E3SN
Efficient Security Scheme for Sensor Networks

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Abstract: Sensor networks are widely used in various areas and applications, and the need for effective security systems is increasingly essential. But most security systems are based on complex algorithms that require a high complexity and energy consumption, thus have undesirable consequences. To reduce them, a new security system called E3SN is defined. It is based on an invertible and flexible key dependent matrix to mix the contents of the packets. Our proposal can achieve simultaneously the information's confidentiality, packet's integrity and source's authentication, with a minimum of computational complexity, communication overhead and memory consumption. This matrix is secret and only the transmitter and receiver can produce it in counter mode. We evaluate our system by comparing E3SN to AES algorithm, considered reliable and robust in several standards of sensor networks such as ZigBee, WirelessHART and ISA100.11a. The results show that the proposed technique is much more efficient than AES, with the same quality of cryptography.

1 INTRODUCTION

Recently, the security of Wireless Sensor Networks (WSN) is becoming principal for researchers and industry. These kinds of communication are susceptible to several attacks. The existing attacks can be divided into two classes: active and passive. The passive attacks can seriously impair the confidentiality of data, while the active attacks can damage their authentication. Moreover, The nature of passive attacks makes them rather difficult to be detected compared to the active ones. The active attacks may insert, delete or modify packet contents while passive aim to know them. Encrypting packets among sensor nodes can solve the problems of passive attacks, but it requires a distributed scheme and a robust key exchange. The traditional scheme uses symmetric key cryptography for data encryption, while it provides efficient memory and computational complexity compared to Asymmetric Key Cryptography (AKC). AKC is used for the secret key communication among sensor nodes. Secured services such as data confidentiality, integrity and source authentication are essential for safe WSN transmission. The confidentiality can be achieved using symmetric key cipher like the Advanced Encryption Standard (AES) (Daemen et al., 1998). This algorithm is not only known for its robustness, but also for its complexity and time consuming in WSN. In addition, the family of SHA (200, 2002) (e.g. SHA-2, SHA-512) is used to ensure data integrity while HMAC (Krawczyk et al., 1997) for source authentication. Moreover, some security protocols have been presented to provide security solution like IPSec as in (Doraswamy and Harkins, 1999), and others (Perrig et al., 2002), (Karlof et al., 2004), (Luk et al., 2007), (Rogaway et al., 2001) especially for WSN.

However, the security of WSN suffers from various limitations such as higher memory consumption, computation overhead, and power consumption. Also, it may require a communication overhead. In general, major techniques of secure WSN have a trade-off between security and performance. They are attempting to design a secure Shannon network, but this causes a decrease in the throughput. The WSN limitations require cipher scheme with low computation complexity. This provokes a hard challenge with the available resource constraints. This paper presents a new efficient and robust security scheme that attains low complexity computation. Compared to previous works, a new technique based on the mixing of several packets in a secret dynamic manner is proposed. Therefore, it can solve the above challenge. The mixing process is realized by using a new method of key dependent, flexible and invertible matrix. The overall computation complexity is reduced to one mixing iteration in packet level. In addition, a new header is introduced for each packet with 8 bytes length. The ba-

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sic structure of our scheme is a combination between the HMAC algorithm and the proposed mixing layer.

The aim of this paper is to realize a security protocol that can ensure a safe transmission with a remarkable efficiency. The rest of this paper is organized as follows. Section 2 describes the proposed secure scheme, and presents a new construction technique of key dependent, flexible and invertible matrix. Performance and security of the proposed scheme are analyzed in section 3. Finally, section 4 presents our conclusion.

```
1: procedure KEY_UPDATE(MK, adin, i, j, c1, c2)
2:     if i ≥ w then
3:         c1 ← c1 + 1
4:         MK_c1 ← SHA_512(MK||c1||adin)
5:     else
6:         if j ≥ d then
7:             V_c1 ← SHA_256(MK_c1||adin||c1)
8:             c2 ← c2 + 1
9:             SK_c1,c2 ← SHA_256(V_c1||adin||c2)
10:        end if
11:    end if
12:    return SK_c1,c2, c1, c2
13: end procedure
```

Figure 1: Key update 's algorithm.

2 THE PROPOSED SECURE SCHEME

Most security mechanisms that exist today require intensive computation and memory. They apply the security service on the block level of packets which requires a high computational complexity. This proves clearly that this method is not efficient especially in the case of constrained resources as WSN. Our idea is based on the mixing characteristic of Network Coding (NC). This section features a new efficient and secure scheme for WSN. Usually, the term efficiency means having the fastest time while keeping secure conditions of the WSN. This work can overcome the above-described disadvantages of previously presented works and define a new technique to ensure the security. In fact, the ease of implementation is attained when operating with constrained devices. The secure scheme primarily consists of three stages: source encryption, intermediate forwarding, and destination decryption. The proposed Authentication Cipher Scheme (ACS) and the proposed Authentication-Decipher Scheme (ADS) is applied at the source and destination side respectively. No modifications or supplementary operations are necessary at the intermediate nodes, since our solution is transparent.First, a general description of the proposed scheme is described,then the proposed ACS and ADS are described in details.

2.1 The proposed Secure Scheme at Emitter Side

In practical WSN scenarios, the source may need to transmit a large volume of data M. In this case, the source should first divide M into different generations $M_1, M_2, ..., M_n$. Then divide each generation into different packets $M_i = \{m_1, m_2, ..., m_g\}$. We propose that the authentication and encryption using different keys to strengthen the level of security. The different steps of the proposed scheme at the emitter side are described below in details:

2.1.1 Dynamic Key Generation

This section describes two processes: the first one defines the process of updating the master key and how produces the section key. Then the process of generating the dynamic key is presented. This process is introduced to overcome the problem of fixed key. The Master Key (MK) should be updated after several transmissions to strengthen the level of security. A new scheme for generating the Section Key (SK) using the master key (Mk_{c1}) is defined. The cycle length of each master key is w generations. Let $Sk_{c1,c2}$ denote the section key used in the $c2$ interval of Mk_{c1}. The cycle length of each section key is d generations, which were obtained as described in Figure 1 as a pseudo code. The variables i and j are integer values representing the number of requests for the master key and the section key from an instantiation of the section key and the master key respectively. Each generation is encrypted and authenticated using a key produced different key obtained from the dynamic key (Kd). The dynamic key is derived from the section key, Nonce, and the source/ destination nodes (Physical and/or IP address) as additional information. In our simulation, the value of the parameters d and w are set to 2^{10} and 2^{16} respectively. The elements of Nonce can be considered as a unique element to guarantee that the obtained key is new for each generation.

2.1.2 Construction of the Secret Matrix G

As described above, the process of encryption is implemented using the secret matrix G, which was obtained from the proposed flexible invertible key dependent matrix. This method is divided into two steps: The first one is the generation of the binary key-stream that used to construct the sub matrix, which was used to form the Primary Matrix(PM).

MICKEY_128 is used as a stream cipher. It is defined to be efficient in hardware implementation as in (Robshaw and Billet, 2008). This matrix has a determinant equal to 1, which means it is invertible (non singular matrix). Then a shuffle algorithm is applied to reorder the lines, then the columns of the PM. The secret matrix G is the result of the shuffling algorithm.

Note. *The determinant of the PM of size (h,h) is equal to 1. Therefore, the determinant of the shuffled matrix stays equal to 1, this means that the process of shuffling reserves the invertibility.*

KE and KA are calculated by flipping the even and odd bits of Kd respectively. MICKEY_128 is iterated with KE as a seed for it iterations to produce the keystream S, where $it = 2 \times m \times l$. Then S is divided in two equal parts to form the sub-matrix parameter Mu and Mv.

This method based on four different invertible matrices as the determinant is $\pm$ 1. The proposed technique is simple, and flexible in an efficient manner and effortless to implement in hardware. In the following, our method to build dynamic secret matrix is described.

Note. *The determinant of the product of two square matrices A and B of size (h,h), is equal to the product of the determinant of two matrices. Thus, if a and b are respectively, the determinant of the matrix A and that of the matrix B.Therefore, the determinant of the matrix, obtained from the multiplication of $A \times B$, is $a \times b$.*

Thus, to ensure a good layer of diffusion among the packets of a generation, the multiplication of two different matrices is performed. Which were used the sub matrices Mu and Mv respectively to form these matrices. The final form of the secret matrix G depends on the Parity Bit (PB) of the dynamic key:
$If\ PB = 0, G = M_0 \times M_2,\ Else\ G = M_1 \times M_3$
The four matrices can be used $(M_0, M_1, M_2, and M_3)$ to construct the invertible secret matrix G are given as below:

$$M_0 = \begin{bmatrix} I_m & Mu \\ Mv & I_l + MuMv \end{bmatrix},\ M_1 = \begin{bmatrix} Mu & I_m \\ I_l + MuMv & Mv \end{bmatrix}$$
$$M_2 = \begin{bmatrix} Mv & Il + MuMv \\ I_m & MU \end{bmatrix},\ M_3 = \begin{bmatrix} Il + MuMv & Mv \\ MU & I_m \end{bmatrix}$$

The determinant of the various matrices $M_w, w = 0,1,2,3$ is equal to ± 1, then these matrices are invertible. I_m and I_l are two identity matrices of size m and l respectively. M_u and M_v are two non-zero matrices of size $m \times l$ and $l \times m$ respectively, with $m = \lceil h/2 \rceil$ and $l = h - m$. The elements of M_u and M_v can be freely chosen from any Galois field such that M_w is full rank. In our simulation, the elements of this sub-matrix is binary $\{0,1\}$ to avoid the overhead for higher h. M_u and M_v are used for the various structures. The use of different M_u and M_v for the various structures increase the key space of secret matrix G but require double iteration of MICKEY_128. The invertible of each matrix can be proven as follows.

Having a matrix M constructed from four sub-matrix (A,B,C,D)

$$M = \begin{bmatrix} A & B \\ C & D \end{bmatrix}$$

its determinant is given by:

$$det(M) = det(A) \times det(D - CA^{-1}B) \qquad (1)$$

For example , if $M = M_0$, the determinant of M_0 will be:

$$\begin{aligned} det(M_0) &= det(I_m) \times det(I_l + M_{v0}M_{u0} - M_{v0}I_l^{-1}M_{u0}) \\ &= det(I_m) \times det(I_l + M_{v0}M_{u0} - M_{v0}M_{u0}) \\ &= det(I_m) \times det(I_l) = 1 \qquad (2) \end{aligned}$$

This means that the necessary condition to possess an inverse and get the original data at the receivers is achieved. In Figure 2, an example of the different steps applied to construct the secret matrix G is shown for $h = 4$, $PB = 0$ and

$$Mu = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix},\ Mv = \begin{bmatrix} 0 & 1 \\ 1 & 1 \end{bmatrix}$$

M_u or M_v is formed by the binary key stream with length $h^2/2$. In Figure 3, the primary matrix for $h = 64$ is shown. Therefore, the high value of PM is concentrated in the above right sub-zone. From the viewpoints of security, it can remain limited to our proposal. The process of shuffle is applied to diffuse these values in the whole space. The G matrix is obtained by permuting the rows of PM according to the permutation vector Ind_L, then the columns is interchanged according to the given permutation vector Ind_C.

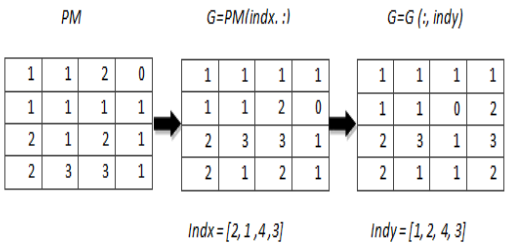


Figure 2: An example of construction secret matrix G for $h = 4$.

2.1.3 Encryption of Generation

The buffering model divides the stream of packets into generations of size g, such the packets of the

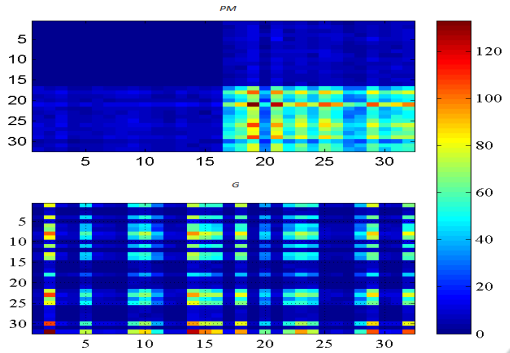


Figure 3: An example of constructed *PM* and its correspondent *G* after the process of shuffle for $h = 32$.

same generation are tagged with a common generation number *NG*. When performing encryption on a series of source packets $\{m_1, m_2, ..., m_g\}$, a pseudo-random linear combinations of the source packets are created and sent instead of the original source packets. Our scenario of encryption is by performing a modular multiplication matrix using *G* to get the cipher generation *X*. The process of encryption/decryption can treat in parallel to reduce the complexity, since each encrypted packet is independent of others. The encryption/decryption packets are the result of *h* random linear combination packets in a dynamic manner. The coefficients $\{c_1, c_2, ..., c_g\}$ is described as the encryption vectors. Each encryption vector is represented as a sequence of independent random numbers from a field. The original source packets can be retrieved from the encrypted packets when *h* different linear independent packets are present at the receiver. The relationship among encryption packets, encryption vectors and source packets can be described in the matrix equation as follows:

$$X = G \times (M) = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_h \end{bmatrix} = \begin{bmatrix} G_{1,1}G_{1,2}\cdots G_{1,h} \\ G_{2,1}G_{2,2}\cdots G_{2,h} \\ \vdots \quad \vdots \quad \ddots \quad \vdots \\ G_{h,1}G_{h,2}\cdots G_{h,h} \end{bmatrix} \cdot \begin{bmatrix} m_1 \\ m_2 \\ \vdots \\ m_h \end{bmatrix} \quad (3)$$

Where m_i is a source packet, $c_{i,j}$ is an encryption coefficient varies between 0 and $q-1$ for the line i and column j and $i, j = 1, 2, ..., h$. Moreover, q is the size of finite field over which WSN is performed. x_i is the resulting encryption packets, g is the number of source packets, h is the number of generating packets, also known as *GS*, and $h \geq g$ to allow receivers to decrypt when a failure channel decoding occur. That is, the encrypted packets are combinations of the form $c_1 \cdot m_1 + c_2 \cdot m_2 + ... + c_h \cdot m_h$. Therefore, $h = g + \lceil g \times pe \rceil$. While $m_i, i = h - g + 1$ is a null packet (all elements are zero). Another possibility could be used for the proposed secure scheme is MDS (Gupta and Ray, 2013). We don't recommend it, while it requires a high computational complexity compared to our proposal.

2.1.4 Authentication of the *h* Encrypted Packets

The different steps to obtain the MAC value are designed to ensure the effectiveness. The overall cost for authenticating the stream data is close to that of hashing these data, especially as data gets large. To reduce the complexity, the contents of the *h* encrypted packets are xored together to form a unique payload called $(temp)$. *HMAC* is used with SHA-512 to avoid hash collision. The input of HMAC is composed of the vector *temp*, the extension header $NG||GS$ and the authentication keyKa. Then, the output of *HMAC* is transformed into matrix with 4 rows and 128 columns. The 4 rows are xored together to obtain the MAC value *MAC* with a size of 128 bits.

2.1.5 Asymmetric Encryption of the MAC value *E_MAC*

The *MAC* is encrypted using the RSA public-key crypto-system, which was performed with the private key *Kr*. Then, it is transmitted to the receiver in an encrypted form. The use of private key provides the non repudiation of the source, which is a principal service. The algorithm could be more secure, if the (public, private) keys (Ku, Kr) are renewed after every periodic interval. This interval depends on the area of application. Two kinds of keys are used for the encryption and the decryption processes.This setting has additional advantage, since the cryptanalyst requires applying two different attacks. It is a hard task, while symmetric and asymmetric cryptosystems have to be tackled separately (hybrid encryption), which will enhance the security level.

2.1.6 Transmission(X, E_MAC)

The transmitted informations to the receiver are the cipher *E_MAC* and the encrypted packets *X*. If the opportunity of transmission at an outgoing edge is possible, the sending node first sends the encrypted generation, then the cipher *E_MAC* must be transmitted for verification of data integrity and source authentication.The contents of packets are mixed via dynamic secret matrix *G*, and the intermediate nodes have no knowledge about *G*, it is rather difficult for them to reconstruct the source packets. In addition, the proposed scheme introduces a small overhead of 8 bytes per packet ($NG||GS||NP$).

2.2 The Proposed Secure Scheme at the Receiver Side

The different steps of the proposed scheme at the receiver side are described below in details:

2.2.1 Asymmetric Decryption of the MAC Value

At the receiver end, the recipient uses the public emitter RSA key *Ku* to decrypt *E_MAC*.

2.2.2 Sort packets Based on *NG*

The receiver buffering model sorts the packet stream into generations according to their *NG*, such that the packets of the same generation are put in a single buffer.

2.2.3 Dynamic Key Generation *R_Kd*

The dynamic keys of authentication (*R_Ka*) and decryption (*R_Ke*)are generated using the same approach, which was applied at the emitter side.

2.2.4 Verification of Source Authentication (C_MAC,R_MAC)

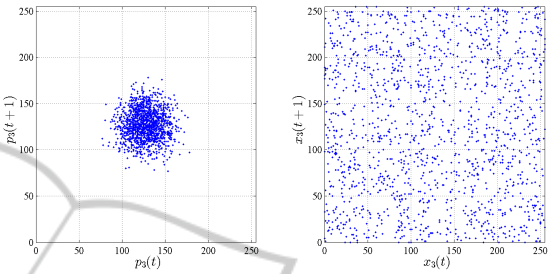
The proposed solution is efficient since it prevents the attacker from requesting the decrypts of any cipher-generation unless he verifies correctly using the proposed authentication scheme, which implies that he already knows the cipher key. Once *h* different encrypted messages are collected from an arbitrary generation, a new MAC is calculated at the receiver side called C_MAC using the same approach, which was applied at the emitter side. If *C_MAC* is equal to *R_MAC*, the source is verified. Otherwise, the authentication of the source is not valid.

2.2.5 Decryption of the Encrypted Generation

If the source is verified, then the destination can start the decryption process. Once *h* linearly independent messages are collected, the destination produces the secret matrix *G* using its correspondent dynamic key. The decryption of the encrypted generation X is obtained by using the inverse secret matrix G^{-1} as follows: $M = G^{-1} \times X$.

3 PROPERTIES ANALYSIS

To qualify the future usages of our key dependent invertible matrix, it is important to understand their characteristics. Two important properties should be achieved to ensure a high level of security, which are the random recurrence and the mixing nature. In our simulation, the proposed security scheme is considered as a black box and randomly choosing a set of initial packets with 1500 byte length, which are normally distributed with a mean equal to 128 and a standard deviation equal to 16.

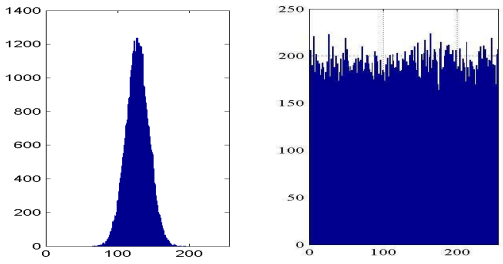


(a) (b)

Figure 4: Recurrence plot of the 1 th original packet (a) and its correspondent encrypted ones (b).

3.1 Recurrence

The recurrence plot serves to measure the evaluation of randomness and estimates the correlations among the data of a sequence as in (Rodgers and Nicewander, 1988). Considering a packet sequence $x_i = x_{i,1}, x_{i,2}, ..., x_{i,m}$, a vector with delay $t \geq 1$ can be constructed by: $x_i(t) = x_i, x_{i+t}, x_{i,2*t}, ..., x_{i,m*t}$. In Figure 4 a-b, the variation between $x_i(t)$ and $x_i(t+1)$ from the original and the encrypted packets respectively are shown. It is clearly shown that no clear pattern is obtained after encryption.



(a) (b)

Figure 5: Recurrence plot of the 1 th original packet (a) and its correspondent encrypted ones (b).

3.2 Correlation Analysis

As a general requirement for all the encryption schemes, the encrypted data should be greatly different from its original form. The encrypted packets, should have redundancy and correlation as low as possible. First, the correlation coefficient between the original and encrypted packets is measured, then

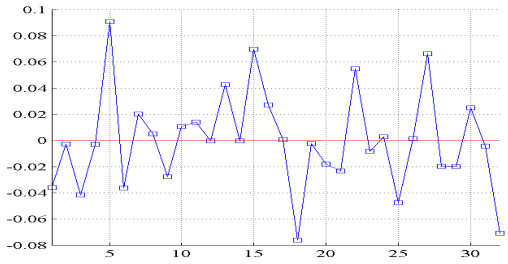


Figure 6: The coefficient correlation between the original and encrypted contents packets for $h = 32$.

among the different encrypted packets. The correlation coefficient is computed according to the following formulas:

$$\rho_{x,y} = \frac{cov(x,y)}{\sqrt{D(x) \times D(y)}} \quad (4)$$

$$where\ cov(x,y) = E[\{x - E(x)\}\{y - E(y)\}];$$

$$E(x) = \frac{1}{n} \times \sum_{k=1}^{n} x_i$$

$$and\ D(x) = \frac{1}{n} \times \sum_{k=1}^{n} \{x_i - E[x]\}$$

In Figure 6, the average coefficient correlation between the original and encrypted packets for 10000 different secret matrix with $h = 32$ is shown. This result indicates that no detectable correlation exists between the original and its corresponding cipher packets.

3.3 Mixing Nature

The mixing nature serving as a measure of the uniformity and it can quantify by a statistical approach. If the frequency counts of the encrypted generation are close to a uniform distribution, then it is possible to categorize that the concerned cipher under test have a good level of mixing. In Figure 5-a and b, the distribution of the original generation and its corresponding cipher generation respectively is shown. This result shows clearly that the contents of the encrypted packet are spread overall the space and have a uniform distribution. To validate this uniformity, the chi-square test (Bates and VA., 1966) is applied and works as follow:

$$\chi^2_{test} = \sum_{i=1}^{l} \frac{o_i - e_i}{e_i} \quad (5)$$

The distribution of the tested histogram is uniform for h$\geq$12, that means an acceptable mixing and a stronger mixing property can be obtained when the generation size is higher.

3.4 Flexibility and Execution Time

Our proposed scheme ensures the flexibility, while it is able to extend with the increase/decrease of the number of packets in generation h. Additionally, we ensure a low computation Complexity and by consequence fast execution time. The operation speed is significant especially for constrained resources application such WSN. The average calculation times (on 10000 times) to encrypt a generation M against h in s is presented in Figure 7. These calculations are given in the following environment software and material: Matlab on 2012 and micro-computer Intel Core 2 Duet 2.1 GHZ CPU with 2 GB RAM Intel, under Windows Live. Clearly, the variation of average time is linear. The average times necessary against h is estimated (approximately) using the linear interpolation method. It shows that the proposed method is indeed the fastest and sufficiently fast for WSN applications. We compare the mean encryption time (in seconds), versus h, of the proposed cipher with AES.The proposed secure scheme is at least $5 \times h$ times faster than the AES algorithm.

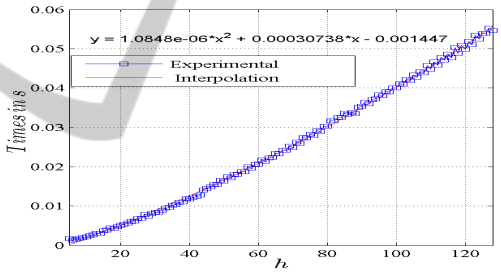


Figure 7: Variations of the average time for encryption generation versus h.

4 CONCLUSIONS

The WSN security becomes more and more important, since WSN are used for many kinds of applications such as environmental monitoring and military applications. The existing schemes use cryptographic algorithms that fail to achieve low execution time for high security level like AES, which is considered as robust algorithm but requires a high complexity and energy consumption. In this paper, a new security scheme has been described to provide a safe WSN called E3SN, which requires less complexity and energy consumption. E3SN is based on a new flexible and invertible key dependent diffusion layer. It provides at the same time the data confidentiality, integrity and the source authentication. Therefore, E3SN has been analyzed to quantify its degree of

randomness, uniformity, sensibility of key and cryptographic strengthen (dynamic key in counter mode) against different attacks (statistical, linear, differential). In addition, the results in terms of processing time and complexity indicate a significant reduction compared to AES CTR, which leads to decrease energy consumption by consequence. In the future, our work will be extended to resist against pollution attacks and more WSN security services will be introduced.

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