
Two Security Layers for Hierarchical Data Aggregation in Sensor Networks

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Abstract:

Due to resource restricted sensor nodes, it is important to minimize the amount of data transmission among sensor networks. To reduce the amount of sending data, an aggregation approach can be applied along the path from sensors to the sink. However, as sensor networks are often deployed in untrusted and even hostile environments, sensor nodes are prone to node compromise attacks. Hence, an end-to-end secure aggregation approach is required to ensure a healthy data reception. In this paper, we propose two layers for secure data aggregation in sensor networks. Firstly, we provide an end-to-end encryption scheme that supports operations over cypher-text. It is based on elliptic curve cryptography that exploits a smaller key size, allows the use of higher number of operations on cypher-texts, and prevents the distinction between two identical texts from their cryptograms. Secondly, we propose a new watermarking-based authentication that enables sensor nodes to ensure the identity of other nodes they are communicating with. Our experiments show that our hybrid approach of secure data aggregation enhances the security, significantly reduces computation and communication overhead, and can be practically implemented in on-the-shelf sensor platforms.

Keywords: wireless sensor networks; secure data aggregation; authentication; confidentiality; homomorphic encryption; elliptic curves; digital watermarking.

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1 Introduction

A typical sensor network is expected to consist of a large number of sensor nodes deployed randomly in a large scale. Usually, these nodes have limited power, storage, communication, and processing capabilities, making energy consumption an issue.

A major functionality of a sensor node is to measure environmental values using embedded sensors, and transmit it to a base station called "sink". The sensed data needs to be analyzed, which eventually serves to initiate some action. Almost this analysis presumes computation of the maximum, minimum, average, *etc.* It can be either done at the base station or by the nodes themselves, in a hierarchical scenario. In order to reduce the amount of data to be

transmitted to the sink, it is beneficial that this analysis can be done over the network itself. To save the overall energy resources of the network, it is agreed that the sensed data needs to be aggregated on the way to its final destination. Sensor nodes send their values to certain special nodes, i.e., aggregators. Each aggregator then condenses the data prior to sending it on. In terms of bandwidth and energy consumption, aggregation is beneficial as long as the aggregation process is not too central processing unit (CPU) intensive. The aggregators can either be special (more powerful) nodes or regular sensors nodes.

At the same time, sensor networks are often deployed in public or otherwise untrusted and even hostile environments, which prompts a number of security issues (e.g., key management, privacy, access control, authentication, *etc.*). Then, if security is a necessary in other (e.g., wired or MANET) types of networks, it is much more so in sensor networks. Actually, it is one of the most popular research topic in this field and many advances have been reported on in recent years.

From the above observations, we can notice the importance of a cooperative secure data aggregation in sensor networks. In other terms, after the data gathering and during transmissions to the base station, each node along the routing path cooperatively integrates and secures the fragments messages. Therefore, secure data aggregation protocols require sensor nodes to encrypt or authenticate any sensed data prior to its transmission, implement data aggregation at every intermediate node (without decryption), and prefer data to be decrypted by the sink so that energy efficiency is maximized.

The benefit and vulnerability, as well as the need to secure in-network aggregation, have been identified by numerous schemes in the literature. One approach [1] proposed a secure information aggregation protocol to answer queries over the data acquired by the sensors. Even though their method provided data authentication to guarantee secrecy, the data still sent in plain text format, which removes the privacy during transmission. Another one [2] proposed a secure energy efficient data aggregation (ESPDA) to prevent redundant data transmission in data aggregation. Unlike conventional techniques, their scheme prevents the redundant transmission from sensor nodes to the aggregator. Before transmitting sensed data, each sensor transmits a secure pattern to the aggregator. Only sensors with different data are allowed to transmit their data to the cluster-head. However, since each sensor at least needs to transmit a packet containing a pattern once, power cannot be significantly saved. In addition, each sensor node uses a fixed encryption key to encrypt data, which can lead to severe security flaws. In [3], the authors presented a secure encrypted-data aggregation scheme for wireless sensor networks. The idea is based on eliminating redundant sensor readings without using encryption and maintains data secrecy and privacy during transmission. This scheme saves energy on sensor nodes but still do not guarantee the privacy of sent data.

In this paper, we provide for the first time an hybrid approach for secure data aggregation in sensor networks. Firstly, our approach ensures that secrecy of sensed data

is never disclosed to unauthorized parties by providing a secure homomorphic cypher-system that allows efficient aggregation of encrypted data. We show that our encryption method allows many operations over cypher-texts that prevents data decryption at intermediate nodes (aggregators) and reduces energy consumption. Secondly, we extend our homomorphic secure data aggregation level to two layers hierarchical data aggregation protocol, by including a watermarking-based authentication level. To assess the practicality of our technique, we evaluate it and compare it to existing cypher-system. The obtained results show that we significantly reduce computation and communication overhead as well as our secure aggregation method can be practically implemented in on-the-shelf sensor platforms.

The rest of this paper is organized as follows. After having recalled some previous related work in the fields of data confidentiality and authentication, the next section introduces our two security layers. In Section 4 the first one, namely the secure data aggregation using an almost fully homomorphic cryptosystem over elliptic curves, is presented in detail. Its security is evaluated qualitatively and through experiments in Section 4.6. In the next section, our second complementary approach for security in WSN is proposed. This is a nodes authentication protocol based on information hiding security field. Advanced notions of security are taken from this field and translated in WSN terms. Then an existing authentication scheme is evaluated and improved in Section 5.3. Finally, in Section 5.4, a new secure authentication method based on watermarking is proposed and evaluated. This research work ends by a conclusion section, where our contribution is summarized and intended future work is presented.

2 Security in sensor networks

Because sensor networks may interact with sensitive data and be deployed in hostile unattended environments, it is imperative to protect sensitive information transmitted by sensor nodes. Moreover, wireless sensor networks introduce severe resource constraints due to their lack of data storage and power. Therefore, they have security problems that traditional networks (computer security) do not face and there are many security considerations that should be investigated. In this paper, we treat the essential security requirements that are raised in a wireless sensor network environment, mainly: data confidentiality, node authentication, and how they relate with data aggregation process.

2.1 Data confidentiality

In critical applications, data confidentiality ensures that secrecy of transmitted data is never disclosed to unauthorized parties. Therefore, it is very important to build secure channels between sensor networks. The standard technique for keeping sensitive data secret is to encrypt them such that only intended receivers can realize decryption, hence achieving confidentiality.

Data encryption becomes necessary in sensor networks when this type of sensors can be subject of many types

of attacks [4]. Without encryption, adversaries can monitor and inject false data into the network. In a general manner the encryption process is done as follows: sensor nodes must encrypt data on a hop-by-hop basis. An intermediate node (*i.e.*, aggregator) possessing the keys of all sending nodes, decrypts the received encrypted value, aggregates all received values, and encrypts the result for transmission to the base station. Though viable, this approach is fairly expensive and complicated, due to the fact of decrypting each received value before aggregation, which generates an overhead imposed by key management and prevents end-to-end data confidentiality.

Some privacy homomorphism based researches have been proposed recently [5, 6, 7] that, without participating in checking, the aggregators can directly aggregate the encrypted data. The problem of aggregating encrypted data in sensor networks was introduced in [6] and further refined in [5]. The authors propose to use homomorphic encryption schemes to enable arithmetic operations over cypher-texts that need to be transmitted in a multi-hop manner. However, these approaches provide a higher level of system security, since nodes would not be equipped with private keys, which would limit the advantage gained by an attacker compromising some of the nodes. Unfortunately, existing privacy homomorphisms used for data aggregation in sensor networks have exponential bound in computation. For instance, Rivest Shamir Adleman (RSA) based cryptosystems [8, 9] are used, which require high CPU and memory capabilities to perform exponential operations. It is too computationally expensive to implement in sensor nodes. Moreover, the expansion in bit size during the transformation of plain text to cypher-text introduces costly communication overhead, which directly translates to a faster depletion of the sensors energy. On the other hand and from security viewpoint, the cryptosystems [10] used in these approaches were cryptanalyzed [11, 12], which means they cannot guarantee anymore high security levels.

In this paper we try to relax the statements above by investigating elliptic curve cryptography that allows feasible and suitable data aggregation in sensor networks beside the security of homomorphisms schemes. First of all, our proposed scheme for secure data aggregation in sensor networks is based on a cryptosystem that has been proven safe and has not been cryptanalyzed. Indeed, it is known to be the sole secure and almost fully homomorphic cryptosystem usable now. Another property that enforces the security level of such an approach is coming from the fact that, as it is the case in ElGamal cryptosystem, for two identical messages it generates two different cryptograms. This property suggested fundamental for security in sensor networks [13, 3, 14], to the best of our knowledge, was not addressed in previous homomorphism-based security data aggregation researches. Beside all these properties and due to the use of elliptic curves, our approach saves energy by allowing nodes to encrypt and aggregate data without the need of high computations. Lastly, the scheme we use allows more aggregations types over cypher data than the homomorphic cryptosystems used until now. This approach is detailed in Section 4 and is evaluated in Section 4.6.

2.2 Node authentication

In wireless sensors networks an adversary can change the whole packet stream by injecting additional packets. Therefore, the receiver needs to ensure that the data used in any decision-making process originates from the correct source. Without authentication, an adversary could masquerade a node, thus gaining unauthorized access to resource and sensitive information, and interfering with the operation of other nodes. Moreover, a compromised node may send data to its data aggregator under several fake identities so that the integrity of the aggregated data is corrupted. Node authentication enables a sensor node to ensure the identity of the peer node it is communicating with. In the case of only two-nodes communication, authentication can be achieved through a purely symmetric key cryptography: the sender and the receiver share a secret key to compute the message authentication code (MAC) of all communicated data.

In-network processing presents a critical challenge for data authentication in wireless sensor networks. Current schemes relying on MAC cannot provide natural support for this operation, because a MAC computation is a very energy-consuming operation. Additionally, even a slight modification to the data invalidates the MAC.

The authors in [15] propose a key-chain distribution system for their μ TESLA secure broadcast protocol. The basic idea of the μ TESLA system is to achieve asymmetric cryptography by delaying the disclosure of the symmetric keys. In this case a sender will broadcast a message generated with a secret key. After a certain period of time, the sender will disclose the secret key. The receiver is responsible for buffering the packet until the secret key has been disclosed. After disclosure the receiver can authenticate the packet, provided that the packet was received before the key was disclosed. One major limitation of μ TESLA is that some initial information must be unicast to each sensor node before authentication of broadcast messages can begin.

In [16] a new way to achieve authentication through wireless sensor networks is introduced. It is based on digital watermarking and proposes an end-to-end, statistical approach for data authentication that provides inherent support for in-network processing. In this scheme, authentication information is modulated as a watermark and superposed on the sensory data at the sensor nodes. The key idea formerly presented in [16] is to visualize the sensory data at a certain time snapshot as an image. Each sensor node is viewed as a pixel and its value corresponds to the gray level of the pixel. Due to this equivalence, information hiding techniques can be used to authenticate a wireless sensor network.

In some well-defined situations, the watermarked data can be aggregated by the intermediate nodes without incurring any in route checking. In this context, aggregation is for instance related to DCT or DWT compression, that is, to any operation over images that is able to reduce their weights without removing the watermarks. Upon reception of the sensory data, the sink is able to authenticate the data by finding and validating the watermark, thereby detecting

whether the data has been illegitimately altered. In this way, the aggregation-survivable authentication information is only added at the sources and checked by the data sink, without any involvement of intermediate nodes. To realize such an authentication, the authors of [16] propose to use a data hiding scheme based on spread spectrum techniques. In their proposal, "each sensor node embeds part of the whole watermark into its sensory data, while leaving the heavy computational load of watermark detection at the sink". Moreover, as stated before, their scheme supports in-network aggregation. Such an approach, its issues and security consequences, and how to improve their scheme, are detailed in the last sections of this research work.

3 Tree-based data aggregation

Data aggregation schemes aim to combine and summarize data packets of several sensor nodes so that amount of data transmission is reduced. An example of data aggregation schemes is the tree based data aggregation protocol as presented in Figure 1 where sensor nodes collect information from a region of interest. When the user (sink) queries the network, instead of sending each sensor node's data to the base station, aggregators collect the information from its neighboring nodes, aggregates them, and send the aggregated data to the base station over a multihop path.

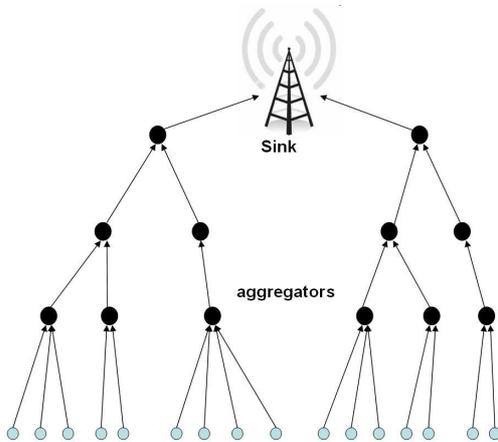


Figure 1 Tree-based data aggregation in sensor networks

The main objective of data aggregation is to increase the network lifetime by reducing the resource consumption of sensor nodes, especially the battery energy and bandwidth. While increasing network lifetime, data aggregation protocols might take into account an important quality of service metric: the security. Therefore, encryption of the sensed data before its transmission becomes necessary and it is preferable to decrypt the data only at the base station level. In the next section, we present our model for sensor data encryption compliant with this requirement.

4 Sensor data encryption using fully homomorphic cryptosystem

In this work, we are primarily concerned with data privacy in sensor networks. Our goal is to prevent attackers from gaining any information about sensor data. Therefore, ensuring an end-to-end privacy between sensor nodes and the sink becomes problematic. This is largely because popular and existing cyphers are not additively homomorphic. In other words, the summation of encrypted data does not allow for the retrieval of the sum of the plain text values. Moreover, privacy existing homomorphisms have usually exponential bound in computation. To overcome this problem, in our model we propose a security scheme for sensor networks using elliptic curve based cryptosystem. We show that our model permits many operations on encrypted data and does not demand high sensor capabilities and computation.

4.1 Operations over Elliptic Curves

In this section, we give a brief introduction to elliptic curve cryptography. The reader is referred to [17] for more details.

Elliptic curve cryptography (ECC) is an approach to public-key cryptography based on the algebraic structure of elliptic curves over finite fields [17]. Elliptic curves used in cryptography are typically defined over two types of finite fields: prime fields \mathbb{F}_p , where p is a large prime number, and binary extension fields \mathbb{F}_{2^m} [18]. In our paper, we focus on elliptic curves over \mathbb{F}_p . Let $p > 3$, then an elliptic curve over \mathbb{F}_p is defined by a cubic equation $y^2 = x^3 + ax + b$ as the set

$$\mathcal{E} = \{(x, y) \in \mathbb{F}_p \times \mathbb{F}_p, y^2 \equiv x^3 + ax + b \pmod{p}\}$$

where $a, b \in \mathbb{F}_p$ are constants such that $4a^3 + 27b^2 \not\equiv 0 \pmod{p}$. An elliptic curve over \mathbb{F}_p consists of the set of all pairs of affine coordinates (x, y) for $x, y \in \mathbb{F}_p$ that satisfy an equation of the above form and an infinity point \mathcal{O} .

The point addition and its special case, point doubling over \mathcal{E} is defined as follows (the arithmetic operations are defined in \mathbb{F}_p) [17]:

Let $P = (x_1, y_1)$ and $Q = (x_2, y_2)$ be two points of \mathcal{E} . Then:

$$P + Q = \begin{cases} \mathcal{O} & \text{if } x_2 = x_1 \text{ and } y_2 = -y_1, \\ (x_3, y_3) & \text{otherwise.} \end{cases} \quad (1)$$

where:

- $x_3 = \lambda^2 - x_1 - x_2$,
- $y_3 = \lambda \times (x_1 - x_3) - y_1$,

$$\lambda = \begin{cases} (y_2 - y_1) \times (x_2 - x_1)^{-1} & \text{if } P \neq Q, \\ (3x_1^2 + a) \times (2y_1)^{-1} & \text{if } P = Q. \end{cases} \quad (2)$$

Finally, we define $P + \mathcal{O} = \mathcal{O} + P = P, \forall P \in \mathcal{E}$, which leads to an abelian group $(\mathcal{E}, +)$. On the other hand the multiplication $n \times P$ means $P + P + \dots + P$ n times and $-P$ is the symmetric of P for the group law $+$ defined above for all $P \in \mathcal{E}$.

Algorithm 1 Keys generation program in Python/Sage.

```

1: def GG1e(n):
2:     l = 1
3:     p = l*n-1
4:     while not isprime(p) or not p%3 == 2:
5:         l += 1
6:         p += n
7:     F = GF(p)
8:     H = EllipticCurve(F, [0, 1])
9:     X = H.gen(0)
10:    g = l*X
11:    G,y = [],g
12:    flag = True
13:    while flag:
14:        y = randint(0,n-1)*g
15:        if y.order() == n:
16:            G.append(y)
17:            if len(G) == 2:
18:                flag = False
19:    return G,p
20:
21: def G(t):
22:    q1 = generatePrime(t)
23:    q2 = generatePrime(t)
24:    n = q1*q2
25:    GG,p = GG1e(n)
26:    return (q1,q2,GG,p)
27:
28: def KeyGen(bits):
29:    (q1,q2,GG,p) = G(bits)
30:    n = q1*q2
31:    g,u = GG
32:    h = q2*u
33:    return ((n,G,g,h,p),q1)

```

4.2 Public/Private Keys Generation with ECC

In this section we show how we can generate the public and private keys for encryption, following the cryptosystem proposed by Boneh *et al.* [13]. The analysis of the complexity will be treated in a later section.

Let $\tau > 0$ be an integer called “security parameter”. To generate public and private keys, first of all, two τ -bits prime numbers must be computed. Therefore, a cryptographic pseudo-random generator can be used to obtain two vectors of τ bits, q_1 and q_2 . Then, a Miller-Rabin test can be applied for testing the primality or not of q_1 and q_2 . We denote by n the product of q_1 and q_2 , $n = q_1q_2$, and by l the smallest positive integer such that $p = l \times n - 1$. l is a prime number while $p = 2 \pmod{3}$.

In order to find the private and public keys, we define a group H , which presents the points of the super-singular elliptic curve $y^2 = x^3 + 1$ defined over \mathbb{F}_p . It consists of $p + 1 = n \times l$ points, and thus has a subgroup of order n , we call it G . In another step, we compute g and u as two generators of G and $h = q_2 \times u$. Then, following [13], the public key will be presented by (n, G, g, h) and the private key by q_1 .

To give illustration of such a keys generation, a program is presented in Algorithm 1. It is written with the Python 2.6 language and the Sage library to manipulate elliptic curves. The *randint(a,b)* function is provided by the random library;

it generates an integer randomly picked into the interval $[a, b]$. The *generatePrime(n)* function is not detailed here. It receives an integer n as its input argument and generates a prime number of n bits.

4.3 Encryption and Decryption

After the private/public keys generation, we proceed now to the two encryption and decryption phases:

- **Encryption** : Assuming that our messages space consists of integers in the set $\{0, 1, \dots, T\}$, where $T < q_2$, and m the (integer) message to encrypt. Firstly, a random positive integer is picked from the interval $[0, n - 1]$. Then, the cypher-text is defined by

$$C = m \times g + r \times h \in G,$$

in which $+$ and \times refer to the addition and multiplication laws defined previously.

- **Decryption** : Once the message C arrived to destination, to decrypt it, we use the private key q_1 and the discrete logarithm of $(q_1 \times C)$ base $q_1 \times g$ as follows:

$$m = \log_{q_1 \times g} q_1 \times C.$$

This takes expected time \sqrt{T} using Pollard’s lambda method. Moreover, this decryption can be speed-up by precomputing a table of powers of $q_1 \times g$.

Algorithm 2 Python program for Encryption and Decryption

```

1: def Encrypt(Kp, M):
2:    (n,G,g,h,p) = Kp
3:    r = randint(0,n-1)
4:    return M*g+r*h
5:
6: def Decrypt(Kp,Ks,C):
7:    (n,G,g,h,p), q1 = Kp, Ks
8:    P = q1*g
9:    return P.discrete-log(q1*C)
10:
11: def Decrypt-product(Kp,Ks,C):
12:    (n,G,g,h,p), q1 = Kp, Ks
13:    g1 = modified-weil(g,g,p)
14:    return log(C,g1)

```

In Algorithm 2 is detailed an example of encryption and decryption programs in Python/Sage. The *modified_weil* and *discrete_log* functions are provided by Sage.

4.4 Homomorphic Properties

As we mentioned before, our approach ensures easy encryption/decryption without any need of extra resources. This will be proved in the next section. Moreover, our approach supports homomorphic properties, which gives us the ability to execute operations on values even though they

have been encrypted. Indeed, it allows N additions and one multiplication directly on cryptograms, which prevents the decryption phase at the aggregators level and saves nodes energy, which is crucial in sensor networks.

Additions over cypher-texts are done as follows: let m_1 and m_2 be two messages and C_1, C_2 their cypher-texts respectively. Then the sum of C_1 and C_2 , let's call it C , is represented by

$$C = C_1 + C_2 + r \times h,$$

where r is an integer randomly chosen in $[0, n-1]$ and $h = q_2 \times u$ as presented in the previous section. This sum operation guarantees that the decryption value of C is the sum $m_1 + m_2$. The addition operation can be done several times, which means we can do sums of encrypted sums.

The multiplication of two encrypted values and its decryption are done as follows: let e be the modified Weil pairing on the curve and g, h the points of G as defined previously. Let us recall that this modified Weil pairing e is obtained from the Weil pairing E [13], [19] by the formula: $e(P, Q) = E(x \times P, Q)$, where x is a root of $X^3 - 1$ on \mathbb{F}_{p^2} . Then, the result of the multiplication of two encrypted messages C_1, C_2 is given by

$$C_m = e(C_1, C_2) + r \times h_1,$$

where $h_1 = e(g, h)$ and r is a random integer pick in $[1, n]$.

The decryption of C_m is equal to the discrete logarithm of $q_1 \times C_m$ to the base $q_1 \times g_1$:

$$m_1 m_2 = \log_{q_1 \times g_1} (q_1 \times C_m)$$

where $g_1 = e(g, g)$.

The decryption program of a product is given in Algorithm 2 whereas the addition and multiplication over cryptograms programs are given in Algorithm 3.

Algorithm 3 Python/Sage program of homomorphic operations

```

1: def multiply(Kp,cr1,cr2):
2:   (n,G,g,h,p) = Kp
3:   r = randint(0,n-1)
4:   return modified-weil(cr1,cr2,p)
5:     +r*modified-weil(g,h,p)
6:
7: def add(Kp,cr1,cr2):
8:   (n,G,g,h,p) = Kp
9:   r = randint(0,n-1)
10:  return cr1+cr2+r*h

```

4.5 Encryption for Sensor Networks

Our contribution compared to existing secure data aggregation. In previous secure data aggregation protocols, security and data aggregation are almost always achieved together in a hop-by-hop manner. That is, data aggregators must decrypt every message they receive, aggregate the messages according to the corresponding aggregation function, and encrypt the aggregation result before forwarding it. Therefore, these techniques cannot provide

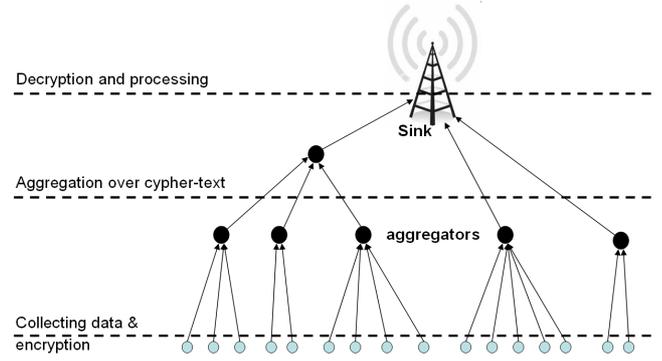


Figure 2 Secure data aggregation in sensor networks

data confidentiality at data aggregators and result in latency because of the decryption/encryption process.

In our work, we propose an encryption protocol that performs data aggregation without requiring the decryption of the sensor data at data aggregators. We adopt the following scenario as shown in Figure 2: after collecting information, each sensor node encrypts its data according to elliptic curve encryption (*c.f.* Section 4.1) and sends it to the nearest aggregator. Then, aggregators aggregate the received encrypted data (without decryption) and send it to the base station, which in his turn decrypts the data and aggregates it. We notice that all aggregators can do N additions and the final layer of aggregators can do one multiplication on encrypted data.

4.5.1 Illustrative Examples

- **Computing the Arithmetic Mean**

The arithmetic mean is the "standard" average, often simply called the "mean", defined for n values x_1, \dots, x_n by

$$\bar{x} = \frac{1}{n} \cdot \sum_{i=1}^n x_i.$$

To compute the average of nodes measurements, aggregators can calculate the sum of the encrypted measurements and the number of nodes took these measurements and send it to the base station. More precisely, when using our scheme, each sensor encrypts its data x_i to obtain cx_i . The sensor then forwards cx_i to its parent, who aggregates all the cx_j 's of its k children by simply adding them up. The resulting value and the encryption of k are then forwarded. The sink can thus compute the average value with all of these data.

- **Computing the Variance**

Another common aggregation is to estimate the variance of the sensed values. Let us recall that the variance of n values x_1, \dots, x_n is defined by:

$$s_n^2 = \frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})^2 = \left(\frac{1}{n} \sum_{i=1}^n x_i^2 \right) - \bar{x}^2.$$

Our scheme can also be used to derive the variance of the measured and encrypted data, by the same method as in [20]. In this case, each sensor i must compute $y_i = x_i^2$, where x_i is the measured sample, and encrypts y_i to obtain cy_i . x_i must also be encrypted, as explained in the previous section. The sensor forwards cy_i , together with cx_i , to its parent. The parent aggregates all the cy_j of its k children by simply adding them up. It also aggregates, separately, the cx_j , as explained in the previous section. The two resulting values are then forwarded. The sink ends up with values $Cx = \sum_{i=1}^n cx_i$ and $Cy = \sum_{i=1}^n cy_i$. Cx is used to compute the average Av , when Cy is used to compute the variance as follows: $Var = \frac{Vy}{n} - Av^2$, where Vy is the decryption of Cy .

• Computing the Weighted Mean

The weighted mean of a non-empty set of data x_1, x_2, \dots, x_n with non-negative weights w_1, w_2, \dots, w_n , is the quantity

$$\bar{x} = \frac{w_1x_1 + w_2x_2 + \dots + w_nx_n}{w_1 + w_2 + \dots + w_n}.$$

We suppose now that each aggregator i of the first aggregation layer has computed the mean x_i of the encrypted values received from its sensor node. Additionally, we suppose that these aggregators are weighted, depending on their importance. For security reasons, this weight is also encrypted and the cypher value is denoted by w_i . This w_i can be proportional to the number of aggregated sensors. This weight can also illustrate the fact that two given regions have not the same relevance. To achieve weighted mean, each aggregator multiplies its encrypted mean x_i with encrypted weight w_i as it has been explained previously. The resulting value is then forwarded to the sink, which can decrypt $w_i \times x_i$ and sum all these decrypted values, to obtain the weighted mean defined above.

4.6 Evaluation of the homomorphic approach

4.6.1 Practical Issues

In this section we present some practical issues to our data encryption model. Firstly, we study the sizes of the encryption keys and we compare it to existing approaches. Then, we show how we can optimize the sizes of cryptograms in order to save more sensors energy.

Sizes of the Keys. Cryptograms are points of the elliptic curve \mathcal{E} . They are constituted by couples of integer coordinates lesser than or equal to $p = lq_1q_2 - 1$.

It is commonly accepted [21], [22] that for being secure until 2020, a cryptosystem:

- must have $p \approx 2^{161}$, for EC systems over \mathbb{F}_p ,
- must satisfy $p \approx 2^{1881}$ for classical asymmetric systems, such as RSA or ElGamal on \mathbb{F}_p .

Thus, for the same level of security, using elliptic curve cryptography does not demand high keys sizes, contrary to the case of RSA or ElGamal on \mathbb{F}_p . The use of small keys leads to small cryptograms and fast operations for encryption.

Reducing the Size of Cryptograms. In this section we show how we can reduce the size of cryptograms while using ECC. This is benefit for sensor nodes in terms of reducing energy consumption by sending data with smaller size. The messages are encrypted with q_2 bits, which leads to cryptograms with a mean of 160 bits long.

Let us suppose that $p \equiv 3 \pmod{4}$. As the cryptogram is an element (x, y) of \mathcal{E} , which is defined by $y^2 = x^3 + 1$, we can compress this cryptogram (x, y) to $(x, y \bmod 2)$ before sending it to the aggregator (as the value of y^2 is known). In this situation, we obtain cryptograms with a mean of 81 bits long for messages between 20 and 40 bits long.

To decompress the cryptogram (x, i) , the aggregator must compute $z = x^3 + 1 \bmod p$ and $y = \sqrt{z} \bmod p$, which can be written as $y = z^{(p+1)/4} \bmod p$, then :

- if $y \equiv i \pmod{2}$, then the decompression of (x, i) is (x, y) .
- else the decompression point is $(x, p - y)$.

4.6.2 Security study

Due to hostile environments and unique characteristics of sensor networks, it is a challenging task to protect sensitive information transmitted by nodes to the end user. In addition, this type of networks has security problems that traditional networks do not face. In this section, we outline a security study dedicated to wireless sensor networks.

In a sensor network environment adversaries can commonly use the following attacks:

Known-plain text attack: They can use common key encryption to see when two readings are identical. By using nearby sensors under control, attackers can conduct a known-plain text attack.

Chosen-plain text attack: Attackers can tamper with sensors to force them to predetermined values.

Man-in-the-middle: They can inject false readings or resend logged readings from legitimate sensor motes to manipulate the data aggregation process.

In Tables 1, 2 and similar to [18], we present a comparison between different encryption policies and possible attacks. In our method, as data are encrypted by public keys, and these public keys are sent by the sink to the sole authenticated motes, the wireless sensor network is then not vulnerable to a Man-in-the-middle attacks. On the other hand, our approach guarantees that for two similar texts gives two different cryptograms, which prevents the Chosen-plain text attacks and the Man-in-the-middle attacks. Finally, as the proposed scheme possesses the homomorphic property, data aggregation is done without decryption, and no private key is used in the network.

Table 1 Encryption polices and vulnerabilities

Encryption Policy	Possible attacks
Sensors transmit readings without encryption	Man-in-the-middle
Sensors transmit encrypted readings with permanent keys	Known-plain text attack Chosen-plain text attack Man-in-the-middle
Sensors transmit encrypted readings with dynamic keys	None of above
Our scheme	None of above

Table 2 Encryption polices and aggregation

Encryption Policy	Data aggregation
Sensors transmit readings without encryption	Generating wrong aggregated results
Sensors transmit encrypted readings with permanent keys	Data aggregation is impossible, unless the aggregator has encryption keys
Sensors transmit encrypted readings with dynamic keys	Data aggregation cannot be achieved unless the aggregator has encryption keys
Our scheme	Data aggregation can be achieved

4.7 Experimental Results

4.7.1 Simulations

To show the effectiveness of our approach we conducted a series of simulations comparing our method to another existing one based on RSA cryptosystem. We considered a network formed of 500 sensor nodes, each one is equipped by a battery of 100 units capacity. We consider that the energy consumption “ E ” of a node is proportional to the computational time t , *i.e.*, $E = kt$. The same coefficient of proportionality k is taken while comparing the two encryption scenarii. Sensor nodes are then connected to 50 aggregators chosen randomly. Each sensor node choose the nearest aggregator. The running of each simulation is as follows: each sensor node takes a random value, encrypts it using one of the encryption methods then sends it to its aggregator. Aggregators compute the sum of the encrypted received data and send it to the sink. We compared our approach to the known RSA public-key cryptographic algorithms, and we evaluated the energy consumption of the network while varying the sizes of the keys and obviously the security levels. The energy consumption is the units of the battery used to do the encryption.

Tables 3 and 4 show the energy consumption of sensor nodes to do the encryption operations using our encryption method and the RSA one respectively. We varied the keys sizes and obviously the security levels. A security level is just an indicative factor of security, just to say that level 4 provides higher security level. We notice that for the same level of security in our approach we used small keys while saving more energy. For instance, for high security levels (4 for example) a node using our approach needs to use a key of 167 bits instead of 1891 in the case of RSA and consumes 0.1 % of the battery power instead of 3.63 %.

Security level	Size p of the key	E (battery units)
1	46	0.02
2	85	0.05%
3	125	0.07
4	167	0.10

Table 3 Security vs energy at the nodes level using our approach

Security level	Size of the key	E (battery units)
1	472	0.08
2	945	0.53
3	1416	1.63
4	1891	3.63

Table 4 Security vs energy at the nodes level using RSA

Security level	Size p of the key	E (battery units)
1	46	0.02
2	85	0.04
3	125	0.07
4	167	0.10

Table 5 Security vs energy at the aggregator level using our approach

Tables 5 and 6 give the energy consumption E at the aggregation stage. The same hypothesis as above have been made, the sole difference is that aggregator nodes have a battery of 1000 units of energy. It can be seen that the energy needed by aggregators are between 50 and 500 times more important in the RSA-based scheme, for the same level of security.

Figure 3 gives the comparison between RSA and elliptic curve based encryption, concerning the average energy consumption of an aggregating wireless sensor network. We

Security level	Size of the key	E (battery units)
1	472	1.13
2	945	8.09
3	1416	24.74
4	1891	56.27

Table 6 Security vs energy at the aggregator level using RSA

can notice that our approach saves the energy largely greater than the case of RSA, where its depletion is so fast. Finally let us notice that, in addition of reducing the amount of energy units needed for encryption and aggregation, the sink receives many more values per second in EC-based networks than in RSA-based one.

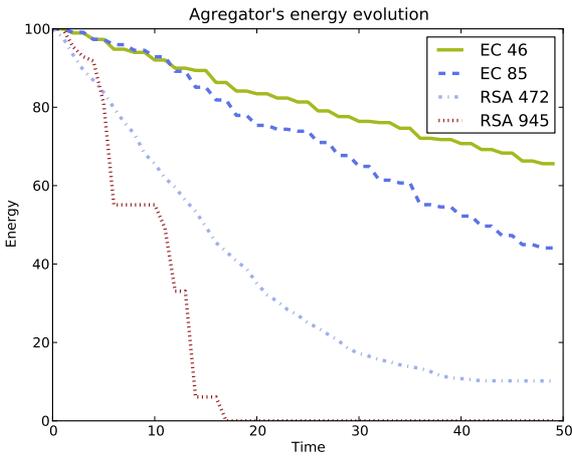


Figure 3 Comparison of energy consumption

5 Authentication over Homomorphic Sensor Networks

In the previous sections, we have proposed to use a homomorphism encryption scheme to support in-network processing while preserving privacy. Compared to existing secure aggregation schemes based on homomorphism encryption, our method has not been cryptanalysed. Moreover, due to the possibility to realize n additions and one product over the cypher values, this scheme enlarges the variety of allowing aggregation operations through cyphertexts.

However, all of the secure homomorphism encryption schemes only allow some specific query-based aggregation functions, *e.g.*, sum, average, *etc.* Indeed data encryption guarantees that only intended parties obtain the un-encrypted plain data, it does not protect the network from malicious or spoofed packets. Node authentication enables a sensor node to ensure the identity of the packet's sender. Another way to achieve secure data aggregation in wireless sensor networks is then to authenticate sensing values.

Finally, an hybrid approach of secure data aggregation in wireless sensor networks can be obtained by combining homomorphic encryption and watermarking-based

authentication, as it is summed up in Figure 4. In the next section we present our proposed scheme for node authentication in sensor networks.

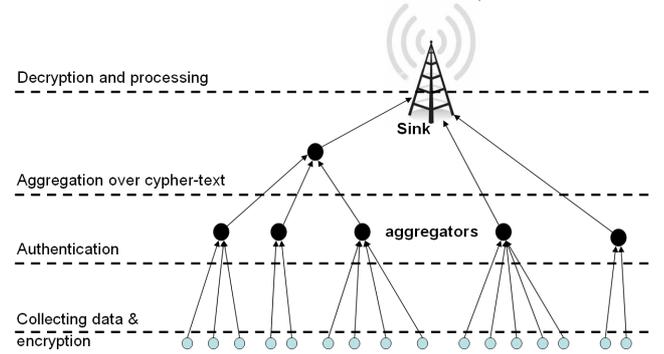


Figure 4 Two layers secure data aggregation in sensor networks

5.1 Information hiding-based authentication

In this paper we consider that authentication information is modulated as watermark and superposed on the sensory data at the sensor nodes. The watermarked data can be aggregated by the intermediate nodes without incurring any en route checking. Upon reception of the sensory data, the data sink is able to authenticate the data by validating the watermark, thereby detecting whether the data has been illegitimately altered.

Let us firstly give some recalls concerning the information hiding framework.

5.1.1 Robustness versus Security

Robustness and security are two major concerns in information hiding. Even if security and robustness are neighboring concepts without clearly established definitions [23], robustness is often considered to be mostly concerned with blind elementary attacks, whereas security is not limited to certain specific attacks. Indeed, security encompasses robustness and intentional attacks [24, 25]. The best attempt to give an elegant and concise definition for each of these two terms was proposed by Kalker in [24]. Following Kalker, we will consider in this research work that: "Robust watermarking is a mechanism to create a communication channel that is multiplexed into original content [...]. It is required that, firstly, the perceptual degradation of the marked content [...] is minimal and, secondly, that the capacity of the watermark channel degrades as a smooth function of the degradation of the marked content. [...]. Watermarking security refers to the inability by unauthorized users to have access to the raw watermarking channel. [...] to remove, detect and estimate, write or modify the raw watermarking bits." On the contrary, a *fragile* watermarking is such that any alteration of the watermarked medium, as small as possible, will lead to the destruction of the watermark.

5.1.2 Information hiding security

In the framework of watermarking and steganography, security has seen several important developments since the last decade [26, 27, 28]. The first fundamental work in security was made by Cachin in the context of steganography [29]. Cachin interprets the attempts of an attacker to distinguish between an innocent image and a stego-content as a hypothesis testing problem. In this document, the basic properties of a stegosystem are defined using the notions of entropy, mutual information, and relative entropy. Mittelholzer, inspired by the work of Cachin, proposed the first theoretical framework for analyzing the security of a watermarking scheme [30].

These efforts to bring a theoretical framework for security in steganography and watermarking have been followed up by Kalker, who tries to clarify the concepts (robustness vs. security), and the classifications of watermarking attacks [24]. This work has been deepened by Furon *et al.*, who have translated Kerckhoffs' principle (Alice and Bob shall only rely on some previously shared secret for privacy), from cryptography to data hiding [31]. They used Diffie and Hellman methodology, and Shannon's cryptographic framework [32], to classify the watermarking attacks into categories, according to the type of information Eve has access to [27, 33], namely: Watermarked Only Attack (WOA), Known Message Attack (KMA), Known Original Attack (KOA), and Constant-Message Attack (CMA). These categories of attacks are recalled below.

Watermark-Only Attack (WOA) occurs when an attacker has only access to several watermarked contents.

Known-Message Attack (KMA) occurs when an attacker has access to several pairs of watermarked contents and corresponding hidden messages.

Known-Original Attack (KOA) is when an attacker has access to several pairs of watermarked contents and their corresponding original versions.

Constant-Message Attack (CMA) occurs when the attacker observes several watermarked contents and only knows that the unknown hidden message is the same in all contents.

Levels of security have been recently defined in these setups. The highest level of security in WOA is called stego-security [34], whereas chaos-security tends to improve the ability to withstand attacks in KMA, KOA, and CMA setups [35].

5.1.3 Stego-security and chaos-security

Stego-security. In the prisoner problem of Simmons [36], Alice and Bob are in jail, and they want to, possibly, devise an escape plan by exchanging hidden messages in innocent-looking cover contents. These messages are to be conveyed to one another by a common warden, Eve, who over-drops all contents and can choose to interrupt the communication if they appear to be stego-contents.

The stego-security, defined in this framework, is the highest security level in WOA setup [34]. To recall it, we need the following notations:

- \mathbb{K} is the set of embedding keys,
- $p(X)$ is the probabilistic model of N_0 initial host contents,
- $p(Y|K)$ is the probabilistic model of N_0 watermarked contents with the same embedding key $K \in \mathbb{K}$.

In this framework, it is then supposed in this context that each host content has been watermarked with the same secret key K and the same embedding function e .

It is now possible to define the notion of stego-security:

Stego-Security: The embedding function e is *stego-secure* if and only if:

$$\forall K \in \mathbb{K}, p(Y|K) = p(X).$$

Chaos-security. We finally detail the highest level of security in KMA, KOA, and CMA setups. It is called chaos-security and is defined as follows.

To check whether an information hiding scheme S is chaos-secure or not, S must be written as an iterate process $x^{n+1} = f(x^n)$ on a metric space (\mathcal{X}, d) , where the phase space \mathcal{X} is the set of all possible contents and d is a distance that must be carefully chosen, depending on the objectives to reach ($d(x, y)$ must be small iff x is undistinguishable from y).

This formulation is always possible [37]. So,

Chaos-Security: An information hiding scheme S is said to be chaos-secure on (\mathcal{X}, d) if its iterative process has a chaotic behavior according to Devaney.

In other words, the iteration process must satisfy the following chaos properties:

- iterations of f are regular (*i.e.*, periodic points of f are dense in \mathcal{X}),
- f is topologically transitive (*i.e.*, for any pair of open sets $U, V \subset \mathcal{X}$, there exists some natural number $k > 0$ s. t. $f^k(U) \cap V \neq \emptyset$),
- f has sensitive dependence on initial conditions (*i.e.*, there exists $\delta > 0$ s.t. for any $X \in \mathcal{X}$ and any neighborhood V of X , there exist $Y \in V$ and $k \geq 0$ with $d(f^k(X), f^k(Y)) > \delta$).

In the approach presented in [35], a data hiding scheme is secure if it is unpredictable. Its iterative process must satisfy the Devaney's chaos property and its level of chaos-security increases with the number of chaotic properties satisfied by it.

One of these chaos property, namely the expansivity, is an important quantitative measure of disorder. It is recalled below.

Definition 5.3: A function f is said to have the property of *expansivity* if

$$\exists \varepsilon > 0, \forall x \neq y, \exists n \in \mathbb{N}, d(f^n(x), f^n(y)) \geq \varepsilon. \quad (3)$$

Then ε is the *constant of expansivity* of f : an arbitrarily small error on any initial condition is *always* amplified until ε . It has been proven in [35] that an information hiding scheme that is not expansive is unable to face an attacker in KOA and KMA setups [35].

This new concept of security for data hiding schemes has been proposed in [37] as a complementary approach to the existing framework. It contributes to the reinforcement of confidence put into existing secure data hiding schemes. Additionally, the study of security in KMA, KOA, and CMA setups is realizable in this context. Finally, this framework can replace stego-security in situations that are not encompassed by it. In particular, this framework is more relevant to give evaluation of data hiding schemes claimed as chaotic.

5.2 Application to nodes authentication

We explain in this section why, in our opinion, the framework recalled above is useful for studying wireless sensor network authentication nodes.

5.2.1 Robustness for authenticated wireless sensor networks

We now adapt the concepts recalled above for nodes authentication based on information hiding techniques. First of all, robustness means that the watermark still remains after geometric and frequency attacks. The interest to have a robust watermarking for authentication in WSN is then twofold.

On the one hand, the network is not always fixed and can possibly evolve over time. Nodes can be moved for various reasons, some of them can stop to transmit their sensed and watermarked data (for technical reasons, or when they have consumed all of their energies), noise can appear during transmission, and so on. Nevertheless, the authentication capability of the whole network must be preserved into the sink, and thus the watermarking scheme used for authentication must be compliant with such alterations. That is to say, if the wireless sensor network can be slightly altered for reasonable and natural reasons, then the authentication scheme must be robust. Table 7 gives some relationships between geometric and frequency attacks in the information hiding framework, and natural alteration of a wireless sensor network.

On the other hand, some information hiding schemes are robust against image compression attacks like JPEG or JPEG2000 compressions. Such a resistance is obtained for instance by inserting the watermark into the DCT or DCT coefficients of the image instead of using the gray level of each pixel. The idea formerly proposed by [16] is to use this resistance for aggregation. Indeed, in situation of JPEG or JPEG2000 compression resistance, watermarked data sent by sensor nodes can be aggregated by using a DCT or DWT compression. Due to the robustness of the well-chosen information hiding scheme against these attacks, the

Digital Watermarking	WSN
pixel picture	node network
zeroing attack rotation and resize attacks uniform or gaussian noise contrast attacks blur attacks	death of nodes nodes displacement transmission errors unbalanced signals signal attenuation

Table 7 Relationship between digital watermarking and WSN

watermark still remains after such compressions, and the aggregation preserves authentication.

Furthermore, a fragile watermarking can be useful too in an information hiding based authentication of nodes into a WSN. Let us consider for instance that an attacker adds one of his node into a given wireless sensor network that use a fragile watermarking scheme for authentication. Additionally, we suppose that he can send corrupted sensed values without being detected, either to the aggregation layer or to the sink. Under this situation, the “watermarked image” received by the sink will be such that at least one pixel (*i.e.*, the corrupted node) has not a correct piece of watermark. Due to the fragility of the scheme, this alteration will be magnified and the extracted watermark will be completely different from what was expected, leading to the detection of the attack. Such a fragile authentication scheme can be useful too in situations where an attacker tries to modify an authorized node. In this case, as the node can embeds different pieces of watermark, the sink will be able to detect such anomaly.

Finally, there exist some watermarking schemes that are fragile in almost all situations, but are robust against some well defined threats. So fragile and robust properties can help to choose the best watermarking scheme for a given WSN authentication context. For instance, some schemes can be found in the literature that are robust against JPEG attacks with small compression rate, but are fragile in all of the other types of attacks. Such an algorithm is helpful when the network cannot evolve geographically, must use compression based aggregation, and is in an hostile environment. As a conclusion, we can see that using a watermarking scheme for authentication through WSN is useful in many situations.

5.2.2 Security for authenticated WSN

As robustness, information hiding security can be useful when authenticating nodes into wireless sensor networks. The four classes of attacks presented in Section 5.1.2 can be translated to WSN security as follows.

Watermark-Only Attack (WOA) occurs when an attacker has only access to several transmitted authenticated data. That is to say, he can only observe transmissions.

Known-Message Attack (KMA) occurs when an attacker has access to several pairs of watermarked contents and corresponding hidden messages. In other words, the adversary can observe the transmissions, and has

find a way to make an altered node insert the attacker's watermark.

Known-Original Attack (KOA) is when an attacker has access to several pairs of watermarked contents and their corresponding original versions. That is to say, the attacker can determine which value a node has sensed and can see the resulted watermarked data sent by this node.

Constant-Message Attack (CMA) occurs when the attacker observes several watermarked contents and only knows that the unknown hidden message is the same in all contents. In that situation, the adversary can observe another time the transmitted data. Additionally, he knows that always the same watermark is used to authenticate these data.

Other categories of attacks can be found in the literature, such as the Estimated-Original Attack. They all can be translated into the wireless sensor network security framework.

The Simmons' prisoner problem put into the WSN context can be translated too, as follows. Eve observes the transmission between two nodes called Alice and Bob. She tries to determine whether a given transmission is authenticated or not. Obviously, this is for her the starting point of an attack to authentication. For instance, if she is able to make the difference between authenticated and unauthenticated data, then she can:

- Replace unauthenticated data with her own values without being detected.
- Concentrate her efforts on a subset of authenticated data.
- Try to understand the differences between authenticated and unauthenticated data, with a view to forge her own "authenticated" values.
- Try to determine, by using statistical models and tools, the embedding key (the piece of watermark used to authenticate these values).
- *etc.*

The stego-security means that such a separation between authenticated and unauthenticated data is impossible, as the use of any key does not change the probabilistic model of the transmitted data. Obviously, there is a lack of security if an authentication scheme of data sending through a WSN, with an adversary being able to observe transmissions (Simmons' prisoner problem, WOA setup), is based on a watermarking algorithm that is not stego-secure. Similar conclusions can be obtained with the chaos-security notion in the KOA, KMA, and CMA setups: if situations covered by these setups can possibly occur, then the watermarking scheme used for authentication must be chaos-secure.

To the best of our knowledge, until now, only two data hiding schemes have been used to authenticate data sending

through a WSN. The first one is a spread-spectrum technique, used in [16]. The second one uses chaotic iterations.

In what follows, these information hiding techniques are recalled and their security is evaluated.

5.3 Security study of Zhang et al. authentication scheme

As Zhang *et al.* nodes authentication scheme for WSN is based on the spread-spectrum data hiding, we must firstly recall this technique before studying its security.

5.3.1 Spread-spectrum data hiding techniques

Let $x \in \mathbb{R}^{N_v}$ be a host vector in which we want to hide a message $m \in \{0, 1\}^{N_c}$. N_c is the size of the hidden payload (in bits) and N_v the size of the stego or host vector (in samples). A key \mathcal{K} is used to initialize a PRNG (Pseudo-Random Number Generator) to obtain N_c secret carries $\{u^i\}$ taken in \mathbb{R}^{N_v} , which can be supposed to be orthonormalized. Thus in classical SS the watermark signal w is constructed as follows:

$$w = \sum_{i=0}^{N_c-1} \gamma(-1)^{m^i} u^i,$$

where γ is a given distortion level. The watermarked signal y is then defined by:

$$y = x + w.$$

Let us now suppose that the components of the watermark are bounded by a finite value N_b : $\max(\{w_i, i \in \llbracket 1, N_v \rrbracket\}) \leq N_b$. This bound can be as large as needed, however a very large N_b seems to be contradictory with the aims of a data hiding scheme. Let us consider $\mathcal{X} = \left([-N_b, N_b]^{N_v}\right)^{\mathbb{N}} \times \mathbb{R}^{N_v}$ and

$$G((S, E)) = (\sigma(S); i(S) + E),$$

where σ is the *shift* function defined by $\sigma : (S^n)_{n \in \mathbb{N}} \in \left([-N_b, N_b]^{N_v}\right)^{\mathbb{N}} \rightarrow (S^{n+1})_{n \in \mathbb{N}} \in \left([-N_b, N_b]^{N_v}\right)^{\mathbb{N}}$ and the *initial function* i is the map which associates to a sequence, its first term: $i : (S^n)_{n \in \mathbb{N}} \in \left([-N_b, N_b]^{N_v}\right)^{\mathbb{N}} \rightarrow S^0 \in [-N_b; N_b]^{N_v}$. E will be the vector describing the part of the host that can be altered without sensitive damages, when S will give the location of the alteration at each iteration (S will depend on the hidden message and the secret key).

Spread-spectrum data hiding techniques are thus the result of N_c iterations of the following dynamical system:

$$\begin{cases} X^0 \in \mathcal{X}, \\ X^{n+1} = G(X^n), \end{cases}$$

and the watermarked media is the second component of X^{N_c} . Indeed, the second component of X^k corresponds to the host image after k alterations, whereas the first component explains how to alter it another time.

Classical SS, *i.e.* with BPSK modulation [34], is defined by $X^0 = (S^0, E^0)$ where E^0 is the host vector x and S^0 is the sequence

$$\left((-1)^{m^0} \gamma u^0, (-1)^{m^1} \gamma u^1, \dots, (-1)^{m^{N_c-1}} \gamma u^{N_c-1}\right),$$

in which γ allows to achieve a given distortion, whereas in ISS (Improved Spread Spectrum [38]), S^0 is defined by

$$\left((-1)^{m^i} \alpha - \lambda \frac{\langle x, u^i \rangle}{\|u^i\|^2} \right)_{i=0, \dots, N_c-1},$$

where α and λ are computed to achieve an average distortion and to minimize the error probability [34]. Lastly, in natural watermarking NW, S^0 is defined by

$$\left(- \left(1 + \eta (-1)^{m^i} \frac{\langle x, u^i \rangle}{|\langle x, u^i \rangle|} \right) \frac{\langle x, u^i \rangle}{\|u^i\|^2} \right)_{i=0, \dots, N_c-1}.$$

This last modulation consists in a model-based projection on the different vectors u^i followed by a η -scaling along the direction of u^i .

Natural watermarking has been proven stego-secure when $\eta = 1$, whereas all of the other spread-spectrum techniques are not stego-secure (see [34]). Additionally, this scheme is reputed to be not robust. Finally, these four techniques are chaos-secure so they can be considered when facing an attacker in the CMA context [35]. However, as these techniques are not expansive, they are unable to face an attacker in KOA and KMA setups [35].

5.3.2 Cryptanalysis of the Zhang et al. authentication scheme

As recalled previously, spread spectrum is known to be not robust: even if their scheme survives to a certain degree of distortion, spread-spectrum cannot face to elementary blind attack. Furthermore, spread-spectrum data hiding techniques are only stego-secure in the "Natural Watermarking" situation [34]. The spread-spectrum subclass used in [16] is related to classical SS, *i.e.* with BPSK modulation [34]. This subclass is neither stego-secure [34], nor chaos-secure [37]. These lack of security allow an attacker who observes the network to access to the secret embedding key in all of the following situations: WOA, KMA, KOA, and CMA setups.

To improve the security of the network in WOA setup, the use of Natural Watermarking instead of BPSK modulation is required [34]. However, Natural Watermarking is less chaos-secure than the data hiding algorithm presented in [39]. This algorithm, based on chaotic iterations, is able to withstand attacks in KMA, KOA and CMA setups [40]. Moreover, this technique is more robust than spread-spectrum, as it is stated in [41]. To sum up, the use of the scheme proposed in [39] improves the security and robustness of the scheme presented in [16]. This algorithm is recalled in the next section and evaluated in the last one.

5.4 Information hiding based on chaotic iterations

For easy understanding, our information hiding scheme based on chaotic iteration is explained by using pictures instead of networks. As there is an equivalency between pixels and nodes, this discussion and the evaluation of the next section holds for a wireless sensor network, *mutatis mutandis*.

5.4.1 Chaotic iterations

In the sequel S^n denotes the n^{th} term of a sequence S and V_i is for the i^{th} component of a vector V . Finally, the following notation is used: $\llbracket 0; N \rrbracket = \{0, 1, \dots, N\}$.

Let us consider a *system* of a finite number N of elements (or *cells*), so that each cell has a boolean *state*. A sequence of length N of boolean states of the cells corresponds to a particular *state of the system*. A sequence that elements belong into $\llbracket 1; N \rrbracket$ is called a *strategy*. The set of all strategies is denoted by \mathcal{S} .

Definition 5.4: The set \mathbb{B} denoting $\{0, 1\}$, let $f : \mathbb{B}^N \rightarrow \mathbb{B}^N$ be a function and $S \in \mathcal{S}$ be a strategy. The so-called *chaotic iterations* are defined by $x^0 \in \mathbb{B}^N$ and $\forall (n, i) \in \mathbb{N}^* \times \llbracket 0; N-1 \rrbracket$:

$$x_i^n = \begin{cases} x_i^{n-1} & \text{if } S^n \neq i, \\ (f(x^{n-1}))_{S^n} & \text{if } S^n = i. \end{cases} \quad (4)$$

5.4.2 Chaotic iterations and Devaney's chaos

In this section we give outline proofs of the properties on which our nodes authentication is based. The complete theoretical framework is detailed in [39].

Denote by Δ the *discrete boolean metric*, $\Delta(x, y) = 0 \Leftrightarrow x = y$. Given a function f , define the function: $F_f : \llbracket 1; N \rrbracket \times \mathbb{B}^N \rightarrow \mathbb{B}^N$ such that $F_f(k, E) = (E_{j \cdot \Delta(k, j)} + f(E)_{k \cdot \Delta(k, j)})_{j \in \llbracket 1; N \rrbracket}$.

Let us consider the phase space $\mathcal{X} = \llbracket 1; N \rrbracket^N \times \mathbb{B}^N$ and the map $G_f(S, E) = (\sigma(S), F_f(i(S), E))$, where σ is defined by $\sigma : (S^n)_{n \in \mathbb{N}} \in \mathcal{S} \rightarrow (S^{n+1})_{n \in \mathbb{N}} \in \mathcal{S}$, and i is the map $i : (S^n)_{n \in \mathbb{N}} \in \mathcal{S} \rightarrow S^0 \in \llbracket 1; N \rrbracket$. So the chaotic iterations can be described by the following iterations:

$$X^0 \in \mathcal{X} \text{ and } X^{k+1} = G_f(X^k).$$

We have defined in [39] a new distance d between two points $(S, E), (\check{S}, \check{E}) \in \mathcal{X}$ by $d((S, E); (\check{S}, \check{E})) = d_e(E, \check{E}) + d_s(S, \check{S})$, where:

- $d_e(E, \check{E}) = \sum_{k=1}^N \Delta(E_k, \check{E}_k) \in \llbracket 0; N \rrbracket$
- $d_s(S, \check{S}) = \frac{9}{N} \sum_{k=1}^{\infty} \frac{|S^k - \check{S}^k|}{10^k} \in [0; 1]$.

It is then proven that,

Proposition 5.1: G_f is a continuous function on (\mathcal{X}, d) .

In the metric space (\mathcal{X}, d) , the vectorial negation $f_0 : \mathbb{B}^N \rightarrow \mathbb{B}^N, (b_1, \dots, b_N) \mapsto (\bar{b}_1, \dots, \bar{b}_N)$ satisfies the three conditions for Devaney's chaos: regularity, transitivity, and sensitivity [39]. So,

Proposition 5.2: G_{f_0} is a chaotic map on (\mathcal{X}, d) according to Devaney.

To explain how to use chaotic iterations for information hiding and thus for nodes authentication, we must firstly define the significance of a given coefficient.

5.4.3 Most and least significant coefficients

We first notice that into each node, the alteration of the sensed value for authentication must not be important. That is to say, terms of the original content x that may be replaced by terms issued from the watermark y are less important than other: they could be changed without be perceived as such. More generally, a *signification function* attaches a weight to each sensed value, depending on its position t .

Definition 5.5: A *signification function* is a real sequence $(u^k)_{k \in \mathbb{N}}$.

Example 1: To illustrate this notion, we use a picture representation of a given WSN. Let us consider a set of grayscale images stored into portable graymap format (P3-PGM): each pixel ranges between 256 gray levels, i.e., is memorized with eight bits. In that context, we consider $u^k = 8 - (k \bmod 8)$ to be the k -th term of a signification function $(u^k)_{k \in \mathbb{N}}$. Intuitively, in each group of eight bits (i.e., for each pixel) the first bit has an importance equal to 8, whereas the last bit has an importance equal to 1. This is compliant with the idea that changing the first bit affects more the image than changing the last one.

Definition 5.6: Let $(u^k)_{k \in \mathbb{N}}$ be a signification function, m and M be two reals s.t. $m < M$.

- The *most significant coefficients (MSCs)* of x is the finite vector

$$u_M = \left(k \mid k \in \mathbb{N} \text{ and } u^k \geq M \text{ and } k \leq |x| \right);$$

- The *least significant coefficients (LSCs)* of x is the finite vector

$$u_m = \left(k \mid k \in \mathbb{N} \text{ and } u^k \leq m \text{ and } k \leq |x| \right);$$

- The *passive coefficients* of x is the finite vector

$$u_p = \left(k \mid k \in \mathbb{N} \text{ and } u^k \in]m; M[\text{ and } k \leq |x| \right).$$

For a given WSN x , MSCs are then ranks of x that describe the relevant part of the sensed values, whereas LSCs translate its less significant parts. These two definitions are illustrated on Figure 5, where the significance function (u^k) is defined as in Example 1, $M = 5$, and $m = 6$.

5.4.4 Presentation of the scheme

Authors of [41] have proposed to use chaotic iterations as an information hiding scheme, as follows. Let:

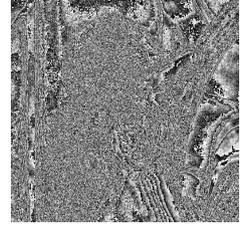
- $(K, N) \in [0, 1] \times \mathbb{N}$ be an embedding key,
- $X \in \mathbb{B}^N$ be the N LSCs of a cover C ,



(a) Sensed values of a WSN.



(b) MSCs of the WSN.



(c) LSCs of the WSN ($\times 17$).

Figure 5 Most and least significant coefficients of the WSN.

- $(S^n)_{n \in \mathbb{N}} \in \llbracket 1, N \rrbracket^{\mathbb{N}}$ be a strategy, which depends on the message to hide $M \in [0, 1]$ and K ,
- $f_0 : \mathbb{B}^N \rightarrow \mathbb{B}^N$ be the vectorial logical negation.

So the watermarked media is C whose LSCs are replaced by $Y_K = X^N$, where:

$$\begin{cases} X^0 = X \\ \forall n < N, X^{n+1} = G_{f_0}(X^n). \end{cases} \quad (5)$$

To sum up, chaotic iterations are realized on the least significant part of the sensed values.

Two ways to generate $(S^n)_{n \in \mathbb{N}}$ are given by these authors, namely Chaotic Iterations with Independent Strategy (CIIS) and Chaotic Iterations with Dependent Strategy (CIDS). In CIIS, the strategy is independent from the cover media C , whereas in CIDS the strategy will be dependent on C . As we will use the CIIS strategy in this document, we recall it below. Finally, MSCs can be used as a parameter of the CIIS.

5.4.5 CIIS strategy

Let us firstly give the definition of the Piecewise Linear Chaotic Map (PLCM, see [42]):

$$F(x, p) = \begin{cases} x/p & \text{if } x \in [0; p], \\ (x-p)/(\frac{1}{2}-p) & \text{if } x \in [p; \frac{1}{2}], \\ F(1-x, p) & \text{else,} \end{cases} \quad (6)$$

where $p \in]0; \frac{1}{2}[$ is a “control parameter”.

Then, the general term of the strategy $(S^n)_n$ in CIIS setup is defined by the following expression: $S^n = \lfloor N \times K^n \rfloor + 1$, where:

$$\begin{cases} p \in [0; \frac{1}{2}] \\ K^0 = M \otimes K \\ K^{n+1} = F(K^n, p), \forall n \leq N_0 \end{cases} \quad (7)$$

in which \otimes denotes the bitwise exclusive or (XOR) between two floating part numbers (i.e., between their binary digits representation), K is (one of) the embedding key, and M is:

UNAUTHENTICATION		AUTHENTICATION	
Size (pixels)	Similarity	Size (pixels)	Similarity
10	99.08%	10	89.81%
50	97.31%	50	54.54%
100	92.43%	100	52.24%

Table 8 Zeroing attacks.

UNAUTHENTICATION		AUTHENTICATION	
Angle	Similarity	Angle	Similarity
5	94.67%	5	59.47%
10	91.30%	10	54.51%
25	80.85%	25	50.21%

Table 9 Rotation attacks.

- either the sequence of MSCs, in the particular situation where each node has access to the other ones and when a fragile watermarking is needed (*Authentication*),
- or the rest of the embedding key, when robustness is required (*Unauthentication*).

5.5 Our proposed method

To prove the efficiency and the robustness of the proposed algorithm, some attacks are applied to our chaotic watermarked image. For each attack, a similarity percentage with the watermark is computed, this percentage is the number of equal bits between the original and the extracted watermark. These results have been formerly obtained in [41].

5.5.1 Zeroing Attack

In this kind of attack, some nodes of the WSN are put to 0. In this case, the results in Table 8 have been obtained. We can conclude that in case of unauthentication, the watermark still remains after a cropping attack: the desired robustness is reached. In case of authentication, even a small change of the carrier sensed values lead to a very different extracted watermark. In this case, any attempt to alter the WSN will be signaled.

5.5.2 Rotation Attack

Let r_θ be the rotation of angle θ around the center (128, 128) of the carrier image. So, the transformation $r_{-\theta} \circ r_\theta$ is applied to the watermarked WSN. The good results in Table 9 are obtained.

5.5.3 JPEG Compression

A JPEG compression is applied to the sensed values, depending on a compression level. Let us notice that this attack leads to a change of the representation domain (from spatial to DCT domain). In this case, the results in Table 10 have been found. A good authentication through a compression-based aggregation is obtained. As for the unauthentication case, the watermark still remains after a compression level equal to 10. This is a good result if we take into account the fact that we use “spatial” embedding.

UNAUTHENTICATION		AUTHENTICATION	
Ratio	Similarity	Ratio	Similarity
2	82.95%	2	54.39%
5	65.23%	5	53.46%
10	60.22%	10	50.14%

Table 10 JPEG compression attacks.

UNAUTHENTICATION		AUTHENTICATION	
Standard dev.	Similarity	Standard dev.	Similarity
1	74.26%	1	52.05%
2	63.33%	2	50.95%
3	57.44%	3	49.65%

Table 11 Gaussian noise attacks.

5.5.4 Gaussian Noise

Watermarked image can be also attacked by the addition of a Gaussian noise, depending on a standard deviation. In this case, the results in Table 11 have been found.

6 Conclusion

In this paper, we presented a two layers secure data aggregation for sensor networks. The first layer is based on data encryption with homomorphic properties that provide the possibility to operate on cypher-text. It prevents the decryption phase at the aggregators layers and saves nodes energy. Existing works have exponential bound in computation and are not suitable for sensor networks, which we tried to relax in our approach. The proposed scheme permits the generation of shorter encryption asymmetric keys, which is so important in the case of sensor networks. The second layer proposes a watermarking-based authentication scheme. The distinct advantage of this layer is to achieve end-to-end authentication where the sink can directly validate the received data from the sources. The experimental results show that our method significantly reduces computation and communication overhead compared to other works, and can be practically implemented in on-the-shelf sensor platforms.

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