (FN), recent works were proposed including QTL [40], Substitution–permutation Fiestel Network (SFN) [41], to benefit from the advantages of both approaches (SPN and FN). However, using the traditional round function structures (SPN, FN and SFN) with static cryptographic primitives still requires a high number of rounds and operations. Therefore, these ciphers, by design, are not really suitable for limited IoV devices or real-time IoV applications.

Alternatively, chaotic cryptographic algorithms have been proposed to address this issue. However, these algorithms are prone to various security and performance issues such as the need for conversion operations, floating-point computations, and a finite periodicity, in addition to a complex hardware implementation. Moreover, these solutions also use a multi-round structure [42], [43].

On the other hand, stream cipher algorithms, considering only one block of data at a time, are by nature more lightweight than block ciphers, and they require less computational and memory overhead. In this context, different lightweight stream cipher solutions with software and hardware acceleration were proposed such as Grain [44], Trivium [45], Grain-128 [46], Salsa-20 [47], Sosemanuk [48], MICKEY [49], Chacha [50], Encoro-80 [51], Encoro-128 [52], SNOW3G [53], A2U2 [54], and Quavium [55]. In the second generation of lightweight stream cipher cryptography, widely adopted stream ciphers include WG-8 [56], Sprout cipher [57], Fruit [58], Plantlet [59], Espresso [60], and Lizard [61]. However, as indicated previously, these solutions are based on a static round function that iterates for r rounds. Thus, reducing the number of rounds will make them prone to several statistical and analytical attacks.

In summary, the existing encryption algorithms are not designed to be applied for real-time IoV applications, and with tiny devices that are constrained in terms of computational power, resources, and battery lifespan. IoV applications and devices with stringent QoS re-

Table I: List of Notations

Symbol	Definition
SK	Shared secret session key
$nonce$	Nonce that changes per input message
DK	Dynamic key updated per input message
k_{S1} and k_{S2}	Substitution sub-keys
S_1 and S_2	Substitution tables
k_p	Permutation sub-key
k_{RK}	PRNG Seed
RM and IV	Pseudo-random blocks, where IV is required for chaining operation modes (CBC and CTR).
k_{PRM}	Permutation sub-Key used to produce the permutation table π_{RM}
X	PRNG seed, which is updated after each PRNG iteration (each input block)
len	Length of input message
$\lceil x \rceil$	Rounds x to the nearest integer above its current value
nb	Blocks number per input message and is equals to $\lceil \frac{len}{h} \rceil$
h	Bytes number per block message
M	Original message
m_i	i^{th} original plain block
C	Encrypted message
c_i	i^{th} encrypted block
KSA	Key Setup Algorithm of RC4
$MKSA$	Modified KSA of RC4 presented in [18].
$S(m,\ S_1,\ S_2)$	Substitute the bytes of m with odd and even indices by using first substitution table S_1 and S_2, respectively.
$[Y, X] = XorShift64(X)$	Iterates the XorShift PRNG with an input value (block) X to produce a pseudo-random block y (round key).
$x << n$	Left shift operator.
$x >> n$	Right shift operator.

quirements need new security measures that cater to their limitations. Such algorithms and protocols must be "lightweight": they should exhibit a low overhead in terms of resources, computational power, latency and overhead [62], [63].

To this end, researchers tend to design new lightweight round functions that consist of simple operations, or to reduce the number of rounds. Recently, various lightweight cryptographic algorithms have been proposed in [15], [16], [18], [64]. These solutions rely on the dynamic key approach to reduce the required number of rounds and to maintain a high-security level. For example, the cipher schemes described in [15]–[17] require two rounds, while the scheme described in [18] requires only one round and processes two blocks at a time, making it more efficient compared to the previous solutions [15]–[17].

In this work, we aim at enhancing the work done in [18] by designing new block and stream cipher variants that exhibit lower latency and memory consumption in addition to using variable cryptographic primitives (dynamic key-streams: X and RM). The proposed cipher variants achieve a better throughput compared to [18], in addition to reinforcing the security level.

In the following, we describe the proposed key derivation function and the employed techniques to construct the required cryptographic primitives. Then, the proposed block and stream cipher are presented.

III. Proposed Key Derivation Function

The used notations in this section are listed in Table I, and the steps of the dynamic key derivation are illustrated in Figure 4. The input to this function is a shared secret session Key (SK) and a nonce (a unique block that is used for only one session). SK can be renewed per session (or sub-session) according to the IoV application requirements and constraints. Note that the key management between the different IoV entities is outside the scope of this paper. For more information about possible key management solutions, please refer to [7], [65].

For every new input message (or a set of messages, depending on the configuration), a new dynamic key is generated by first xor-ing SK and a $nonce$ and then, hashing the result, as indicated in Eq. 1:

$$DK = hash_{SHA-512}(SK \oplus nonce) \tag{1}$$

where the $nonce$ can be generated by the communicating parties. The size of the nonce is 512 bits, with a corresponding space of potential nonces of 2^{512}, and hence a very low probability of nonce collision. Also, we use the secure hash function SHA-512 [66], which is highly resistant against collisions to produce the required dynamic key with a length of 512 bits (64 bytes). Figure 5 shows a numerical example of this process where all values are represented as bytes with decimal values.

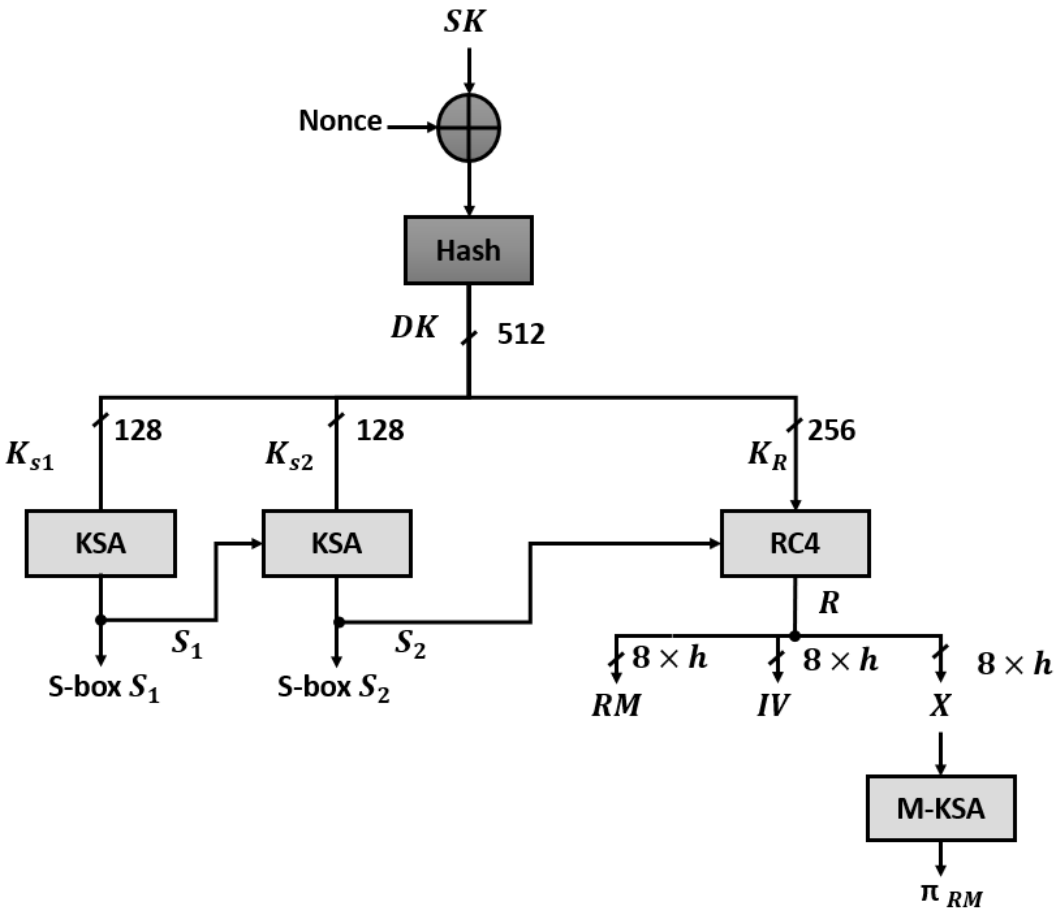


Figure 4: Proposed technique to generate the dynamic key and cryptographic primitives

SK

129	157	236	68	225	16	240	139	212	156	247	229	103	150	164	250

Nonce

33	126	77	80	206	244	186	9	123	88	139	250	100	68	141	28

$SK \oplus Nonce$

160	227	161	20	47	228	74	130	175	196	124	31	3	210	41	230

$DK = hash(Secretkey \oplus Nonce)$

165	198	230	248	146	180	14	229	228	113	11	10	45	141	173	31
176	231	125	118	80	163	79	61	183	236	126	235	169	168	219	162
200	44	217	43	158	30	180	174	249	38	117	78	158	57	187	222
0	218	26	92	55	216	227	58	163	142	144	195	5	137	96	8

Figure 5: A numerical example of the dynamic key generation process

$Sbox\ S_1$

118	89	49	75	110	212	122	113	35	149	94	32	254	44	204	156
47	66	83	64	160	186	90	42	8	165	124	170	196	98	159	57
52	139	114	95	18	58	65	125	27	134	0	140	50	84	167	187
48	199	69	132	175	174	30	115	63	185	246	179	46	4	148	191
23	117	39	252	101	223	255	129	152	97	12	26	15	70	2	161
29	9	56	25	54	40	221	228	240	82	232	230	137	105	177	6
207	121	13	227	120	203	72	34	248	194	85	164	195	20	1	45
162	67	33	218	55	119	74	244	36	68	142	28	193	236	155	77
153	135	200	138	206	197	51	128	171	163	238	231	188	172	92	104
10	99	130	150	143	190	202	78	216	141	127	249	192	14	220	224
169	146	53	158	31	209	166	79	21	205	80	43	103	184	157	108
222	109	219	243	253	215	208	62	38	7	81	71	239	107	131	147
3	126	226	217	24	247	242	229	19	250	123	61	176	60	116	180
181	93	245	112	76	201	235	183	237	211	59	173	86	16	96	102
234	144	233	22	100	241	225	5	88	182	87	37	251	213	168	210
111	91	41	136	151	17	178	133	154	198	106	214	189	11	73	145

(a)

$Sbox\ S_2$

15	102	209	82	84	239	185	18	10	57	69	124	252	43	155	126
174	92	158	187	131	87	146	130	125	233	247	129	141	26	104	23
149	68	255	65	228	194	150	9	64	254	225	62	40	202	0	175
203	55	59	186	183	97	176	48	210	30	192	90	91	117	17	106
165	63	50	240	188	214	157	238	76	151	98	244	61	114	85	249
32	116	81	21	101	45	148	208	145	128	133	193	231	33	147	196
154	8	2	51	99	83	222	110	140	39	60	19	1	66	16	4
251	56	204	153	3	250	123	31	223	242	207	22	156	205	136	12
220	181	88	245	107	71	170	253	134	78	206	119	219	190	80	143
112	191	138	41	184	215	49	111	163	179	79	75	14	211	20	160
168	180	161	108	73	37	243	11	169	172	152	58	212	47	224	121
105	230	142	198	137	36	197	67	127	24	200	38	109	246	144	103
5	94	201	27	189	6	44	235	182	213	95	29	236	241	35	118
70	199	96	115	53	173	227	171	195	86	248	72	166	234	42	74
77	132	216	13	217	89	100	159	122	237	93	162	28	229	52	139
221	177	7	167	120	25	218	34	226	164	178	232	46	135	54	113

(b)

Figure 6: A numerical example of the generation of substitution tables (Sbox S_1 and Sbox S_2)

RM

57	92	83	193	75	243	80	145	56	5	63	81	223	152	7	27

IV

89	171	147	14	17	160	182	133	247	72	99	100	225	10	61	148

X

39	106	203	225	157	10	115	158	45	63	127	52	29	47	204	216

π_{RM}

4	12	9	6	3	16	15	13	7	1	5	11	10	2	14	8

Figure 7: A numerical example of the corresponding reset cryptographic primitives (bytes representation) of RM, IV, X and π_{RM}

On the other hand, NIST recommends 4 secure Deterministic Random Bit Generator (DRBG) algorithms that can be used for the generation of nonces or session keys. These algorithms are detailed in the NIST SP800-90A report [67], where two of them are based on hash functions, one being key-based and the other is unkeyed. The unkeyed DRBG hash-based technique can be used for nonce generation with LoRCA since it requires low overhead compared to the keyed one. This unkeyed technique ensures that the generated nonces have a high periodicity and low collision probability. Moreover, in practical scenarios, a new session key is produced for each new session. Hence, even if the same nonce is regenerated in a different session, a different dynamic key will be produced since it also depends on the session secret key. Note that, in the same session, the produced dynamic key DK is constantly changing since the $nonce$ can be changed per input message or for a set of messages (depending on the configuration). Consequently, the attacker should know which nonce and session key are used for each message (or a set of messages), which complicates the attacker task tremendously.

The produced dynamic key is divided into three subkeys $DK = \{k_{S1},\ k_{S2},\ k_R\}$. k_{S1} and k_{S2} have a size of 128 bits, while k_R is 256 bits, as illustrated in Figure 4 and described next.

- **Substitution sub-key** k_{S1}: is used to construct the first substitution table S_1, and it consists of the first most significant 16 bytes of DK. The substitution table is generated by using KSA , which is described in the next subsection (see Algorithm 1). In fact, the substitution is applied at the byte level, with the values of elements in the tables S_1 or S_2 ranging between 0 and 255.
- **Substitution sub-key** k_{S2}: this sub-key consists of the next most significant 16 bytes of DK. it is used to construct the second substitution table, S_2, also by applying KSA but with a slight modification; S_1 is used as the initial substitution table, as described in the next subsection. As such, S_2 depends on the first 32 most significant bytes of DK. Figure 6 provides a numerical example for the generation of tables S_1 and S_2.
- **Pseudo-random sub-key** k_R: it consists of the least significant 32 bytes of DK, and it is used to generate a key-stream R of $(3 \times h)$ bytes length. R will be divided later into three equal parts, where each one has a length of h bytes:

  1) Pseudo-random vector;
  2) An initial vector IV;
  3) An initial Condition X;

  In this step, to generate R, we use RC4 [68], with k_R as a seed and S_2 as initial substitution table. The first, second and third h bytes of R are used to form the RM, IV and X vectors, respectively. Thus, RM, IV and X depend on all bits of DK.

We reduce, modulo h, each byte of X to produce the permutation key k_{PRM}, which will be used as a seed with the modified KSA algorithm [18] to generate the permutation table π_{RM}. The only required modification compared to the original KSA of RC4 is changing the length of the state table L_S from 256 to h. The permutation table elements have values ranging from 0 to $h-1$. As such, π_{RM} depends on all the dynamic key bits. Note that k_{PRM} has also h elements with values varying between 0 and $h-1$.

Figure 7 illustrates a numerical example for the construction of π_{RM}, along with RM, IV and X.

All cipher primitives are highly sensitive to any bit change in the secret key, nonce and also the dynamic key. Hence, a different *nonce*, session key or dynamic key will lead to totally different cipher primitives. As such, the proposed block and stream cipher algorithms exhibit a high sensitivity (key avalanche effect) in terms of session, nonce, and dynamic key . This also increases the randomness of the ciphertext and makes the crypt-analysis attacks even more difficult.

After detailing the key and sub-keys derivation, in the next sub-sections, we present the construction of the cryptographic primitives.

A. Cryptographic Primitives Construction

In this work, we use simple techniques to construct the required cryptographic primitives that are based on the RC4 stream cipher algorithm or one of its corresponding steps, namely (KSA).

(KSA) and the Pseudo-Random Generator Algorithm (PRGA) are steps of RC4, that have to be implemented sequentially as shown in Figure 8.

KSA is used to produce the dynamic substitution tables, S_1 and S_2. The modified KSA is used to produce the required dynamic permutation table, π_{RM}. Also, RC4 is used to produce the key-stream, R, which is divided to form the remaining cryptographic primitives (RM, IV and X).

1) Substitution and Permutation Tables Construction: According to RC4, KSA (see Algorithm 1) has a variable key length, which ranges between 64 and 256 bits. KSA produces a state table $S \triangleq \{S[0], \cdots, S[L_S - 1]\}$ with $L_S = 256$ elements, varying from $S[0]$ to $S[255]$. In Algorithm 1, the parameter L_K is the length of the initial key in bytes, and i and j are iteration variables. For a secure use of the key setup of RC4, the input sub-key size should be set at least to 128 bits ($L_K = 16$).

The original implementation of KSA initializes the state table elements to their corresponding indices, such as $S[i] = i$ for $i = 0, 1, \ldots, 255$. However, in this paper, we propose a new state table initialization method, which sets the current state table to the previous one. This helps to reach the dynamic key avalanche effect. However, for the first iteration of (KSA) (case of the construction of the first substitution table S_1), the initialization of the original (KSA) is used, which means that $S[i] = i$ and $i = 0, 1, \ldots, 255$.

As indicated previously, we use the modified (KSA) to construct the permutation table π_{RM}, that requires to modify L_S from 256 to h compared to the original (KSA) [18].

B. X, RM and IV Construction

The pseudo-code of the PRGA steps of RC4 is included in Algorithm 2. To generate the required key-stream, first, we iterate (KSA) with S_2 as initial state and K_R as a seed to produce the update state, which is used in PRGA to produce the key-stream R that is divided into three parts, as described previously.

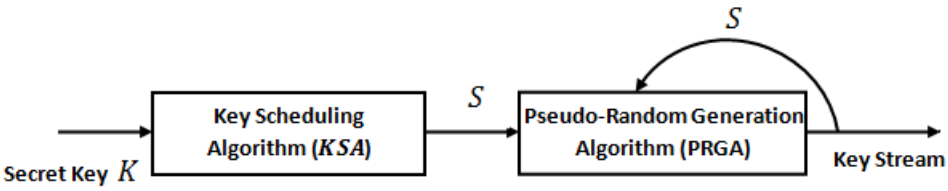


Figure 8: RC4 stream cipher algorithm

Algorithm 1 KSA algorithm of RC4

Input: L_K key length; $K \triangleq \{k_1,\ k_2,\ \ldots,\ k_{L_K}\}$; L_S length of state array S, an initial substitution table $S \triangleq \{S[0],\ S[1],\ \cdots, S[L_S-1]\}$
Output: The updated substitution table $S \triangleq \{S[0],\ S[1],\ \cdots, S[L_S-1]\}$
procedure $S = \mathsf{RC4\text{-}KSA}(S,\ K,\ L_K,\ L_S)$
  $j \leftarrow 0$
  for $i \leftarrow 0$ to $L_S - 1$ **do**
    $j \leftarrow j + S[i] + k[i \pmod{L_K}] \pmod{L_S}$
    $\mathsf{SWAP}(S[i], S[j])$ ▷ swap values of S[i] and S[j]
  end for
  return S
end procedure

Algorithm 2 PRG for RC4

Input: L_R represents the required number of key-stream bytes,
L_S represents the length of the state array S;
$S \triangleq \{s[0], \cdots, s[L_S-1]\}$
Output: Key-stream $R \triangleq \{R[0],\ R[1],\ \ldots,\ R[L_R-1]\}$ with L_R bytes length
procedure $R = \mathsf{PRNGA}(S, L_S)$
  $i \leftarrow 0$
  $j \leftarrow 0$
  for $w \leftarrow 0$ to $L_R - 1$ **do**
    $i \leftarrow i + 1 \pmod{L_S}$
    $j \leftarrow j + S[i] \pmod{L_S}$
    $\mathsf{SWAP}(S[i], S[j])$ ▷ swap values of S[i] and S[j]
    $R[w] \leftarrow S[S[i] + S[j] \pmod{L_S}]$
  end for
  return R
end procedure

In the next section, the proposed LoRCA stream and block ciphers will be described in detail. LoRCA stream and block ciphers use the produced dynamic cryptographic primitives (S_1, S_2, RM, IV, and X) for each input message or a set of messages (depending on the configuration).

IV. LoRCA Block and Cipher Schemes

For each input message, LoRCA uses a new dynamic key along with an updated set of cipher primitives (S_1, S_2, RM, IV, π_{RM}). The common part between the block and stream algorithms is that an input message M is divided into nb blocks $M = m_1,\ m_2,\ \ldots,\ m_{nb}$, where each block has a length of h bytes, with h being configured based on the IoV application security and performance requirements. A small h value is typically used for real-time applications.

Note that the block cipher scheme uses the dynamic Electronic Code Book (ECB) mode of operation without degrading the security level since the same input message (plaintext) produces a different ciphertext due to the different cryptographic primitives used with the two messages.

In the block cipher case, the i^{th} ciphertext block c_i is obtained by applying the proposed encryption algorithm E_K (see Figure 9), which is detailed in Algorithm 3, and described in Eq. 2:

$$c_i = E_K(m_i)\ ;\ \ i = 1,\ 2,\ \ldots,\ nb \tag{2}$$

The proposed cipher consists of two sub-functions, Round Function (RF) and UpdateRM Function (URM). RF is iterated once to produce a ciphertext c_i, while RM should be updated for each input block iteration. This is done by calling the UpdateRM Function (URM). Similarly, X is also updated for each input block iteration by using the same update process.

A. LoRCA Block Cipher Round Function (RF)

The LoRCA block cipher **Round Function** (RF) produces the i^{th} ciphertext via the following six steps (Algorithm 1):

1) Iterating the Pseudo-Random Generator (PRG) for one round. Note that the PRNG is iterated recursively, meaning that the output X' becomes the next input X.

2) Mixing the input block m_i with the PRNG output using the logical "XOR" operation.
3) Using two substitution tables, S_1 and S_2, to substitute the output to produce the i^{th} substituted block T. In the proposed solution, S_1 is used to substitute the bytes with odd indices, while S_2 is used for substituting those with even indices. For example, S_1 is used to substitute the bytes with indices $1, 3, 5, \ldots$ and S_2 is used to substitute the bytes with indices $2, 4, 6, \ldots$.
4) Updating the pseudo-random vector RM.
5) Mixing the updated RM with the substituted output block T, using also the logical "XOR".
6) Substituting the output using two substitution tables (S_2 and S_1) to produce the i^{th} ciphertext, c_i. In this step, S_1 is used to substitute the bytes with even indices, and S_2 is used to substitute the bytes with odd indices.

The encryption steps to produce the i^{th} ciphertext block, c_i, are illustrated in Figure 9 and described in detail in Algorithm 3.

Algorithm 3 LoRCA block cipher variant

Input: Plaintext block m_i, substitution tables (S_1 and S_2), RM, π_{RM}, X
Output: i^{th} ciphertext block c_i

procedure ENCR($m_i,\ S_1,\ S_2,\ RM,\ \pi_{RM},\ X$)
  $RM \leftarrow UpdateRM(RM, \pi_{RM})$
  $X' \leftarrow XorShift64(X)$
  $T \leftarrow S(m_i \oplus X',\ S_1,\ S_2)$
  $TR \leftarrow RM \oplus T$
  $c_i \leftarrow S(m_i \oplus TR,\ S_2,\ S_1)$
  $X \leftarrow X'$
end procedure

As such, all the plaintext blocks are encrypted to produce C, which is the encrypted message that will be either stored locally, or securely communicated with the desired destination.

To recover the original message, the decryption process follows the same steps as the encryption but in the reverse order, and using the inverse substitution tables. Hence, the original block m_i' is recovered by decrypting the i^{th} ciphertext block c_i, using the corresponding decryption algorithm D, that is described in detail in Algorithm 4 and presented in Eq. 3 :

$$m_i' = D(C_i)\ ;\ \ i = 1,\ 2,\ \ldots,\ nb \tag{3}$$

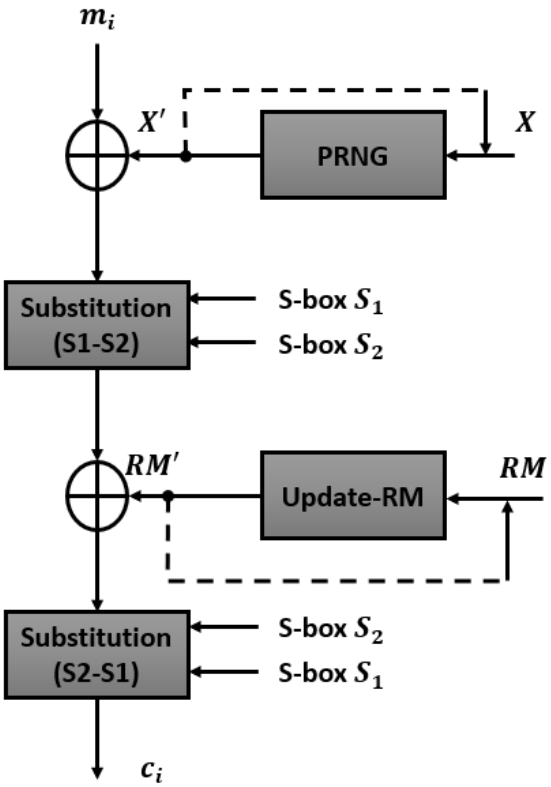


Figure 9: Structure of the proposed LoRCA block cipher

Algorithm 4 The corresponding decryption algorithm D of the proposed block cipher variant

Input: Ciphertext block c_i, inverse substitution tables (S_1^{-1} and S_2^{-1}), RM, π_{RM}, X
Output: The i^{th} plaintext block m_i

procedure DECR($c_i,\ S_1{-}1,\ S_2{-}1,\ RM,\ \pi_{RM},\ X$)
  $RM \leftarrow UpdateRM(RM, \pi_{RM})$
  $X' \leftarrow XorShift64(X)$
  $TR \leftarrow S(c_i,\ S_2^{-1},\ S_1^{-1})$
  $T \leftarrow RM \oplus TR$
  $O \leftarrow S(T,\ S_1^{-1},\ S_2^{-1})$
  $m_i \leftarrow O \oplus X'$
  $X \leftarrow X'$
end procedure

B. LoRCA Stream Cipher Round Function (RF)

To produce the i^{th} key-stream block, the LoRCA stream cipher **Round Function** (**RF**) consists of the following six steps:

1) Iterating the selected PRNG once with a seed vector X. Similarly to block cipher, the selected PRNG should be iterated recursively, with the output X' becoming the next input X.

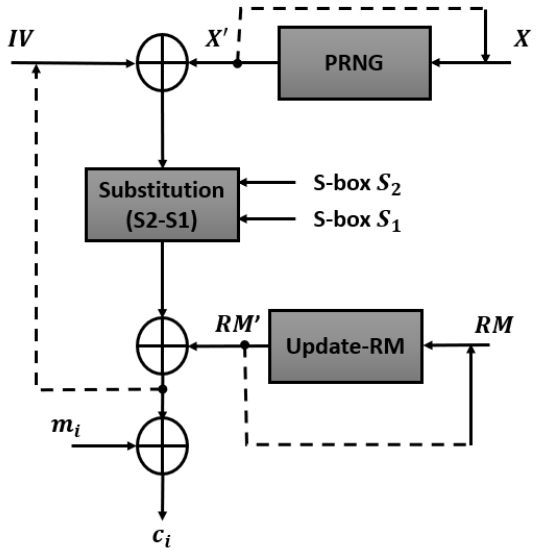


Figure 10: Structure of the proposed LoRCA stream cipher

2) XOR-ing the IV with the PRNG output X'.
3) Substituting the output using S_2 and S_1 to produce the i^{th} substituted block T. This step is similar to the substitution steps described in the block cipher scheme (steps 4 and 6).
4) Updating the pseudo-random vector RM.
5) XOR-ing the updated RM with the substituted output block T to produce the i^{th} key-stream block R. The output of this step R_i is used to update the Initial vector IV.
6) Mixing the i^{th} produced key-stream block R_i with the i^{th} plain block m_i, as described by Eq. 4.

$$c_i = m_i \oplus R_i \; ; \;\; i = 1,\; 2,\; \ldots,\; nb \tag{4}$$

The proposed LoRCA stream cipher is illustrated in Figure 10 and described in Algorithm 5.

Algorithm 5 The proposed LoRCA stream cipher round function

Input: Plaintext block m_i, Initial Vector (IV), two substitution tables (S_1 and S_2), RM, π_{RM}, X
Output: i^{th} ciphertext block c_i

procedure UP_AB_PRIM($IV,\ S_1,\ S_2,\ RM,\ \pi_{RM},\ X$)
    $RM \leftarrow UpdateRM(RM, \pi_{RM})$
    $X \leftarrow \mathsf{PRNG}(X)$
    $T \leftarrow S(IV \oplus X,\ S_2,\ S_1)$
    $R \leftarrow RM \oplus T$
    $c_i \leftarrow m_i \oplus R$
end procedure

In a similar manner, all the plaintext blocks are encrypted to produce C, the encrypted message that is either stored locally, or securely communicated with the desired destination.

On the other hand, to recover the original message, the decryption algorithm follows the same steps to generate the same key-stream sequence that will be mixed with the ciphertext. Thus, to recover the i^{th} original block m'_i, the i^{th} ciphertext block c_i should be mixed (exclusive or) with the same produced R_i, as presented in Eq. 5:

$$m'_i = c_i \oplus R_i \; ; \;\; i = 1,\; 2,\; \ldots,\; nb \tag{5}$$

Next, we describe the URM function to explain the update process of RM.

C. Update Pseudo-Random Vector Function

RM is updated by using a deterministic PRNG, that uses RM as a seed. For example, we use XorShift64 as PRNG since it requires low computational and resource requirements. This variant is similar to the update X approach.

To update X, we use the XorShift64 PRNG, which has an output of 64 bits. Therefore, XorShift64 should be iterated for $\lceil \frac{h}{8} \rceil$ times to get the desired number of bytes h (length of X). For example, XorShift64 should be iterated twice or 4 times to get h =16 or 32, respectively. XorShift64 belongs to the Linear-Feedback Shift Registers (LFSR) PRNG functions and is described in Algorithm 6. In modern processor architectures, XorShift64 is extremely fast due to its efficient implementation without the excessive use of sparse polynomials [69]. Due to the fact that XorShift64 generators do not include non-linear steps, they are prone to fail certain statistical tests [69]. However, they still have numerous advantages such as simple implementation and low execution time.

Algorithm 6 C code of XorShift64 PRNG

Input: 64-bit word of state t
Output: A produced random number word x with 64-bits length

procedure XORSHIFT64(t)
    $x \leftarrow t$;
    $x \leftarrow x \oplus (x \;>> 12)$;
    $x \leftarrow x \oplus (x \;<< 25)$;
    $x \leftarrow x \oplus (x \;>> 27)$;
    return x;
end procedure

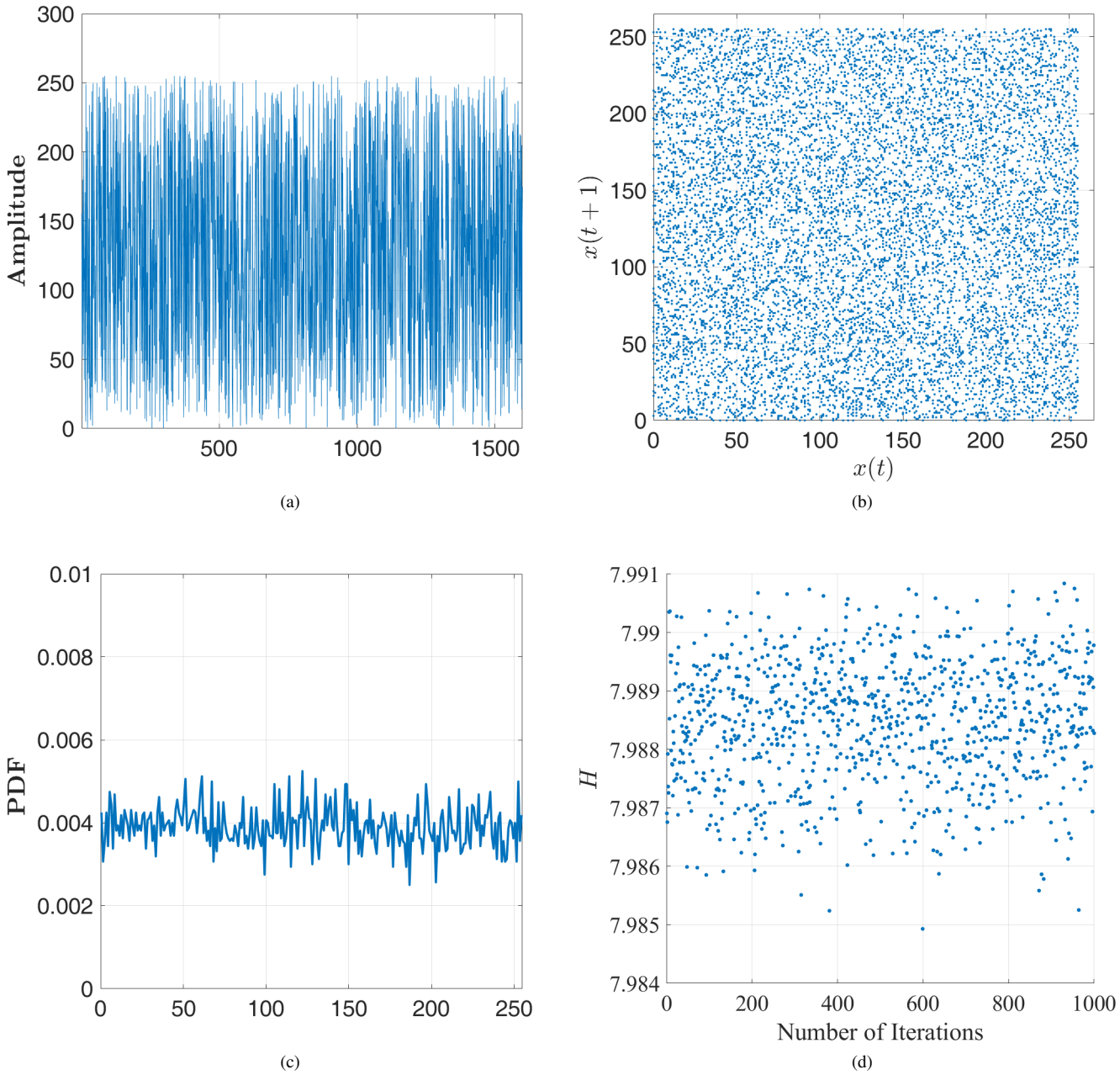
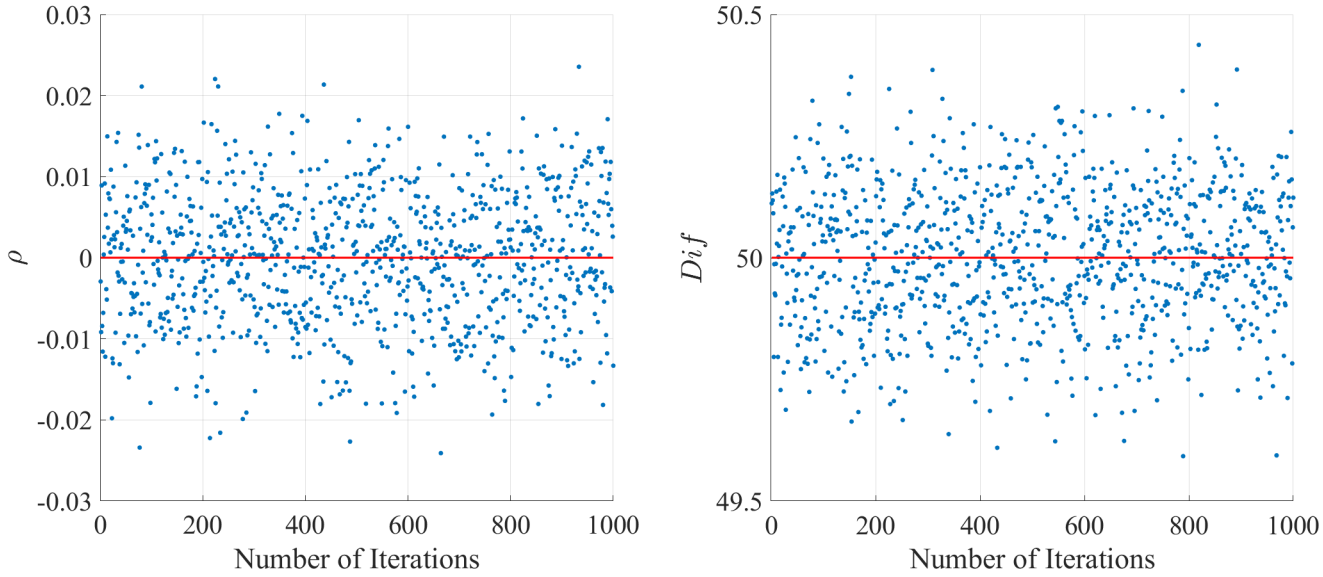


Figure 11: Tests Results of the generated key-stream showing (a) Amplitude variation, (b) recurrence, (c) probability density function, and (d) entropy; for 1,000 random dynamic keys and $h = 16$.

V. Security Analysis

To be secure, the proposed stream and block cipher schemes should resist all types of analytical attacks, including statistical, chosen/known plaintext/ciphertext, brute-force and algebraic attacks [6], [7]. In this section, the immunity of the proposed schemes against these attacks is evaluated and analysed. We consider input messages with "all-zero" bytes.



(a) Dif (b) ρ

Figure 12: Tests Results of (a) the variation of the correlation coefficient, and (b) the difference between original and encrypted messages; for 1,000 random dynamic keys.

A. *Resistance Against Statistical Analysis*

Statistical attacks are typically prevented when the encrypted message exhibits high uniformity and randomness levels, as well as a high periodicity [6], for the stream cipher case.

Several statistical tests including PractRand and TestU01 were carried out on the ciphertext. It is important to state that these tests are among the most difficult randomness tests. The purpose is to validate that the ciphertext achieves the desired randomness and uniformity properties. According to the obtained results, the ciphertext of both schemes successfully passes the TestU01 [70] and "PractRand" [71] tests with all the tested seeds. This confirms that the proposed ciphers can resist statistical attacks.

Moreover, visual results of the ciphertext Probability Density Function (PDF) for a random dynamic key (see Figure 11c), in addition to the entropy of the produced key-stream for 1,000 dynamic keys are presented in Figure 11d. These results show that the produced key-stream follows the required uniform distribution. Furthermore, for the same random dynamic key, the recurrence results of the produced key-stream (see Figure 11a) is presented in Figure 11b), show that the produced key-stream has a uniform random recurrence. Accordingly, the block cipher exhibits similar statistical results in terms of uniformity, recurrence, and sensitivity. To avoid redundancy, only the stream cipher results are included in this paper. Note that more details about the conducted tests can be found in [18], [72].

Figure 12 shows the variation of the correlation coefficient (ρ) and the difference percentage between the original and encrypted messages (Dif) for 1,000 random dynamic keys. Let us indicate that the red line in these figures represents the ideal value, which is 0 for the correlation coefficient test and 50% for the difference percentage test. The results confirm that there is no detectable relation between the plaintext and ciphertext.

B. *Plaintext Sensitivity Test*

This test is needed only for the block cipher algorithm to check the difference between the obtained ciphertexts, when two plaintext messages with a slight difference are encrypted with the same key. However, our proposed block cipher relies on the dynamic key approach. Thus, different keys are used for different messages. Hence, different cipher primitives are employed compared to the previous or next messages, and the different dynamic keys will lead to different ciphertexts for the same plaintext. Considering the same plaintext with 1,000 different keys, the difference between the obtained ciphertexts is

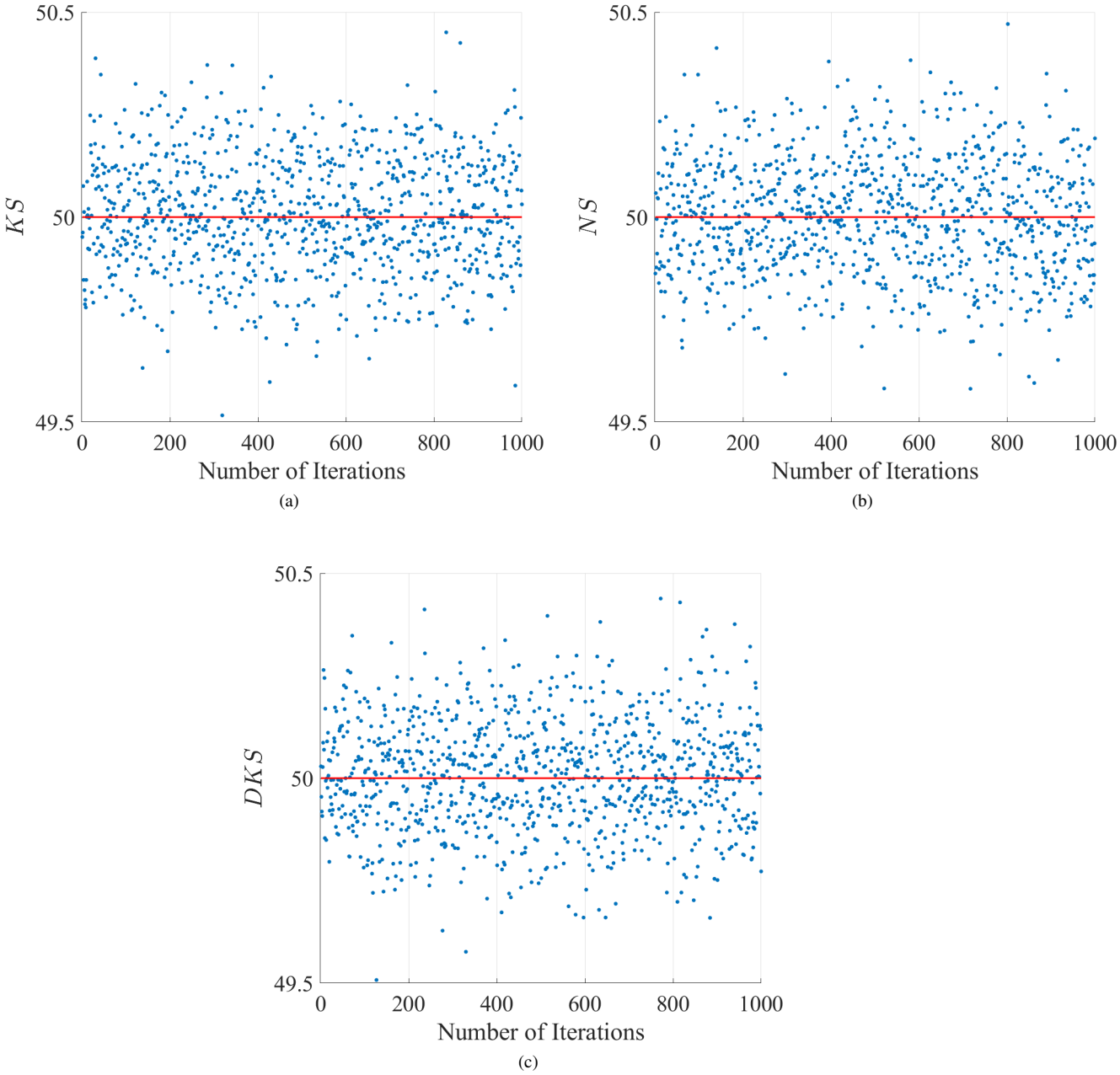
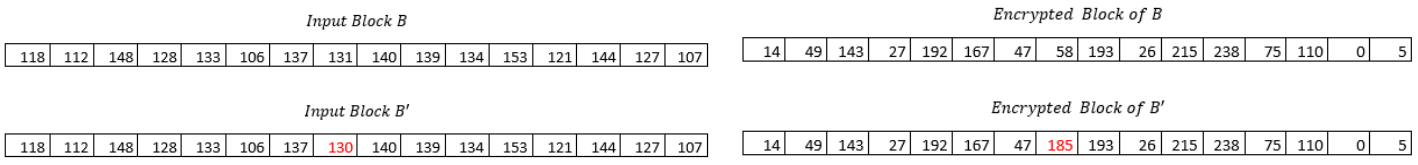


Figure 13: Sensitivity results of the proposed stream cipher with 1,000 random keys of: (a) secret Key, (b) nonce, and (c) dynamic key DKS.

close to 50%, as seen in Figure 13. As such, the proposed LoRCA cipher variants achieve the required plaintext sensitivity (avalanche effect).

C. Key Sensitivity Test

The nonce and key sensitivity tests aim at validating the key avalanche effect. In these tests, we quantify the percentage difference between the produced ciphertexts, for any bit-difference in the nonce or the secret key.



(a) (b)

Figure 14: A numerical example of the message sensitivity, when the LSB of the 8^{th} byte is modified, and for the same DK

According to the structure of the proposed solution, a one-bit difference in the secret key or nonce would lead to the generation of a new dynamic key. Also, different cipher primitives will be generated and hence, different ciphertexts will be obtained. Figure 13 shows the secret key, nonce and dynamic key sensitivity results of the proposed stream cipher for 1,000 random instances. The results are very close to the ideal value of 50% difference at the bit level. Similar sensitivity results are obtained for the proposed block cipher scheme.

D. High Periodicity

Based on the dynamic key approach, the proposed stream cipher can be considered as a perturbation technique. The generated periodicity of the key-stream is directly related to the PRNG generator and the RM update process. Therefore, using a secure cryptographic PRNG along with the proposed RM update process leads to a high periodicity level, while minimizing the probability of repeated dynamic keys.

VI. Cryptanalysis

The proposed block and stream ciphers satisfy the confusion and diffusion properties with the lowest possible number of rounds and operations. These ciphers require a single round that consists of simple addition, substitution and permutation operations. The proposed ciphers avoid the use of the diffusion operation to avoid an increase in the latency.

In order to validate the security and robustness of the proposed LoRCA block and stream cipher variants, we discuss and analyze these schemes in the context of different attacks, namely, statistical attacks, differential attacks, brute force attacks and related key attacks.

We assume that the adversary has full knowledge of the protocols used for transmission, the proposed cipher algorithm, and the ciphertexts that are exchanged between the IoT/IoV and application server(s). The only secret information is the session key.

A. Statistical Attacks

To ensure high resilience against this type of attacks, the cipher scheme should produce highly random and uniform ciphertexts. Based on the security tests presented in the previous section, both of the proposed schemes proved to have a high level of randomness and uniformity via the statistical tests, "Testu01" and "PractRand.

The security tests results confirmed that the encrypted messages are uniformly distributed and have highly dispersed recurrence plots. The schemes also satisfy the independence property since the bit-difference between the input plaintext and the corresponding ciphertext is always close to the desired value of 50%, in addition to a low correlation coefficient as shown in Figure 12.

On the other hand, the statistical results, presented in Table II, and the visual results of the produced ciphertexts validate these conclusions (see Figure 11), and confirm the strong resistance against statistical attacks.

B. Linear and Differential Attacks

In linear and differential attacks, an adversary tries to exploit the relationship between two encrypted messages and their corresponding ciphertexts, to extract the cipher primitives, encryption keys or any useful information. To overcome this issue, we proposed the dynamic update process, which changes the cipher primitives for every input message (or a set of messages). The update process can be based on the re-generation of a dynamic key or in a lightweight manner by simply permuting the cryptographic primitives.

Hence, the produced ciphertexts are uncorrelated, random and independent compared to plaintexts (see Figure 12). This has also been validated using the key sensitivity test for the secret key, nonce and dynamic secret key, as shown in Figure 13. More specifically, the results showed that when the same message is encrypted using two different keys, the resulting ciphertexts have at least 50% bit difference. As a result, no valuable information can be revealed from the encrypted data.

Table II: Statistical results of the proposed stream cipher for 1,000 random keys.

	Min	*Mean*	*Max*	*Std*
Secret Key Sensitivity (KS)	49.4977	50.0011	50.5125	0.1413
Nonce Sensitivity (NS)	49.5797	50.0045	50.4664	0.1356
DK sensitivity	49.48	50.001	50.43	0.138
Dif	49.59	50.004	50.43	0.14
ρ	-0.0245	0.00006	0.026	0.0081
Entropy (H) of ciphertext	7.984	7.988	7.99	0.001

Moreover, the update of cryptographic primitives per input message further complicates the algebraic, linear and differential attacks. Thus makes linear and differential attacks are ineffective in this case.

The proposed schemes are also secure against chosen/-known plaintext/ciphertext attacks, which are a sub-set of linear and differential attacks.

C. Brute Force Attacks

In both cipher schemes, the pre-shared secret key can have a length of 128, 196, or 256 bits. Based on the size of the secret key, the size of the nonce is adjusted (padding) since both should have the same size in order to perform the XOR operation. On the other hand, the size of the generated dynamic key is 512 bits since the SHA-512 hash function is utilized. Such key-size is acceptable for preventing brute force attacks.

D. Related Key Attacks and Weak Keys

From the key sensitivity test results, it is evident that the desired key sensitivity percentage (50%) is achieved (see Figure 13), hence, proposed stream and block cipher schemes are able to resist any related-key attack. In these schemes, a dynamic key is generated from a a nonce and a secret key. This key is, then, divided into a number of smaller sub-keys, each used to derive a specific cipher primitive. To increase the security of the proposed key generation function, a secret key is combined with the nonce to decrease the probability of successfully deriving the dynamic key and the cipher primitives. The secret key is only known to the legitimate user. Moreover, each cryptographic primitive is generated in a way that any bit change in the dynamic key will lead to a different set of cryptographic primitives.

Acquiring the dynamic key or sub-keys is rather a hard task for illegitimate users, since they should be able to, correctly, estimate the nonce and secret session key. Unlike existing symmetric cipher schemes which consist of static cipher primitives, the proposed solution updates the cipher-primitives, frequently and pseudo-randomly. Therefore, the obtained encrypted messages are independent and uncorrelated. The proposed approach complicates the process of recovering transmitted data. Any vulnerability in any of the dynamic keys will not affect the previously processed or the following messages. Moreover, as seen in Figure 13, the sensitivity of the dynamic key, secret session key and nonce are satisfied, which complicates the key-related attacks and make them unfeasible. On the other hand, the proposed solution is also resilient to weak keys.

The existing analytic attacks are unable to break the cipher scheme with the dynamic key-dependent approach since they are designed to break ciphers with static primitives, which is not the case of the proposed cipher scheme. This makes the proposed cipher extremely hard to break by any analytic or implementation attacks such as side channel attacks since dynamic cryptographic primitives lead to different physical properties. As a conclusion, the proposed block and stream ciphers are immune against the different well-known attacks and possibly future ones.

VII. Performance Analysis

In this section, LoRCA's performance is analyzed to quantify its effectiveness. In the following, we present two essential metrics, the error propagation rate and the encryption/decryption computational delay.

A. Error Propagation Rate

In the stream cipher case, any bit error that occurs in the encrypted block, c_i, will affect only the block's corresponding bit in the decrypted message. However, in the block cipher case, the block's corresponding byte will be affected in the decrypted message. As such, the stream cipher variant exhibits a lower error rate compared to the block cipher. Furthermore, the LoRCA block cipher variant has lower error propagation compared to traditional block cipher algorithms such as AES, Simon and speck, since in these algorithms, the plain block avalanche effect is achieved by using the traditional multi-round function structure with diffusion operations. Note that the message avalanche effect is achieved differently in

this work by benefiting from the dynamic key approach. Consequently, LoRCA cipher variants are efficient and can resist better channel errors compared to state-of-the-art ciphers.

B. Encryption/Decryption Computational Delay

The main objective of this work is to achieve a high level of security with minimum computational complexity to reduce the encryption time and the resources overhead, especially in terms of energy consumption. To assess the total computational overhead, the delays associated with the required operations are quantified as follows:

1) T_S stands for the execution time of substituting an N-byte block.
2) T_{xor} is the execution time for the XOR operation between two N-byte blocks.
3) T_{PRNG} is the time to iterate the selected PRNG.
4) T_P is the time needed to permute a block of N bytes.

As a result, the total Computational Delay (CD) to encrypt a single block with the proposed block cipher is:

$$CD = 2 \times T_S + 2 \times T_{xor} + T_{PRNG} + T_P \quad (6)$$

While, the required (CD) to encrypt a single block with the proposed stream cipher is:

$$CD = T_S + 3 \times T_{xor} + T_{PRNG} + T_P \quad (7)$$

On the other hand, the total computational delay to encrypt a single block using the standard AES in [22] is:

$$CD_{AES} = rT_S + (r+1)T_{xor} + (r-1)T_D + rT_{SR} \quad (8)$$

Where T_D represents the AES Mix-column operation time, presenting the highest delay among the other AES operations. Moreover, T_{SR} represents the AES "Shift-rows" operation delay, and r represents the number of rounds. For a 128-bit secret key, the minimum value of r is 10. As a result, the minimum AES computational delay is given by:

$$CD_{AES(r=10)} = 10T_S + 11T_{xor} + 9T_D + 10T_{SR} \quad (9)$$

This clearly shows that the AES computational time is much higher compared to the proposed block and stream ciphers where we intentionally avoided any diffusion operation. Moreover, for AES with 192 and 256-bit length secret key, r is equal to 12 and 14, respectively. This requires even higher execution times compared to the 128-bit secret key case. Note that the proposed stream cipher requires a lower computational complexity compared to the proposed block cipher.

On the other hand, the delay associated with the derivation function of the key and cryptographic primitives (CD_{KDF}) is quantified below and can be described as follows:

1) T_H stands for the needed hash time for an N-byte block.
2) T_{KSA} stands for the needed RC4-KSA execution time.
3) $T_{MKSA}(x)$ stands for the needed execution time of the modified KSA of RC4 for a table with x elements.
4) T_{PRNG} stands for the needed execution time of the RC4's PRNG.

$$CD_{KDF} = T_{xor} + T_H + 2T_{KSA} + T_{MKSA}(h) + T_{PRNG} \quad (10)$$

It can be noticed that the key derivation function introduces computational overhead and thus, a different key derivation strategy should be adopted for low data rate applications communicating small-sized messages. For low data rate applications, the dynamic key and cipher primitives should be updated after δ small-sized messages, or after τ data bytes. Thus, until reaching this threshold, all cipher primitives remain constant, except for the two substitution tables, S_1 and S_2, which will be updated for each message, as follows:

$$\begin{aligned} Temp &= S_1 \\ S_1 &= S_1(S_2) \\ S_2 &= S2(Temp) \end{aligned} \quad (11)$$

As a result, decreasing τ can increase the security level along with the required resources and delays and vice-versa. In fact, δ's configuration depends on the application requirements and the needed security level.

C. Proposed Ciphers Throughput

In this section, the average throughput of the proposed block and stream ciphers is quantified by conducting several experiments (1,000 times) on a real hardware platform ("Rapsberry Pi"), which can be used in IoV applications. Also, several Raspberry device classes are considered in these experiments, namely, RPI0, RPI3, and RPI4. In the following, only the encryption throughput is analysed since the decryption throughput is very close to the encryption one; this is due to the fact that the decryption algorithm for both ciphers requires the same number of operations as the encryption algorithm.

Figure 15 illustrates the variation of the throughput (MB/s) as a function of h for the proposed block and stream ciphers. We can see that the value of h has a

visible and different impact on the encryption performance on different Raspberry PIs (RPI) devices; the best performance, for the RPI0 and RPI3 for both LoRCA ciphers is achieved for h=32 and 8, respectively. While in the case of RPI4, the best performance for the stream cipher variant is achieved for h =64, and 8 for the block cipher variant. As such, h can be fixed to the optimal value that is obtained from the performance analyzing of LoRCA for the device to be used, as shown in Figure 15.

The throughput of the proposed LoRCA cipher schemes is compared to that of AES (OpenSSL implementation). Note that the proposed LoRCA ciphers are implemented using the C programming language, whereas the AES OpenSSL implementation code is well optimized in assembly language. Figure 16 compares the throughput of the proposed ciphers and that of AES OpenSSL with CTR and CBC operation modes. The results indicate that LoRCA always outperforms AES on RPIs. Numerical results are given in Tables III and IV for the throughput ratio between the proposed ciphers as compared to AES OpenSSL. The best performance of LoRCA over AES is obtained with RPI0. However, the performance is slightly reduced with RPI3 and RPI4 since the OpenSSL implementation is optimized in assembly. In summary, considering RPI0, the encryption/decryption throughput of the proposed LoRCA cipher variants is higher compared to AES with or without optimization as indicated in Table III and IV. A significant gain can be achieved by optimizing LoRCA cipher variants using assembly as in AES. This will further improve the throughput for RPI3 and RPI4.

Moreover, the proposed LoRCA variants are compared to state-of-the-art IoV cipher algorithms such as Simon and Speck. Table V presents the throughput results of the proposed cipher variants against (AES, Simon, and Speck) for different Raspberry Pi classes, and Table VI and Table VII show the ratio of the throughput results. Based on these results, Speck seems to require more execution time compared to Simon. According to Table VI, Simon and Speck require at least, 4.87 and 1.67 times, respectively, the overhead of the proposed LoRCA block cipher. Also, according to Table VII, Simon and Speck require at least 2.71 and 1.18 times, respectively, the overhead of the proposed stream cipher. Moreover, the proposed block cipher throughput outperforms, by a factor of 24.113%, 60.05% and 65.38%, the previous one of [18] with RPI0, RPI3, and RPI4, respectively. According to Table VI and VII, both variants present a higher throughput compared to AES, SPECK, SIMON [29] and [18].

This test was also applied on tiny devices that use an ARM CPU such as teensy3.6 (ARM Cortex M4), teensy 4.0 (ARM Cortex-M7) in addition to ESP 32. These devices were selected since they have a cryptographic acceleration unit (AES-NI). The obtained results in Figure 17 demonstrate the efficiency and suitability of the proposed stream cipher solution with this type of architecture when compared to AES.

According to Figure 18, AES with NI instructions require at least 28.5% and 38.5% additional overhead time, respectively, compared to the proposed LoRCA ciphers. Similarly, LoRCA exhibits lower execution time between 55% and 64% as compared to Tennsy 3.6, while the time overhead reduction varies between 32.3% and 41.9% against ESP 32.

D. Memory Consumption

To encrypt one block in both proposed ciphers, we need the input block and two substitution tables ($S1$ and $S2$), each with 256 bytes, in addition to two blocks (X and RM) of h bytes. Therefore, the required memory consumption of both ciphers is $(512 + 3 \times h)$ bytes. For limited memory devices, we can use only one substitution table instead of two to reduce the required memory consumption to $256 + 3 \times h$. Compared to AES, one substitution table (256 bytes) is required in addition to the input key and round key (32). Note that h can be increased, if the devices possess more memory capacity.

VIII. Conclusion & Future Work

In this paper, we proposed LoRCA, an efficient lightweight block and stream cipher schemes for tiny IoV devices. LoRCA relies on the dynamic key-dependent approach to strike the right balance between the security level and the devices' performance. Two different lightweight round functions were proposed, one for block cipher and a simpler one for stream cipher. Each round function needs to be applied for a single iteration, which drastically reduces the computational and resources overhead when compared to standard ciphers such as AES, which requires a higher number of rounds, r. Finally, security and performance analysis were performed to prove LoRCA's effectiveness and robustness. We believe that such work opens a new way for the definition and design of modern lightweight cipher schemes.

Compliance with Ethical Standards

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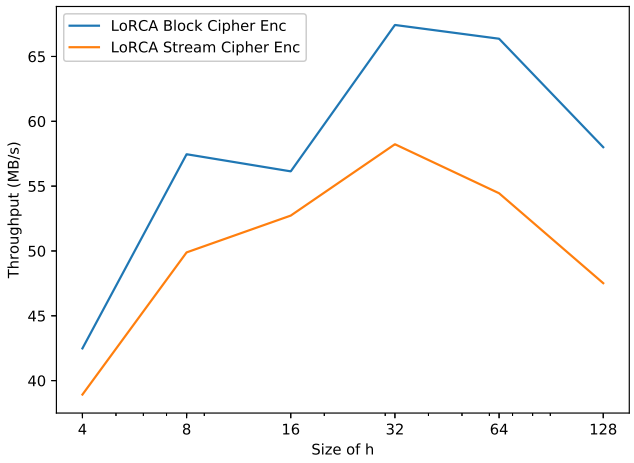
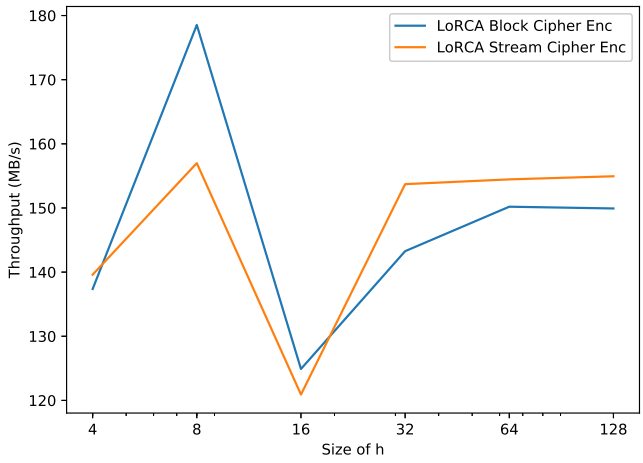
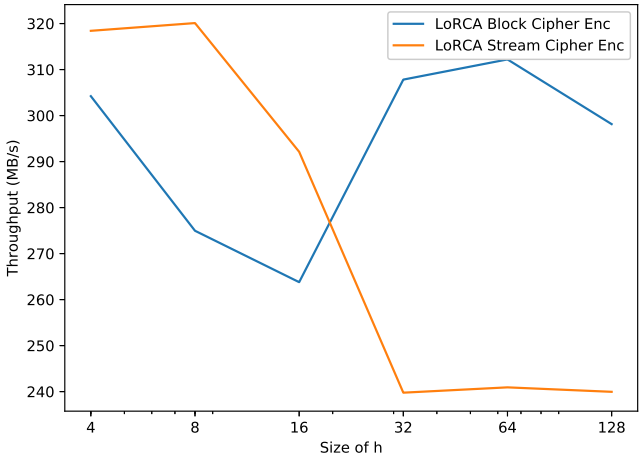


(a) RPI0



(b) RPI3



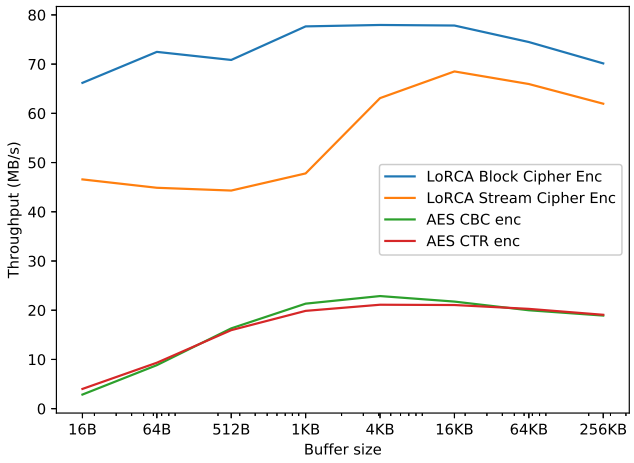
(c) RPI4

Figure 15: Throughput variation (MB/s), with a colored Lena image of size $(512 \times 512 \times 3)$, as a function of h on: (a) RPI0, (b) RPI3, and (c) RPI4.

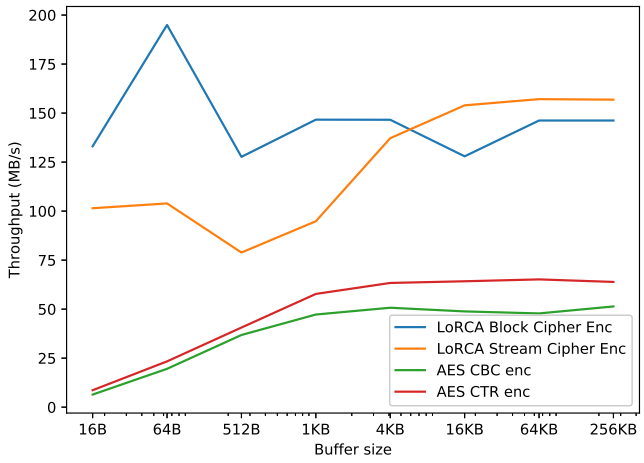
Table III: Speedup results of LoRCA block cipher over AES

Hardware	Protocol comparison	Message Length							
		16B	64B	512B	1KB	4KB	16KB	64KB	256KB
RPI0	LoRCA BC vs AES CBC	23.12	8.20	4.34	3.64	3.40	3.57	3.72	3.70
	LoRCA BC vs AES CTR	16.51	7.77	4.44	3.91	3.69	3.70	3.67	3.68
RPI3	LoRCA BC vs AES CBC	20.72	9.96	3.46	3.10	2.89	2.61	3.0	2.84
	LoRCA BC vs AES CTR	15.40	8.35	3.14	2.54	2.31	1.99	2.24	2.29
RPI4	LoRCA BC vs AES CBC	19.62	7.05	3.94	3.99	3.75	3.67	3.67	3.69
	LoRCA BC vs AES CTR	14.70	5.68	3.34	3.21	3.00	2.89	2.89	2.88

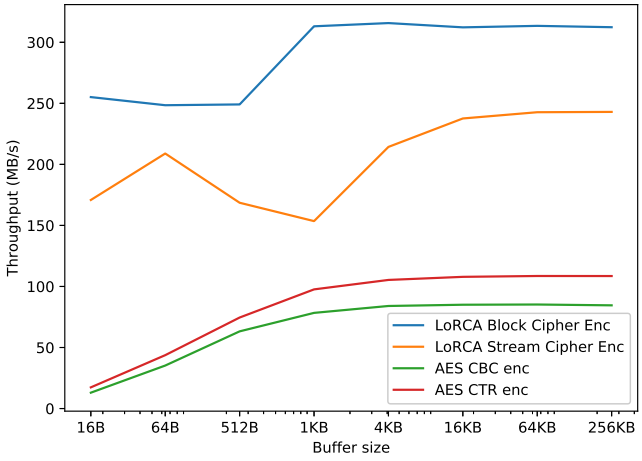
- **Conflict of interest:** The authors declare that they have no conflict of interest.



(a) RPI0



(b) RPI3

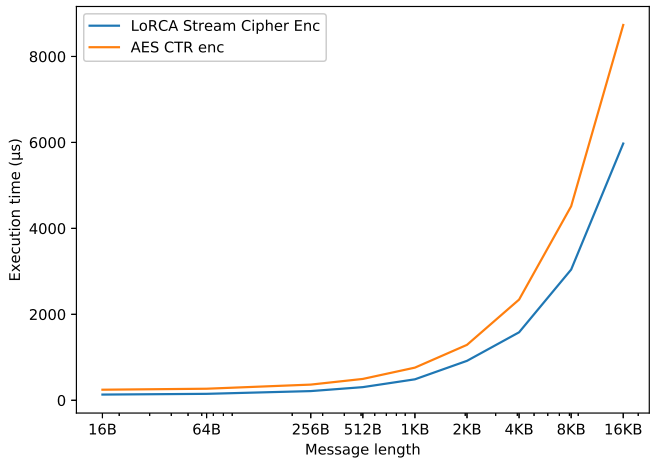


(c) RPI4

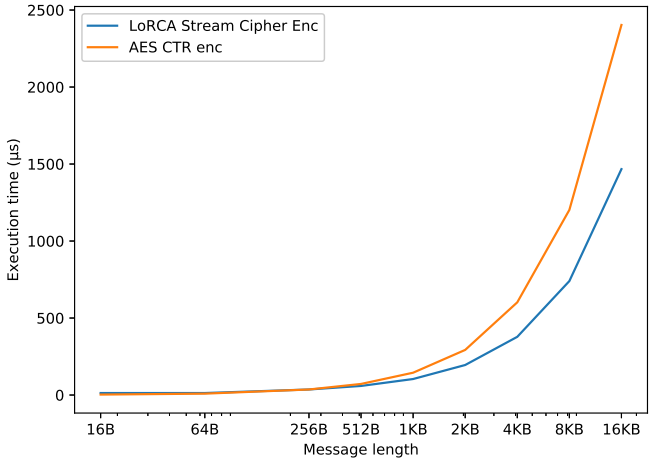
Figure 16: Comparison of the encryption throughput of the proposed block and stream ciphers (LoRCA) and AES OpenSSL (in CTR and CBC mode) on (a) RPI0, (b) RPI3, and (c) RPI4, as a function of the buffer size (in bytes) for h=16.

Table IV: Speedup results of LoRCA stream cipher over AES

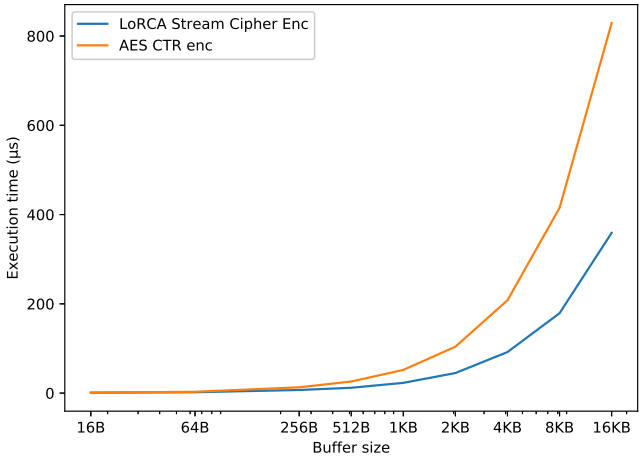
Hardware	Protocol comparison	Message Length							
		16B	64B	512B	1KB	4KB	16KB	64KB	256KB
RPI0	LoRCA SC vs AES CBC	16.27	5.08	2.72	2.24	2.76	3.15	3.30	3.28
	LoRCA SC vs AES CTR	11.62	4.81	2.78	2.41	2.99	3.25	3.25	3.25
RPI3	LoRCA SC vs AES CBC	15.81	5.31	2.14	2.01	2.71	3.15	3.29	3.05
	LoRCA SC vs AES CTR	11.74	4.45	1.94	1.64	2.17	2.40	2.41	2.46
RPI4	LoRCA SC vs AES CBC	13.14	5.93	2.67	1.96	2.55	2.79	2.85	2.87
	LoRCA SC vs AES CTR	9.84	4.78	2.26	1.57	2.03	2.20	2.24	2.24



(a) ESP 32



(b) Tensy3.6



(c) Teensy 4.0

Figure 17: Variation of the encryption throughput of the proposed block and stream ciphers (LoRCA) and AES OpenSSL (in CTR and CBC mode) on ESP32 (a), teensy3.6 (b), and teensy4 (c) in function of the buffer size (in bytes or kilobytes) for h=16.

Table V: Encryption throughput in MB/s of SPECK and SIMON ciphers [29], one round of [18] and the proposed ciphers on different Raspberry Pi devices with a colored Lena image of size ($512 \times 512 \times 3$)

Cipher(Key size, block size)	**Raspberry Pi0**	**Raspberry Pi3**
Speck(256, 128)	14.60	28.12
Speck(64,32)	5.32	9.25
Simon(256, 128)	4.99	9.98
Simon(64, 32)	4.09	7.40
One round [18] (block cipher)	19.62	43.16
Proposed One (Stream Cipher)	28.98	85.14

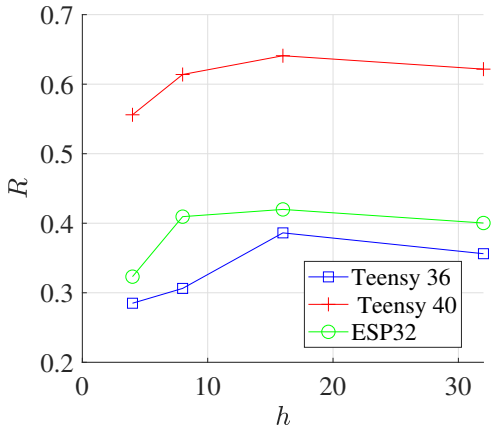


Figure 18: Variation of the encryption reduction ratio, as a function of h, of LoRCA and AES OpenSSL in CTR mode on ESP32, teensy3.6, and teensy4.

Table VI: Throughput ratio of the proposed block cipher and those of Speck and Simon.

Cipher Size(Key, Block)	**Raspberry Pi0**	**Raspberry Pi3**	**Raspberry Pi4**
Speck(256, 128)	1.26	2.69	5.78
Speck(64,32)	3.76	8.01	17.198
Simon(256, 128)	3.13	6.67	14.33
Simon(64, 32)	5.17	11.02	23.64

Table VII: Throughput ratio of the proposed stream cipher and those of Speck and Simon.

Cipher(Key size, block size)	**Raspberry Pi0**	**Raspberry Pi3**	**Raspberry Pi4**
Speck(256, 128)	1.18	2.88	4.5
Speck(64,32)	3.25	8.58	13.39
Simon(256, 128)	2.71	7.15	11.16
Simon(64, 32)	4.47	11.81	18.41

- **Ethical approval:** This article does not contain any studies with human participants or animals performed by any of the authors.

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