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Re-keying Mechanisms for Symmetric Keys
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Abstract

If encryption is performed under a single key, there is a certain maximum threshold amount of data that can be safely encrypted. This amount is called key lifetime. This specification contains a description of a variety of methods to increase the lifetime of symmetric keys. It provides external and internal re-keying mechanisms based on hash functions and on block ciphers that can be used with such modes of operations as CTR, GCM, CCM, CBC, CFB, OFB and OMAC.

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1. Introduction

If encryption is performed under a single key, there is a certain maximum threshold amount of data that can be safely encrypted. This amount is called key lifetime and can be calculated from the following considerations:

1. Methods based on the combinatorial properties of used encryption mode

[Sweet32] is an example of attack that is based on such methods. These methods do not depend on the used block cipher permutation $E_{\{K\}}$. Common encryption modes restrictions resulting from such methods are of order $2^{\{n/2\}}$.

2. Methods based on side-channel analysis issues

In most cases these methods do not depend on the used encryption modes and weakly depend on the used block cipher features. Restrictions resulting from these methods are usually the strongest ones.

3. Methods based on the properties of the used block cipher permutation $E_{\{K\}}$

The most common methods of this type are linear and differential cryptanalysis [LDC]. In most cases these methods do not depend on the used encryption modes. In case of secure block ciphers, restrictions resulting from such methods are roughly the same as the natural limitation 2^n and so can be excluded from consideration as they become trivial.

Therefore, as soon as the total size of a plaintext processed with a single key reaches the key lifetime limitation, that key must be replaced. A specific value of the key lifetime is determined in accordance with safety margin for protocol security and methods outlined above.

Suppose L is a key lifetime limitation in some protocol P . For simplicity, assume that all messages have the same length m . Hence the number of messages q that can be processed with a single key K should be such that $m \cdot q \leq L$. This can be depicted graphically as a rectangle with sides m and q which is enclosed by area L (see Figure 1).

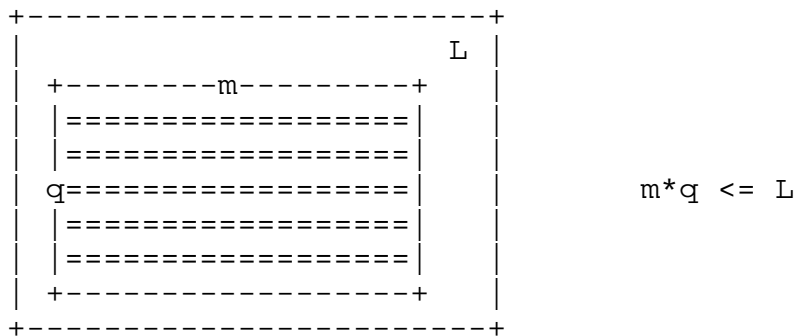


Figure 1: Graphic display of the key lifetime limitation

Thus, with increasing one of the parameters m or q , the second parameter should be reduced in proportion to the first.

In practice, such amount of data that corresponds to limitation L may not be enough. The most simple and obvious way in this situation is a regular renegotiation of a session key. However, this reduces the total performance since it usually entails termination of application data transmission, additional service messages, the use of random number generator and many other additional calculations, including resource-intensive asymmetric cryptography.

This specification presents two approaches that extend the key lifetime for a single symmetric key while avoiding renegotiation: external and internal re-keying. External re-keying is performed by a protocol, and it is independent of block cipher, key size, and mode. External re-keying can use parallel or serial construction. In the first case subkeys K^1, K^2, \dots are generated directly from the key K independently of each other, while in the second case every next subkey depends on the state that is updated after each new subkey generation. Internal re-keying is built into the mode, and it depends heavily on the properties of the block cipher and key size.

The re-keying approaches extend the key lifetime for a single agreed key by providing the possibility to strictly limit the key leakage (to meet side channel limitations) and by improving combinatorial properties of a used block cipher encryption mode.

As for practical issues, re-keying can be particularly useful in such fields as protocols functioning in hostile environments (additional side channel resistance against DPA or EMI style attacks) or lightweight cryptography (usage of ciphers with small block size leads to very strong combinatorial limitations). Moreover, many mechanisms that use external and internal re-keying provide

particular types of PFS security. Also re-keying can provide additional security against possible future attacks on the used ciphers (by limiting the number of plaintext-ciphertext pairs collected by an adversary), however, it must not be used as a method to prolong life of ciphers that are already known to be vulnerable.

2. Conventions Used in This Document

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [RFC2119].

3. Basic Terms and Definitions

This document uses the following terms and definitions for the sets and operations on the elements of these sets:

- (xor) exclusive-or of two binary vectors of the same length.
- V^* the set of all strings of a finite length (hereinafter referred to as strings), including the empty string;
- V_s the set of all binary strings of length s , where s is a non-negative integer; substrings and string components are enumerated from right to left starting from one;
- $|X|$ the bit length of the bit string X ;
- $A|B$ concatenation of strings A and B both belonging to V^* , i.e., a string in $V_{|A|+|B|}$, where the left substring in $V_{|A|}$ is equal to A , and the right substring in $V_{|B|}$ is equal to B ;
- $Z_{\{2^n\}}$ ring of residues modulo 2^n ;
- $\text{Int}_s: V_s \rightarrow Z_{\{2^s\}}$ the transformation that maps a string $a = (a_s, \dots, a_1)$, a in V_s , into the integer $\text{Int}_s(a) = 2^{\{s-1\}}*a_s + \dots + 2*a_2 + a_1$;
- $\text{Vec}_s: Z_{\{2^s\}} \rightarrow V_s$ the transformation inverse to the mapping Int_s ;
- $\text{MSB}_i: V_s \rightarrow V_i$ the transformation that maps the string $a = (a_s, \dots, a_1)$ in V_s , into the string $\text{MSB}_i(a) = (a_s, \dots, a_{\{s-i+1\}})$ in V_i ;
- $\text{LSB}_i: V_s \rightarrow V_i$ the transformation that maps the string $a = (a_s, \dots, a_1)$ in V_s , into the string $\text{LSB}_i(a) = (a_i, \dots, a_1)$ in V_i ;

$\text{Inc}_c: V_s \rightarrow V_s$ the transformation that maps the string $a = (a_s, \dots, a_1)$ in V_s , into the string $\text{Inc}_c(a) = \text{MSB}_{\{|a| - c\}}(a) \mid \text{Vec}_c(\text{Int}_c(\text{LSB}_c(a)) + 1(\text{mod } 2^c))$ in V_s ;

a^s denotes the string in V_s that consists of s 'a' bits;

$E_{\{K\}}: V_n \rightarrow V_n$ the block cipher permutation under the key K in V_k ;

$\text{ceil}(x)$ the least integer that is not less than x ;

k the key K size (in bits), k is multiple of 8;

n the block size of the block cipher (in bits), n is multiple of 8;

b the total number of data blocks in the plaintext ($b = \text{ceil}(m/n)$);

N the section size (the number of bits in a data section);

l the number of data sections in the plaintext;

$\text{phi}_i: V_s \rightarrow \{0,1\}$ the transformation that maps a string $a = (a_s, \dots, a_1)$ into the value $\text{phi}_i(a) = a_i$ for all i in $\{1, \dots, s\}$.

A plaintext message P and a ciphertext C are divided into $b = \text{ceil}(|P|/n)$ blocks denoted as $P = P_1 \mid P_2 \mid \dots \mid P_b$ and $C = C_1 \mid C_2 \mid \dots \mid C_b$, where P_i and C_i are in V_n , for $i = 1, 2, \dots, b-1$, and P_b, C_b are in V_r , where $r \leq n$ if not otherwise stated.

4. Principles of Choice of Constructions and Security Parameters

External re-keying provides an approach, depending to which a key is transformed after encrypting a limited number of messages. A specific external re-keying method is chosen at the protocol level regardless of a used block cipher or encryption mode. External re-keying approach is recommended for usage in protocols that process quite small messages or in protocols that have a way to break a large message into manageable parts. As a result of external re-keying, the number of messages that can be processed with a single symmetric key is substantially increased without loss in message length.

The use of external re-keying has the following advantages:

1. the lifetime of a negotiated key drastically increases by increasing the number of messages processed with one key;

2. it almost does not affect performance in case when a number of messages processed with one key is sufficiently large;
3. provides forward and backward security of session keys for all messages.

However, the use of external re-keying has the following disadvantages:

1. in case of restrictive key lifetime limitations the message sizes can become inconvenient due to impossibility of processing sufficiently large messages, so it could be necessary to perform additional fragmentation at the protocol level;
2. it is not transparent: procedures (like IVs generation) must be handled separately.

Internal re-keying provides an approach according to which a key is transformed during each separate message processing. Such approaches are integrated into the base modes of operations so every internal re-keying mechanism is defined for a particular mode and block cipher (e.g. depending of block and key sizes). Internal re-keying approach is recommended to be used in protocols that process large messages. As a result of internal re-keying, the size of each single message can be substantially increased without loss in number of messages that can be processed with a single symmetric key.

The use of internal re-keying has the following advantages:

1. the lifetime of a negotiated key drastically increases by increasing the size of messages processed with one key;
2. minimal impact on performance;
3. internal re-keying mechanisms without master key does not affect short messages transformation at all;
4. transparent (works like any encryption mode): does not require changes of IV's and restarting MACing.

However, the use of internal re-keying has the following disadvantages:

1. a specific method must not be chosen independently of a mode of operation;
2. internal re-keying mechanisms with master key provide backward security of session keys only for one separate message;

3. internal re-keying mechanisms without master key do not provide backward security of session keys.

Any block cipher modes of operations with internal re-keying can be jointly used with any external re-keying mechanisms. Such joint usage increases both the number of messages processed with one key and their maximum possible size.

The use of the same cryptographic primitives both for data processing and re-keying transformation decreases the code size but can lead to some possible vulnerabilities because the adversary always has access to the data processing interface. This vulnerability can be eliminated by using different primitives for data processing and re-keying, however, in this case the security of the whole scheme cannot be reduced to standard notions like PRF or PRP so security estimations become more difficult and unclear.

5. External Re-keying Mechanisms

This section presents an approach to increase the key lifetime by using a transformation of a previously negotiated key after processing a limited number of integral messages. It provides an external parallel and serial re-keying mechanisms (see [AbBell]). These mechanisms use an initial (negotiated) key as a master key, which is never used directly for the data processing but is used for key generation. Such mechanisms operate outside of the base modes of operations and do not change them at all, therefore they are called "external re-keying" mechanisms in this document.

External re-keying mechanisms are recommended for usage in protocols that process quite small messages since the maximum gain in increasing the key lifetime is achieved by increasing the number of messages.

External re-keying increases the key lifetime through the following approach. Suppose there is a protocol P with some mode of operation (base encryption or authentication mode). Let L_1 be a key lifetime limitation induced by side-channel analysis methods (side-channel limitation), let L_2 be a key lifetime limitation induced by methods based on the combinatorial properties of used mode of operation (combinatorial limitation) and let q_1, q_2 be the total numbers of messages of length m , that can be safely processed with a single key K according to these limitations.

Let $L = \min(L_1, L_2)$, $q = \min(q_1, q_2)$, $q \cdot m \leq L$. As L_1 limitation is usually much stronger than L_2 limitation ($L_1 < L_2$), the final key lifetime restriction is equal to the most restrictive limitation L_1 .

Thus, as displayed in Figure 2, without re-keying only q_1 ($q_1 * m \leq L_1$) messages can be safely processed.

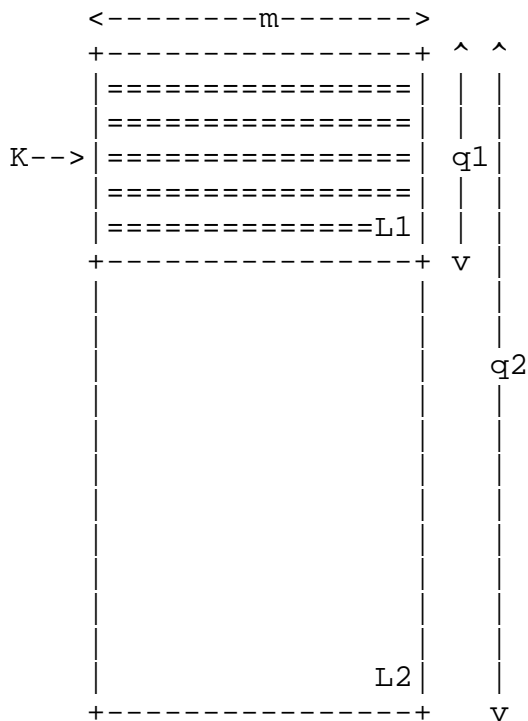


Figure 2: Basic principles of message processing without external re-keying

Suppose that the safety margin for the protocol P is fixed and the external re-keying approach is applied. As the key is transformed with an external re-keying mechanism, the leakage of a previous key does not have any impact on the following one, so the side channel limitation L_1 goes off. Thus, the resulting key lifetime limitation of the negotiated key K can be calculated on the basis of a new combinatorial limitation L_2' . It is proven (see [AbBell]) that the security of the mode of operation that uses external re-keying leads to an increase when compared to base mode without re-keying (thus, $L_2 < L_2'$). Hence, as displayed in Figure 3, the resulting key lifetime limitation in case of using external re-keying can be increased up to L_2' .

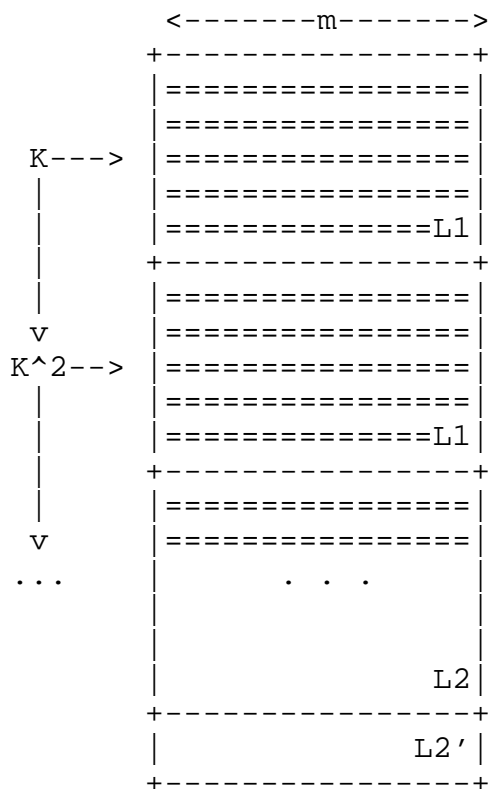


Figure 3: Basic principles of message processing with external re-keying

Note: the key transformation process is depicted in a simplified form. A specific approach (parallel and serial) is described below.

Consider an example. Let the message size in protocol P be equal to 1 KB. Suppose $L1 = 128 \text{ MB}$ and $L2 = 1 \text{ TB}$. Thus, if an external re-keying mechanism is not used, the key K must be renegotiated after processing $128 \text{ MB} / 1 \text{ KB} = 131072$ messages.

If an external re-keying mechanism is used, the key lifetime limitation $L1$ goes off. Hence the resulting key lifetime limitation in case of using external re-keying can be set to 1 TB (and even more). Thus if an external re-keying mechanism is used, then $1 \text{ TB} / 1 \text{ KB} = 2^{30}$ messages can be processed before the master key K is renegotiated. This is 8192 times greater than the number of messages that can be processed, when external re-keying mechanism is not used.

5.1. Methods of Key Lifetime Control

Suppose L is an amount of data that can be safely processed with one key (without re-keying). For i in $\{1, 2, \dots, t\}$ the key K^i (see Figure 1 and Figure 2) should be transformed after processing q_i

integral messages, where q_i can be calculated in accordance with one of the following two approaches:

- o Explicit approach:

$$|M^{i,1}| + \dots + |M^{i,q_i}| \leq L, \quad |M^{i,1}| + \dots + |M^{i,q_i + 1}| > L.$$

This approach allows to use the key K^i in almost optimal way but it cannot be applied in case when messages may be lost or reordered (e.g. DTLS packets).

- o Implicit approach:

$$q_i = L / m_{\max}, \quad i = 1, \dots, t.$$

The amount of data processed with one key K^i is calculated under the assumption that every message has the maximum length m_{\max} . Hence this amount can be considerably less than the key lifetime limitation L . On the other hand this approach can be applied in case when messages may be lost or reordered (e.g. DTLS packets).

5.2. Parallel Constructions

The main idea behind external re-keying with parallel construction is presented in Figure 4:

Maximum message size = m_{max} .

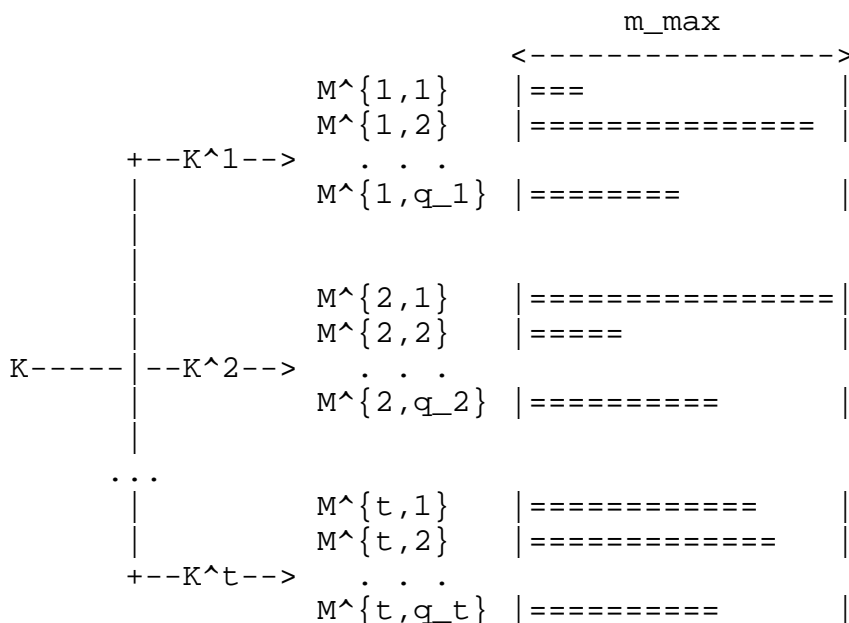


Figure 4: External parallel re-keying mechanisms

The key K^i , $i = 1, \dots, t-1$, is updated after processing a certain amount of data (see Section 5.1).

5.2.1. Parallel Construction Based on a KDF on a Block Cipher

ExtParallelC re-keying mechanism is based on key derivation function on a block cipher and is used to generate t keys for t sections as follows:

$$K^1 \mid K^2 \mid \dots \mid K^t = \text{ExtParallelC}(K, t \cdot k) = \text{MSB}_{\{t \cdot k\}}(E_{\{K\}}(0) \mid E_{\{K\}}(1) \mid \dots \mid E_{\{K\}}(R-1)),$$

where $R = \text{ceil}(t \cdot k/n)$.

5.2.2. Parallel Construction Based on HKDF

ExtParallelH re-keying mechanism is based on HMAC key derivation function HKDF-Expand, described in [RFC5869], and is used to generate t keys for t sections as follows:

$$K^1 \mid K^2 \mid \dots \mid K^t = \text{ExtParallelH}(K, t \cdot k) = \text{HKDF-Expand}(K, \text{label}, t \cdot k),$$

where label is a string (can be a zero-length string) that is defined by a specific protocol.

5.3. Serial Constructions

The main idea behind external re-keying with serial construction is presented in Figure 5:

Maximum message size = m_max.

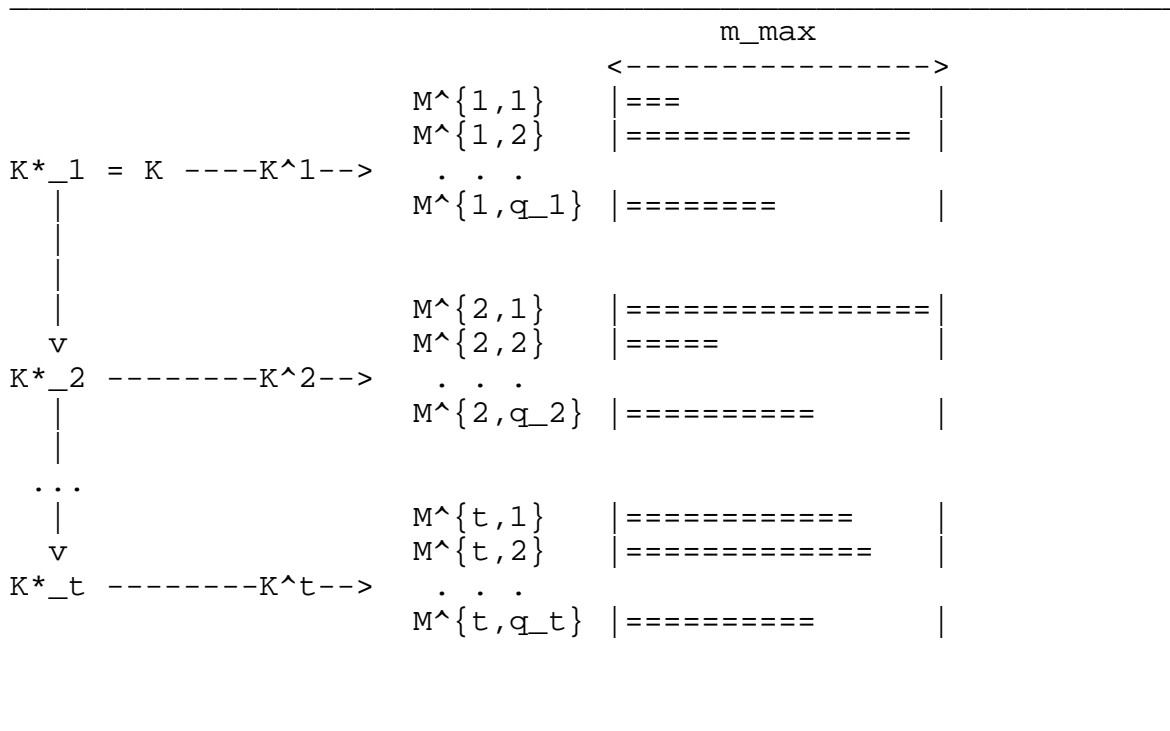


Figure 5: External serial re-keying mechanisms

The key K^i , $i = 1, \dots, t-1$, is updated after processing a certain amount of data (see Section 5.1).

5.3.1. Serial Construction Based on a KDF on a Block Cipher

The key K^i is calculated using ExtSerialC transformation as follows:

$$K^i = \text{ExtSerialC}(K, i) = \text{MSB}_k(E_{\{K^*_i\}}(0) \mid E_{\{K^*_i\}}(1) \mid \dots \mid E_{\{K^*_i\}}(J-1)),$$

where $J = \text{ceil}(k/n)$, $i = 1, \dots, t$, K^*_i is calculated as follows:

$$K^*_1 = K,$$

$$K^*_{\{j+1\}} = \text{MSB}_k(\text{E}_{\{K^*_j\}}(J) \mid \text{E}_{\{K^*_j\}}(J+1) \mid \dots \mid \text{E}_{\{K^*_j\}}(2J-1)),$$

where $j = 1, \dots, t-1$.

5.3.2. Serial Construction Based on HKDF

The key K^i is calculated using ExtSerialH transformation as follows:

$$K^i = \text{ExtSerialH}(K, i) = \text{HKDF-Expand}(K^*_i, \text{label1}, k),$$

where $i = 1, \dots, t$, HKDF-Expand is an HMAC-based key derivation function, described in [RFC5869], K^*_i is calculated as follows:

$$K^*_1 = K,$$

$$K^*_{\{j+1\}} = \text{HKDF-Expand}(K^*_j, \text{label2}, k), \text{ where } j = 1, \dots, t-1,$$

where label1 and label2 are different strings (can be a zero-length strings) that are defined by a specific protocol (see, for example, TLS 1.3 updating traffic keys algorithm [TLSDraft]).

6. Internal Re-keying Mechanisms

This section presents an approach to increase the key lifetime by using a transformation of a previously negotiated key during each separate message processing.

It provides internal re-keying mechanisms called ACPKM (Advanced cryptographic prolongation of key material) and ACPKM-Master that do not use and use a master key respectively. Such mechanisms are integrated into the base modes of operations and actually form new modes of operation, therefore they are called "internal re-keying" mechanisms in this document.

Internal re-keying mechanism is recommended to be used in protocols that process large single messages (e.g. CMS messages) since the maximum gain in increasing the key lifetime is achieved by increasing the length of a message, while it almost does not affect performance for increasing the number of messages.

Internal re-keying increases the key lifetime through the following approach. Suppose there is a protocol P with some base mode of operation. Let L1 and L2 be a side channel and combinatorial

limitations respectively and for some fixed amount of messages q let m_1, m_2 be the length of each separate message, that can be safely processed with a single key K according to these limitations.

Thus, by analogy with the Section 5 without re-keying the final key lifetime restriction, as displayed in Figure 6, is equal to L_1 and only q messages of the length m_1 can be safely processed.

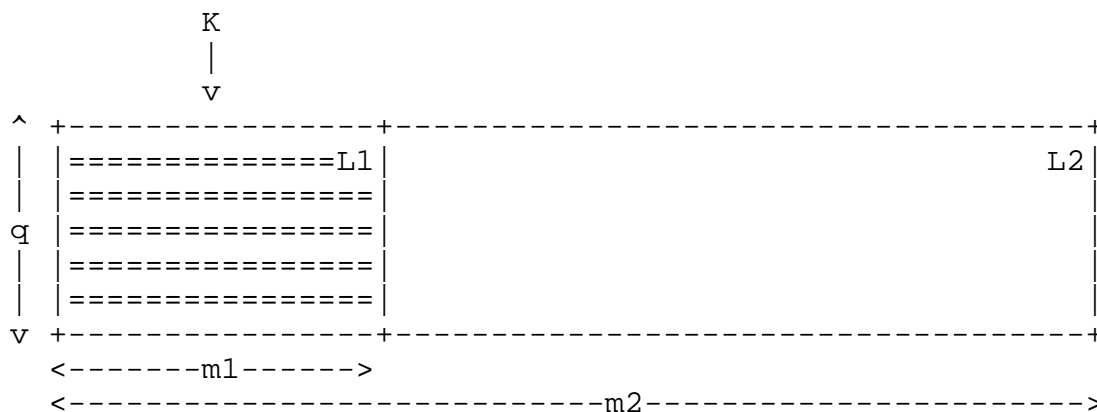


Figure 6: Basic principles of message processing without internal re-keying

Suppose that the safety margin for the protocol P is fixed and internal re-keying approach is applied to the base mode of operation. Suppose further that for every message the key is transformed after processing N bits of data, where N is a parameter. If $q \cdot N$ does not exceed L_1 then the side channel limitation L_1 goes off and the resulting key lifetime limitation of the negotiated key K can be calculated on the basis of a new combinatorial limitation L_2' . The security of the mode of operation that uses external re-keying must lead to an increase when compared to base mode of operation without re-keying (thus, $L_2 < L_2'$). Hence, as displayed in Figure 7, the resulting key lifetime limitation in case of using external re-keying can be increased up to L_2' .

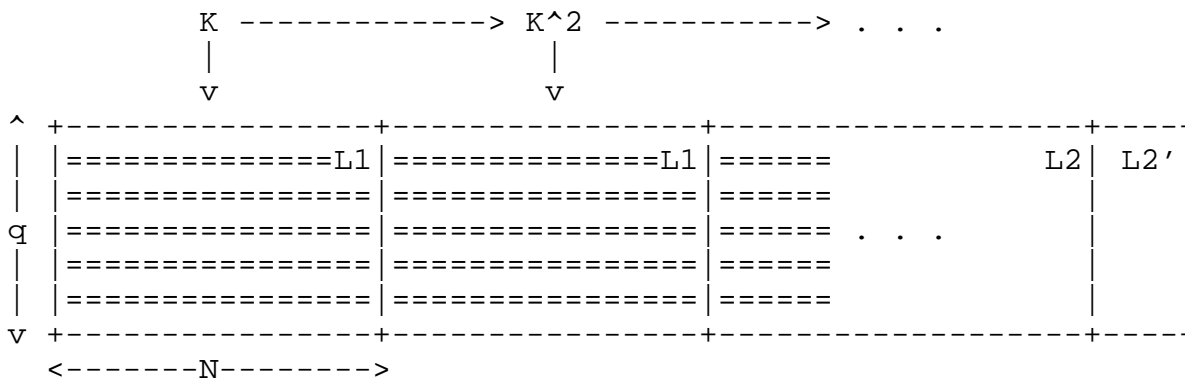


Figure 7: Basic principles of message processing with internal re-keying

Note: the key transformation process is depicted in a simplified form. A specific approach (ACPKM and ACPKM-Master re-keying mechanisms) is described below.

Since the performance of encryption can slightly decrease for rather small values of N , the parameter N should be selected for a particular protocol as maximum possible to provide necessary key lifetime for the adversary models that are considered.

Consider an example. Suppose $L1 = 128$ MB and $L2 = 10$ TB. Let the message size in the protocol be large/unlimited (may exhaust the whole key lifetime $L2'$). The most restrictive resulting key lifetime limitation is equal to 128 MB.

Thus, there is a need to put a limit on the maximum message size m_{max} . For example, if $m_{max} = 32$ MB, it may happen that the renegotiation of key K would be required after processing only four messages.

If an internal re-keying mechanism with section size $N = 1$ MB (see Figure 3 and Figure 4) is used, more than $L1 / N = 128$ MB / 1 MB = 128 messages can be processed before the renegotiation of key K (instead of 4 messages in case when an internal re-keying mechanism is not used). Note that only one section of each message is processed with one key K^i , and, consequently, the key lifetime limitation $L1$ goes off. Hence the resulting key lifetime limitation in case of using external re-keying can be set to at least 10 TB (in the case when the single large message is processed using the key K).

6.1. Methods of Key Lifetime Control

Suppose L is an amount of data that can be safely processed with one key (without re-keying), N is a section size (fixed parameter). Suppose $M^{\{i\}}_1$ is the first section of message $M^{\{i\}}$, $i = 1, \dots, q$ (see Figure 3 and Figure 4), then the parameter q can be calculated in accordance with one of the following two approaches:

- o Explicit approach:

$$|M^{\{1\}}_1| + \dots + |M^{\{q\}}_1| \leq L, \quad |M^{\{1\}}_1| + \dots + |M^{\{q+1\}}_1| > L$$

This approach allows to use the key K^i in an almost optimal way but it cannot be applied in case when messages may be lost or reordered (e.g. DTLS packets).

- o Implicit approach:

$$q = L / N.$$

The amount of data processed with one key K^i is calculated under the assumption that the length of every message is equal or more then section size N and so it can be considerably less than the key lifetime limitation L . On the other hand this approach can be applied in case when messages may be lost or reordered (e.g. DTLS packets).

6.2. Constructions that Do Not Require Master Key

This section describes the block cipher modes that use the ACPKM re-keying mechanism, which does not use master key: an initial key is used directly for the encryption of the data.

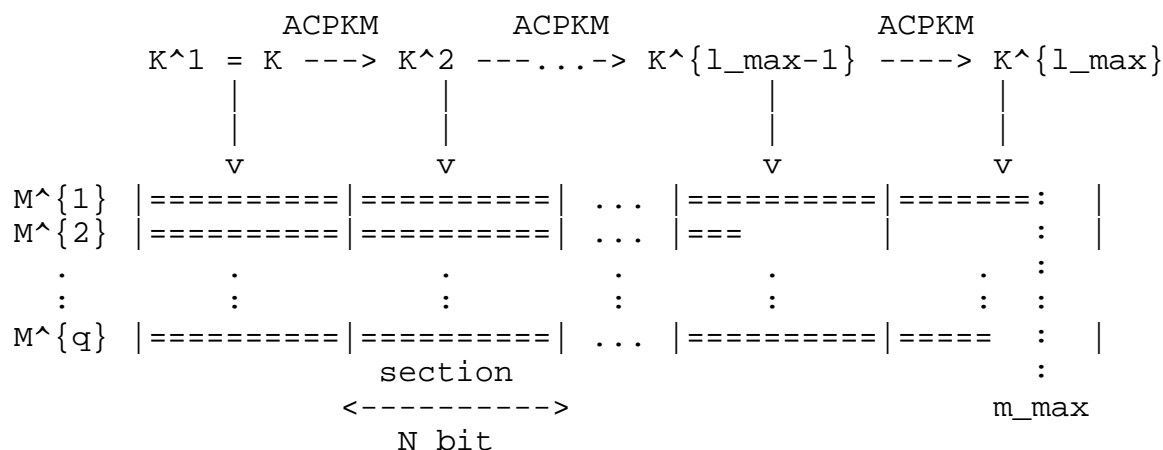
6.2.1. ACPKM Re-keying Mechanisms

This section defines periodical key transformation with no master key which is called ACPKM re-keying mechanism. This mechanism can be applied to one of the basic encryption modes (CTR and GCM block cipher modes) for getting an extension of this encryption mode that uses periodical key transformation with no master key. This extension can be considered as a new encryption mode.

An additional parameter that defines the functioning of base encryption modes with the ACPKM re-keying mechanism is the section size N . The value of N is measured in bits and is fixed within a specific protocol based on the requirements of the system capacity and key lifetime (some recommendations on choice of N will be provided in Section 8). The section size N MUST be divisible by the block size n .

The main idea behind internal re-keying with no master key is presented in Figure 8:

Section size = const = N,
 maximum message size = m_max.



$$l_{max} = \text{ceil}(m_{max}/N).$$

Figure 8: Internal re-keying with no master key

During the processing of the input message M with the length m in some encryption mode that uses ACPKM key transformation of the key K the message is divided into $l = \text{ceil}(m/N)$ sections (denoted as $M = M_1 | M_2 | \dots | M_l$, where M_i is in V_N for $i = 1, 2, \dots, l-1$ and M_l is in V_r , $r \leq N$). The first section of each message is processed with the initial key $K^1 = K$. To process the (i+1)-th section of each message the $K^{\{i+1\}}$ key value is calculated using ACPKM transformation as follows:

$$K^{\{i+1\}} = \text{ACPKM}(K^i) = \text{MSB}_k(E_{\{K^i\}}(D_1) | \dots | E_{\{K^i\}}(D_J)),$$

where $J = \text{ceil}(k/n)$, parameter c is fixed by a specific encryption mode which uses ACPKM key transformation and D_1, D_2, \dots, D_J are in V_n and are calculated as follows:

$$D_1 | D_2 | \dots | D_J = \text{MSB}_{\{J*n\}}(D),$$

where D is the following constant in $V_{\{1024\}}$:

```

D = ( 80 | 81 | 82 | 83 | 84 | 85 | 86 | 87
      | 88 | 89 | 8a | 8b | 8c | 8d | 8e | 8f
      | 90 | 91 | 92 | 93 | 94 | 95 | 96 | 97
      | 98 | 99 | 9a | 9b | 9c | 9d | 9e | 9f
      | a0 | a1 | a2 | a3 | a4 | a5 | a6 | a7
      | a8 | a9 | aa | ab | ac | ad | ae | af
      | b0 | b1 | b2 | b3 | b4 | b5 | b6 | b7
      | b8 | b9 | ba | bb | bc | bd | be | bf
      | c0 | c1 | c2 | c3 | c4 | c5 | c6 | c7
      | c8 | c9 | ca | cb | cc | cd | ce | cf
      | d0 | d1 | d2 | d3 | d4 | d5 | d6 | d7
      | d8 | d9 | da | db | dc | dd | de | df
      | e0 | e1 | e2 | e3 | e4 | e5 | e6 | e7
      | e8 | e9 | ea | eb | ec | ed | ee | ef
      | f0 | f1 | f2 | f3 | f4 | f5 | f6 | f7
      | f8 | f9 | fa | fb | fc | fd | fe | ff )

```

Note : The constant D is such that D_1, \dots, D_J are pairwise different for any allowed n, k values.

Note : The constant D is such that $\text{phi}_c(D_t) = 1$ for any allowed n, k, c and t in $\{1, \dots, J\}$. This condition is important, as it allows to prevent collisions of blocks of transformed key and block cipher permutation inputs.

6.2.2. CTR-ACPKM Encryption Mode

This section defines a CTR-ACPKM encryption mode that uses internal ACPKM re-keying mechanism for the periodical key transformation.

The CTR-ACPKM mode can be considered as the extended by the ACPKM re-keying mechanism basic encryption mode CTR (see [MODES]).

The CTR-ACPKM encryption mode can be used with the following parameters:

- o $64 \leq n \leq 512$;
- o $128 \leq k \leq 512$;
- o the number of bits c in a specific part of the block to be incremented is such that $16 \leq c \leq 3/4 n$, c is multiple of 8.

The CTR-ACPKM mode encryption and decryption procedures are defined as follows:

```

+-----+
| CTR-ACPKM-Encrypt(N, K, ICN, P)
+-----+

```

```

| Input:

```

- ```

| - Section size N,
| - key K,
| - initial counter nonce ICN in $V_{\{n-c\}}$,
| - plaintext $P = P_1 \mid \dots \mid P_b$, $|P| < n * 2^{\{c-1\}}$.

```

```

| Output:

```

- ```

| - Ciphertext C.
+-----+

```

- ```

| 1. $CTR_1 = ICN \mid 0^c$
| 2. For $j = 2, 3, \dots, b$ do
| $CTR_{\{j\}} = Inc_c(CTR_{\{j-1\}})$
| 3. $K^1 = K$
| 4. For $i = 2, 3, \dots, \text{ceil}(|P|/N)$
| $K^i = ACPKM(K^{\{i-1\}})$
| 5. For $j = 1, 2, \dots, b$ do
| $i = \text{ceil}(j*n / N)$,
| $G_j = E_{\{K^i\}}(CTR_j)$
| 6. $C = P \text{ (xor) } MSB_{\{|P|\}}(G_1 \mid \dots \mid G_b)$
| 7. Return C
+-----+

```

```

+-----+
| CTR-ACPKM-Decrypt(N, K, ICN, C)
+-----+

```

```

| Input:

```

- ```

| - Section size N,
| - key K,
| - initial counter nonce ICN in  $V_{\{n-c\}}$ ,
| - ciphertext  $C = C_1 \mid \dots \mid C_b$ ,  $|C| < n * 2^{\{c-1\}}$ .

```

```

| Output:

```

- ```

| - Plaintext P.
+-----+

```

- ```

| 1.  $P = \text{CTR-ACPKM-Encrypt}(N, K, ICN, C)$ 

```

- ```

| 2. Return P
+-----+

```

The initial counter nonce ICN value for each message that is encrypted under the given key must be chosen in a unique manner.

The message size MUST NOT exceed  $n * 2^{\{c-1\}}$  bits.

## 6.2.3. GCM-ACPKM Authenticated Encryption Mode

This section defines GCM-ACPKM authenticated encryption mode that uses internal ACPKM re-keying mechanism for the periodical key transformation.

The GCM-ACPKM mode can be considered as the basic authenticated encryption mode GCM (see [GCM]) extended by the ACPKM re-keying mechanism.

The GCM-ACPKM authenticated encryption mode can be used with the following parameters:

- o  $n$  in  $\{128, 256\}$ ;
- o  $128 \leq k \leq 512$ ;
- o the number of bits  $c$  in a specific part of the block to be incremented is such that  $32 \leq c \leq 3/4 n$ ,  $c$  is multiple of 8.;
- o authentication tag length  $t$ .

The GCM-ACPKM mode encryption and decryption procedures are defined as follows:

```

+-----+
| GHASH(X, H)
+-----+
| Input:
| - Bit string $X = X_1 \mid \dots \mid X_m$, X_i in V_n for i in $1, \dots, m$.
| Output:
| - Block $\text{GHASH}(X, H)$ in V_n .
+-----+
| 1. $Y_0 = 0^n$
| 2. For $i = 1, \dots, m$ do
| $Y_i = (Y_{i-1} \text{ (xor) } X_i) * H$
| 3. Return Y_m
+-----+

```

```

+-----+
| GCTR(N, K, ICB, X)
+-----+
| Input:
| - Section size N ,
| - key K ,
| - initial counter block ICB ,
| - $X = X_1 \mid \dots \mid X_b$, X_i in V_n for $i = 1, \dots, b-1$ and
+-----+

```

$X_b$  in  $V_r$ , where  $r \leq n$ .

Output:

-  $Y$  in  $V_{\{|X|\}}$ .

1. If  $X$  in  $V_0$  then return  $Y$ , where  $Y$  in  $V_0$
2.  $GCTR_1 = ICB$
3. For  $i = 2, \dots, b$  do  
 $GCTR_i = Inc_c(GCTR_{\{i-1\}})$
4.  $K^1 = K$
5. For  $j = 2, \dots, \text{ceil}(l*n / N)$   
 $K^j = ACPKM(K^{\{j-1\}})$
6. For  $i = 1, \dots, b$  do  
 $j = \text{ceil}(i*n / N),$   
 $G_i = E_{\{K_j\}}(GCTR_i)$
7.  $Y = X \text{ (xor) } MSB_{\{|X|\}}(G_1 \mid \dots \mid G_b)$
8. Return  $Y$ .

GCM-ACPKM-Encrypt( $N, K, IV, P, A$ )

Input:

- Section size  $N$ ,
- key  $K$ ,
- initial counter nonce  $ICN$  in  $V_{\{n-c\}}$ ,
- plaintext  $P$ ,  $|P| \leq n*(2^{\{c-1\}} - 2)$ ,  $P = P_1 \mid \dots \mid P_b$ ,
- additional authenticated data  $A$ .

Output:

- Ciphertext  $C$ ,
- authentication tag  $T$ .

1.  $H = E_{\{K\}}(0^n)$
2. If  $c = 32$ , then  $ICB_0 = ICN \mid 0^{31} \mid 1$   
 if  $c \neq 32$ , then  $s = n * \text{ceil}(|ICN| / n) - |ICN|,$   
 $ICB_0 = GHASH(ICN \mid 0^{\{s+n-64\}} \mid \text{Vec}_{64}(|ICN|), H)$
3.  $C = GCTR(N, K, Inc_{32}(ICB_0), P)$
4.  $u = n * \text{ceil}(|C| / n) - |C|$   
 $v = n * \text{ceil}(|A| / n) - |A|$
5.  $S = GHASH(A \mid 0^v \mid C \mid 0^u \mid 0^{\{n-128\}} \mid \text{Vec}_{64}(|A|) \mid$   
 $\mid \text{Vec}_{64}(|C|), H)$
6.  $T = MSB_t(E_{\{K\}}(ICB_0) \text{ (xor) } S)$
7. Return  $C \mid T$

GCM-ACPKM-Decrypt( $N, K, IV, A, C, T$ )

Input:

```

- Section size N,
- key K,
- initial counter block ICB,
- additional authenticated data A.
- ciphertext C, $|C| \leq n \cdot (2^{c-1} - 2)$, $C = C_1 \mid \dots \mid C_b$,
- authentication tag T
Output:
- Plaintext P or FAIL.

```

```

1. $H = E_{\{K\}}(0^n)$
2. If $c = 32$, then $ICB_0 = ICN \mid 0^{31} \mid 1$
 if $c \neq 32$, then $s = n \cdot \text{ceil}(|ICN|/n) - |ICN|$,
 $ICB_0 = \text{GHASH}(ICN \mid 0^{s+n-64} \mid \text{Vec}_{64}(|ICN|), H)$
3. $P = \text{GCTR}(N, K, \text{Inc}_{32}(ICB_0), C)$
4. $u = n \cdot \text{ceil}(|C| / n) - |C|$
 $v = n \cdot \text{ceil}(|A| / n) - |A|$
5. $S = \text{GHASH}(A \mid 0^v \mid C \mid 0^u \mid 0^{n-128} \mid \text{Vec}_{64}(|A|) \mid$
 $\mid \text{Vec}_{64}(|C|), H)$
6. $T' = \text{MSB}_t(E_{\{K\}}(ICB_0) \text{ (xor) } S)$
7. If $T = T'$ then return P; else return FAIL

```

The \* operation on (pairs of) the  $2^n$  possible blocks corresponds to the multiplication operation for the binary Galois (finite) field of  $2^n$  elements defined by the polynomial  $f$  as follows (by analogy with [GCM]):

$n = 128$ :  $f = a^{128} + a^7 + a^2 + a^1 + 1$ .

$n = 256$ :  $f = a^{256} + a^{10} + a^5 + a^2 + 1$ .

The initial vector IV value for each message that is encrypted under the given key must be chosen in a unique manner.

The plaintext size MUST NOT exceed  $n \cdot (2^{c-1} - 2)$  bits.

The key for computing values  $E_{\{K\}}(ICB_0)$  and  $H$  is not updated and is equal to the initial key  $K$ .

#### 6.2.4. CCM-ACPKM Authenticated Encryption Mode

This section defines a CCM-ACPKM authenticated encryption block cipher mode that uses internal ACPKM re-keying mechanism for the periodical key transformation.

The CCM-ACPKM mode can be considered as the extended by the ACPKM re-keying mechanism basic authenticated encryption mode CCM (see [RFC3610]).

Since [RFC3610] defines CCM authenticated encryption mode only for 128-bit block size, the CCM-ACPKM authenticated encryption mode can be used only with the parameter  $n = 128$ . However, the CCM-ACPKM design principles can easily be applied to other block sizes, but these modes will require their own specifications.

The CCM-ACPKM authenticated encryption mode differs from CCM mode in keys that are used for encryption during CBC-MAC calculation (see Section 2.2 of [RFC3610]) and key stream blocks generation (see Section 2.3 of [RFC3610]).

The CCM mode uses the same initial key  $K$  block cipher encryption operations, while the CCM-ACPKM mode uses the keys  $K^1, K^2, \dots$ , which are generated from the key  $K$  as follows:

$$\begin{aligned} K^1 &= K, \\ K^{i+1} &= \text{ACPKM}( K^i ). \end{aligned}$$

The keys  $K^1, K^2, \dots$ , which are used as follows.

CBC-MAC calculation: under a separate message processing during the first  $N/n$  block cipher encryption operations the key  $K^1$  is used, the key  $K^2$  is used for the next  $N/n$  block cipher encryption operations and so on. For example, if  $N = 2n$ , then CBC-MAC calculation for a sequence of  $t$  blocks  $B_0, B_1, \dots, B_t$  is as follows:

$$\begin{aligned} X_1 &= E( K^1, B_0 ), \\ X_2 &= E( K^1, X_1 \text{ XOR } B_1 ), \\ X_3 &= E( K^2, X_2 \text{ XOR } B_2 ), \\ X_4 &= E( K^2, X_3 \text{ XOR } B_3 ), \\ X_5 &= E( K^3, X_4 \text{ XOR } B_4 ), \\ &\dots \\ T &= \text{first-M-bytes}( X_{t+1} ) \end{aligned}$$

The key stream blocks generation: under a separate message processing during the first  $N/n$  block cipher encryption operations the key  $K^1$  is used, the key  $K^2$  is used for the next  $N/n$  block cipher encryption operations and so on. For example, if  $N = 2n$ , then the key stream blocks are generated as follows:

$$\begin{aligned} S_0 &= E( K^1, A_0 ), \\ S_1 &= E( K^1, A_1 ), \\ S_2 &= E( K^2, A_2 ), \\ S_3 &= E( K^2, A_3 ), \\ S_4 &= E( K^3, A_4 ), \\ &\dots \end{aligned}$$



### 6.3. Constructions that Require Master Key

This section describes the block cipher modes that uses the ACPKM-Master re-keying mechanism, which use the initial key  $K$  as a master key  $K$ , so  $K$  is never used directly for the data processing but is used for key derivation.

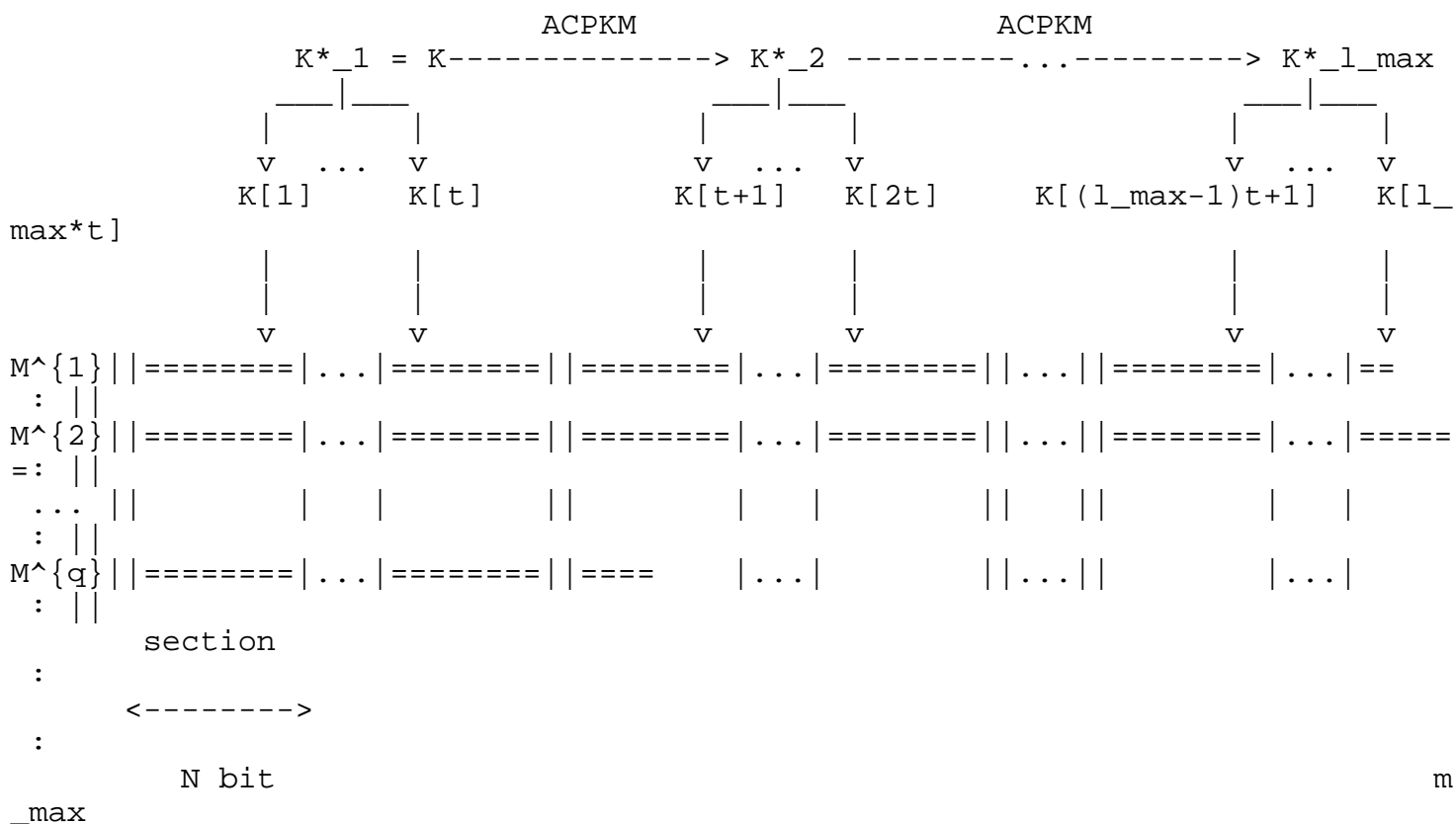
#### 6.3.1. ACPKM-Master Key Derivation from the Master Key

This section defines periodical key transformation with master key  $K$  which is called ACPKM-Master re-keying mechanism. This mechanism can be applied to one of the basic modes of operation (CTR, GCM, CBC, CFB, OFB, OMAC modes) for getting an extension of this modes of operations that uses periodical key transformation with master key. This extension can be considered as a new mode of operation .

Additional parameters that defines the functioning of basic modes of operation with the ACPKM-Master re-keying mechanism are the section size  $N$  and change frequency  $T^*$  of the key  $K$ . The values of  $N$  and  $T^*$  are measured in bits and are fixed within a specific protocol based on the requirements of the system capacity and key lifetime (some recommendations on choosing  $N$  and  $T^*$  will be provided in Section 8). The section size  $N$  MUST be divisible by the block size  $n$ . The key frequency  $T^*$  MUST be divisible by  $n$ .

The main idea behind internal re-keying with master key is presented in Figure 9:

Change frequency  $T^*$ ,  
 section size  $N$ ,  
 maximum message size =  $m_{\max}$ .



$|K[i]| = d,$   
 $t = T^*/d,$   
 $l_{\max} = \text{ceil}(m_{\max}/N).$

Figure 9: Internal re-keying with master key

During the processing of the input message  $M$  with the length  $m$  in some mode of operation that uses ACPKM-Master key transformation with the master key  $K$  and key frequency  $T^*$  the message  $M$  is divided into  $l = \text{ceil}(m/N)$  sections (denoted as  $M = M_1 | M_2 | \dots | M_l$ , where  $M_i$  is in  $V_N$  for  $i$  in  $\{1, 2, \dots, l-1\}$  and  $M_l$  is in  $V_r, r \leq N$ ). The  $j$ -th section of each message is processed with the key material  $K[j]$ ,  $j$  in  $\{1, \dots, l\}$ ,  $|K[j]| = d$ , that has been calculated with the ACPKM-Master algorithm as follows:

$$K[1] | \dots | K[l] = \text{ACPKM-Master}(T^*, K, d \cdot l) = \text{CTR-ACPKM-Encrypt}(T^*, K, 1^{\{n/2\}}, 0^{\{d \cdot l\}}).$$

### 6.3.2. CTR-ACPKM-Master Encryption Mode

This section defines a CTR-ACPKM-Master encryption mode that uses

internal ACPKM-Master re-keying mechanism for the periodical key transformation.

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The CTR-ACPKM-Master encryption mode can be considered as the extended by the ACPKM-Master re-keying mechanism basic encryption mode CTR (see [MODES]).

The CTR-ACPKM-Master encryption mode can be used with the following parameters:

- o  $64 \leq n \leq 512$ ;
- o  $128 \leq k \leq 512$ ;
- o the number of bits  $c$  in a specific part of the block to be incremented is such that  $32 \leq c \leq 3/4 n$ ,  $c$  is multiple of 8.

The key material  $K[j]$  that is used for one section processing is equal to  $K^j$ ,  $|K^j| = k$  bits.

The CTR-ACPKM-Master mode encryption and decryption procedures are defined as follows:

```

+-----+
CTR-ACPKM-Master-Encrypt(N, K, T*, ICN, P)
+-----+

```

```

Input:

```

- Section size N,
- master key K,
- change frequency T\*,
- initial counter nonce ICN in  $V_{\{n-c\}}$ ,
- plaintext  $P = P_1 \mid \dots \mid P_b$ ,  $|P| \leq 2^{\{n/2-1\}} * n * N / k$ .

```

Output:

```

- Ciphertext C.

- ```

+-----+
1. CTR_1 = ICN | 0^c
2. For j = 2, 3, ... , b do
   CTR_{j} = Inc_c(CTR_{j-1})
3. l = ceil(b*n / N)
4. K^1 | ... | K^l = ACPKM-Master(T*, K, k*1)
5. For j = 1, 2, ... , b do
   i = ceil(j*n / N),
   G_j = E_{K^i}(CTR_j)
6. C = P (xor) MSB_{|P|}(G_1 | ... | G_b)
7. Return C
+-----+

```

```

+-----+
CTR-ACPKM-Master-Decrypt(N, K, T*, ICN, C)
+-----+

```

```

Input:

```

- Section size N,
- master key K,
- change frequency T*,
- initial counter nonce ICN in $V_{\{n-c\}}$,
- ciphertext $C = C_1 \mid \dots \mid C_b$, $|C| \leq 2^{\{n/2-1\}} * n * N / k$.

```

Output:

```

- Plaintext P.

- ```

+-----+
1. P = CTR-ACPKM-Master-Encrypt(N, K, T*, ICN, C)
1. Return P
+-----+

```

The initial counter nonce ICN value for each message that is encrypted under the given key must be chosen in a unique manner. The counter ( $CTR_{\{i+1\}}$ ) value does not change during key transformation.

The message size MUST NOT exceed  $(2^{\{n/2-1\}} * n * N / k)$  bits.

## 6.3.3. GCM-ACPKM-Master Authenticated Encryption Mode

This section defines a GCM-ACPKM-Master authenticated encryption mode that uses internal ACPKM-Master re-keying mechanism for the periodical key transformation.

The GCM-ACPKM-Master authenticated encryption mode can be considered as the extended by the ACPKM-Master re-keying mechanism basic authenticated encryption mode GCM (see [GCM]).

The GCM-ACPKM-Master authenticated encryption mode can be used with the following parameters:

- o  $n$  in  $\{128, 256\}$ ;
- o  $128 \leq k \leq 512$ ;
- o the number of bits  $c$  in a specific part of the block to be incremented is such that  $32 \leq c \leq 3/4 n$ ,  $c$  is multiple of 8;
- o authentication tag length  $t$ .

The key material  $K[j]$  that is used for one section processing is equal to  $K^j$ ,  $|K^j| = k$  bits, that is calculated as follows:

$$K^1 \mid \dots \mid K^j \mid \dots \mid K^1 = \text{ACPKM-Master}(T^*, K, k^1).$$

The GCM-ACPKM-Master mode encryption and decryption procedures are defined as follows:

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <p style="margin: 0;">GHASH(X, H)</p> <hr style="border: none; border-top: 1px dashed black;"/> <p style="margin: 0;">Input:</p> <ul style="list-style-type: none"> <li>- Bit string <math>X = X_1 \mid \dots \mid X_m</math>, <math>X_i</math> in <math>V_n</math> for <math>i</math> in <math>\{1, \dots, m\}</math></li> </ul> <p style="margin: 0;">Output:</p> <ul style="list-style-type: none"> <li>- Block GHASH(X, H) in <math>V_n</math></li> </ul> <hr style="border: none; border-top: 1px dashed black;"/> <ol style="list-style-type: none"> <li>1. <math>Y_0 = 0^n</math></li> <li>2. For <math>i = 1, \dots, m</math> do             <ul style="list-style-type: none"> <li><math>Y_i = (Y_{i-1} \text{ (xor) } X_i) * H</math></li> </ul> </li> <li>3. Return <math>Y_m</math></li> </ol> <hr style="border: none; border-top: 1px dashed black;"/> |
| <p style="margin: 0;">GCTR(N, K, T*, ICB, X)</p> <hr style="border: none; border-top: 1px dashed black;"/>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |

## Input:

- Section size  $N$ ,
- master key  $K$ ,
- change frequency  $T^*$ ,
- initial counter block  $ICB$ ,
- $X = X_1 \mid \dots \mid X_b$ ,  $X_i$  in  $V_n$  for  $i = 1, \dots, b-1$  and  
 $X_b$  in  $V_r$ , where  $r \leq n$ .

## Output:

- $Y$  in  $V_{\{|X|\}}$ .

- 
1. If  $X$  in  $V_0$  then return  $Y$ , where  $Y$  in  $V_0$
  2.  $GCTR_1 = ICB$
  3. For  $i = 2, \dots, b$  do  
 $GCTR_i = Inc_c(GCTR_{\{i-1\}})$
  4.  $l = \text{ceil}(b*n / N)$
  5.  $K^1 \mid \dots \mid K^l = ACPKM\text{-Master}(T^*, K, k^*l)$
  6. For  $j = 1, \dots, b$  do  
 $i = \text{ceil}(j*n / N)$ ,  
 $G_j = E_{\{K^i\}}(GCTR_j)$
  7.  $Y = X$  (xor)  $MSB_{\{|X|\}}(G_1 \mid \dots \mid G_b)$
  8. Return  $Y$
- 

GCM-ACPKM-Master-Encrypt( $N, K, T^*, IV, P, A$ )

## Input:

- Section size  $N$ ,
- master key  $K$ ,
- change frequency  $T^*$ ,
- initial counter nonce  $ICN$  in  $V_{\{n-c\}}$ ,
- plaintext  $P$ ,  $|P| \leq n*(2^{\{c-1\}} - 2)$ .
- additional authenticated data  $A$ .

## Output:

- Ciphertext  $C$ ,
- authentication tag  $T$ .

- 
1.  $K^1 = ACPKM\text{-Master}(T^*, K, k)$
  2.  $H = E_{\{K^1\}}(0^n)$
  3. If  $c = 32$ , then  $ICB_0 = ICN \mid 0^{31} \mid 1$   
if  $c \neq 32$ , then  $s = n*\text{ceil}(|ICN|/n) - |ICN|$ ,  
 $ICB_0 = GHASH(ICN \mid 0^{\{s+n-64\}} \mid \text{Vec}_{64}(|ICN|), H)$
  4.  $C = GCTR(N, K, T^*, Inc_{32}(J_0), P)$
  5.  $u = n*\text{ceil}(|C| / n) - |C|$   
 $v = n*\text{ceil}(|A| / n) - |A|$
  6.  $S = GHASH(A \mid 0^v \mid C \mid 0^u \mid 0^{\{n-128\}} \mid \text{Vec}_{64}(|A|) \mid$   
 $\mid \text{Vec}_{64}(|C|), H)$
  7.  $T = MSB_t(E_{\{K^1\}}(J_0) \text{ (xor) } S)$
-

| 8. Return C | T |

GCM-ACPKM-Master-Decrypt(N, K, T\*, IV, A, C, T)

Input:

- Section size N,
- master key K,
- change frequency T\*,
- initial counter nonce ICN in  $V_{\{n-c\}}$ ,
- additional authenticated data A.
- ciphertext C,  $|C| \leq n \cdot (2^{c-1} - 2)$ ,
- authentication tag T,

Output:

- Plaintext P or FAIL.

1.  $K^1 = \text{ACPKM-Master}(T^*, K, k)$
2.  $H = E_{\{K^1\}}(0^n)$
3. If  $c = 32$ , then  $\text{ICB}_0 = \text{ICN} \parallel 0^{31} \parallel 1$   
 if  $c \neq 32$ , then  $s = n \cdot \text{ceil}(|\text{ICN}| / n) - |\text{ICN}|$ ,  
 $\text{ICB}_0 = \text{GHASH}(\text{ICN} \parallel 0^{s+n-64} \parallel \text{Vec}_{64}(|\text{ICN}|), H)$
4.  $P = \text{GCTR}(N, K, T^*, \text{Inc}_{32}(J_0), C)$
5.  $u = n \cdot \text{ceil}(|C| / n) - |C|$   
 $v = n \cdot \text{ceil}(|A| / n) - |A|$
6.  $S = \text{GHASH}(A \parallel 0^v \parallel C \parallel 0^u \parallel 0^{\{n-128\}} \parallel \text{Vec}_{64}(|A|) \parallel \text{Vec}_{64}(|C|), H)$
7.  $T' = \text{MSB}_t(E_{\{K^1\}}(\text{ICB}_0) \text{ (xor) } S)$
8. IF  $T = T'$  then return P; else return FAIL.

The \* operation on (pairs of) the  $2^n$  possible blocks corresponds to the multiplication operation for the binary Galois (finite) field of  $2^n$  elements defined by the polynomial  $f$  as follows (by analogy with [GCM]):

$$n = 128: \quad f = a^{128} + a^7 + a^2 + a^1 + 1.$$

$$n = 256: \quad f = a^{256} + a^{10} + a^5 + a^2 + 1.$$

The initial vector IV value for each message that is encrypted under the given key must be chosen in a unique manner.

The plaintext size MUST NOT exceed  $(2^{\{n/2-1\}} \cdot n \cdot N / k)$  bits.



#### 6.3.4. CCM-ACPKM-Master Authenticated Encryption Mode

This section defines a CCM-ACPKM-Master authenticated encryption mode of operations that uses internal ACPKM-Master re-keying mechanism for the periodical key transformation.

The CCM-ACPKM-Master authenticated encryption mode is differed from CCM-ACPKM mode in the way the keys  $K^1, K^2, \dots$  are generated. For CCM-ACPKM-Master mode the keys are generated as follows:  $K^i = K[i]$ , where  $|K^i|=k$  and  $K[1]|K[2]|\dots|K[l] = \text{ACPKM-Master}(T^*, K, k \cdot l)$ .

#### 6.3.5. CBC-ACPKM-Master Encryption Mode

This section defines a CBC-ACPKM-Master encryption mode that uses internal ACPKM-Master re-keying mechanism for the periodical key transformation.

The CBC-ACPKM-Master encryption mode can be considered as the extended by the ACPKM-Master re-keying mechanism basic encryption mode CBC (see [MODES]).

The CBC-ACPKM-Master encryption mode can be used with the following parameters:

- o  $64 \leq n \leq 512$ ;
- o  $128 \leq k \leq 512$ .

In the specification of the CBC-ACPKM-Master mode the plaintext and ciphertext must be a sequence of one or more complete data blocks. If the data string to be encrypted does not initially satisfy this property, then it MUST be padded to form complete data blocks. The padding methods are outside the scope of this document. An example of a padding method can be found in Appendix A of [MODES].

The key material  $K[j]$  that is used for one section processing is equal to  $K^j$ ,  $|K^j| = k$  bits.

We will denote by  $D_{\{K\}}$  the decryption function which is a permutation inverse to the  $E_{\{K\}}$ .

The CBC-ACPKM-Master mode encryption and decryption procedures are defined as follows:

```

+-----+
| CBC-ACPKM-Master-Encrypt(N, K, T*, IV, P)
+-----+

```

Input:

- Section size N,
- master key K,
- change frequency T\*,
- initialization vector IV in  $V_n$ ,
- plaintext  $P = P_1 \mid \dots \mid P_b$ ,  $|P| \leq 2^{\{n/2-1\}} * n * N / k$ ,  
 $|P_b| = n$ .

Output:

- Ciphertext C.

- ```

+-----+
|
| 1.  $l = \text{ceil}(b * n / N)$ 
| 2.  $K^1 \mid \dots \mid K^l = \text{ACPKM-Master}(T^*, K, k * l)$ 
| 3.  $C_0 = \text{IV}$ 
| 4. For  $j = 1, 2, \dots, b$  do
|      $i = \text{ceil}(j * n / N)$ ,
|      $C_j = E_{\{K^i\}}(P_j \text{ (xor) } C_{\{j-1\}})$ 
| 5. Return  $C = C_1 \mid \dots \mid C_b$ 
+-----+

```

```

+-----+
| CBC-ACPKM-Master-Decrypt(N, K, T*, IV, C)
+-----+

```

Input:

- Section size N,
- master key K,
- change frequency T*,
- initialization vector IV in V_n ,
- ciphertext $C = C_1 \mid \dots \mid C_b$, $|C| \leq 2^{\{n/2-1\}} * n * N / k$,
 $|C_b| = n$.

Output:

- Plaintext P.

- ```

+-----+
|
| 1. $l = \text{ceil}(b * n / N)$
| 2. $K^1 \mid \dots \mid K^l = \text{ACPKM-Master}(T^*, K, k * l)$
| 3. $C_0 = \text{IV}$
| 4. For $j = 1, 2, \dots, b$ do
| $i = \text{ceil}(j * n / N)$
| $P_j = D_{\{K^i\}}(C_j) \text{ (xor) } C_{\{j-1\}}$
| 5. Return $P = P_1 \mid \dots \mid P_b$
+-----+

```

The initialization vector IV for each message that is encrypted under the given key need not to be secret, but must be unpredictable.

The message size MUST NOT exceed  $(2^{\{n/2-1\}} * n * N / k)$  bits.

### 6.3.6. CFB-ACPKM-Master Encryption Mode

This section defines a CFB-ACPKM-Master encryption mode that uses internal ACPKM-Master re-keying mechanism for the periodical key transformation.

The CFB-ACPKM-Master encryption mode can be considered as the extended by the ACPKM-Master re-keying mechanism basic encryption mode CFB (see [MODES]).

The CFB-ACPKM-Master encryption mode can be used with the following parameters:

- o  $64 \leq n \leq 512$ ;
- o  $128 \leq k \leq 512$ .

The key material  $K[j]$  that is used for one section processing is equal to  $K^j$ ,  $|K^j| = k$  bits.

The CFB-ACPKM-Master mode encryption and decryption procedures are defined as follows:

```
CFB-ACPKM-Master-Encrypt(N, K, T*, IV, P)
```

Input:

- Section size N,
- master key K,
- change frequency T\*,
- initialization vector IV in  $V_n$ ,
- plaintext  $P = P_1 \mid \dots \mid P_b$ ,  $|P| \leq 2^{\{n/2-1\}} * n * N / k$ .

Output:

- Ciphertext C.

1.  $l = \text{ceil}(b * n / N)$
2.  $K^1 \mid \dots \mid K^l = \text{ACPKM-Master}(T^*, K, k * l)$
3.  $C_0 = \text{IV}$
4. For  $j = 1, 2, \dots, b$  do
  - $i = \text{ceil}(j * n / N)$
  - $C_j = E_{\{K^i\}}(C_{\{j-1\}}) \text{ (xor) } P_j$
5. Return  $C = C_1 \mid \dots \mid C_b$ .

```
CFB-ACPKM-Master-Decrypt(N, K, T*, IV, C)
```

Input:

- Section size N,
- master key K,
- change frequency T\*,
- initialization vector IV in  $V_n$ ,
- ciphertext  $C = C_1 \mid \dots \mid C_b$ ,  $|C| \leq 2^{\{n/2-1\}} * n * N / k$ .

Output:

- Plaintext P.

1.  $l = \text{ceil}(b * n / N)$
2.  $K^1 \mid \dots \mid K^l = \text{ACPKM-Master}(T^*, K, k * l)$
3.  $C_0 = \text{IV}$
4. For  $j = 1, 2, \dots, b$  do
  - $i = \text{ceil}(j * n / N)$ ,
  - $P_j = E_{\{K^i\}}(C_{\{j-1\}}) \text{ (xor) } C_j$
5. Return  $P = P_1 \mid \dots \mid P_b$

The initialization vector IV for each message that is encrypted under the given key need not to be secret, but must be unpredictable.

The message size MUST NOT exceed  $2^{\{n/2-1\}} * n * N / k$  bits.

### 6.3.7. OFB-ACPKM-Master Encryption Mode

This section defines an OFB-ACPKM-Master encryption mode that uses internal ACPKM-Master re-keying mechanism for the periodical key transformation.

The OFB-ACPKM-Master encryption mode can be considered as the extended by the ACPKM-Master re-keying mechanism basic encryption mode OFB (see [MODES]).

The OFB-ACPKM-Master encryption mode can be used with the following parameters:

- o  $64 \leq n \leq 512$ ;
- o  $128 \leq k \leq 512$ .

The key material  $K[j]$  used for one section processing is equal to  $K^j$ ,  $|K^j| = k$  bits.

The OFB-ACPKM-Master mode encryption and decryption procedures are defined as follows:

```
OFB-ACPKM-Master-Encrypt(N, K, T*, IV, P)
```

Input:

- Section size N,
- master key K,
- change frequency T\*,
- initialization vector IV in  $V_n$ ,
- plaintext  $P = P_1 \mid \dots \mid P_b$ ,  $|P| \leq 2^{\{n/2-1\}} * n * N / k$ .

Output:

- Ciphertext C.

1.  $l = \text{ceil}(b * n / N)$
2.  $K^1 \mid \dots \mid K^l = \text{ACPKM-Master}(T^*, K, k * l)$
3.  $G_0 = \text{IV}$
4. For  $j = 1, 2, \dots, b$  do
  - $i = \text{ceil}(j * n / N)$ ,
  - $G_j = E_{\{K_i\}}(G_{\{j-1\}})$
5. Return  $C = P \text{ (xor) } \text{MSB}_{\{|P|\}}(G_1 \mid \dots \mid G_b)$

```
OFB-ACPKM-Master-Decrypt(N, K, T*, IV, C)
```

Input:

- Section size N,
- master key K,
- change frequency T\*,
- initialization vector IV in  $V_n$ ,
- ciphertext  $C = C_1 \mid \dots \mid C_b$ ,  $|C| \leq 2^{\{n/2-1\}} * n * N / k$ .

Output:

- Plaintext P.

1. Return OFB-ACPKM-Master-Encrypt(N, K, T\*, IV, C)

The initialization vector IV for each message that is encrypted under the given key need not be unpredictable, but it must be a nonce that is unique to each execution of the encryption operation.

The message size MUST NOT exceed  $2^{\{n/2-1\}} * n * N / k$  bits.

#### 6.3.8. OMAC-ACPKM-Master Mode

This section defines an OMAC-ACPKM-Master message authentication code calculation mode that uses internal ACPKM-Master re-keying mechanism for the periodical key transformation.

The OMAC-ACPKM-Master mode can be considered as the extended by the ACPKM-Master re-keying mechanism basic message authentication code calculation mode OMAC, which is also known as CMAC (see [RFC4493]).

The OMAC-ACPKM-Master message authentication code calculation mode can be used with the following parameters:

- o  $n$  in  $\{64, 128, 256\}$ ;
- o  $128 \leq k \leq 512$ .

The key material  $K[j]$  that is used for one section processing is equal to  $K^j \parallel K^{j-1}$ , where  $|K^j| = k$  and  $|K^{j-1}| = n$ .

The following is a specification of the subkey generation process of OMAC:

```

+-----+
| Generate_Subkey(K1, r)
+-----+
| Input:
| - Key K1,
| Output:
| - Key SK.
+-----+
| 1. If $r = n$ then return K1
| 2. If $r < n$ then
| if $MSB_1(K1) = 0$
| return $K1 \ll 1$
| else
| return $(K1 \ll 1) \text{ (xor) } R_n$
+-----+

```

Where  $R_n$  takes the following values:

- o  $n = 64$ :  $R_{\{64\}} = 0^{\{59\}} \parallel 11011$ ;
- o  $n = 128$ :  $R_{\{128\}} = 0^{\{120\}} \parallel 10000111$ ;
- o  $n = 256$ :  $R_{\{256\}} = 0^{\{145\}} \parallel 10000100101$ .

The OMAC-ACPKM-Master message authentication code calculation mode is defined as follows:

```

+-----+
| OMAC-ACPKM-Master(K, N, T*, M)
+-----+
| Input:
| - Section size N,
| - master key K,
| - key frequency T*,
| - plaintext M = M_1 | ... | M_b, |M| <= 2^{n/2}*n^2*N / (k + n).
| Output:
| - message authentication code T.
+-----+
| 1. C_0 = 0^n
| 2. l = ceil(b*n / N)
| 3. K^1 | K^1_1 | ... | K^1 | K^1_1 = ACPKM-Master(T*, K, (k+n)*l
| 4. For j = 1, 2, ..., b-1 do
| i = ceil(j*n / N),
| C_j = E_{K^i}(M_j (xor) C_{j-1})
| 5. SK = Generate_Subkey(K^1_1, |M_b|)
| 6. If |M_b| = n then M*_b = M_b
| else M*_b = M_b | 1 | 0^{n-1-|M_b|}
| 7. T = E_{K^1}(M*_b (xor) C_{b-1} (xor) SK)
| 8. Return T
+-----+

```

The message size MUST NOT exceed  $2^{\{n/2\}}*n^2*N / (k + n)$  bits.

## 7. Joint Usage of External and Internal Re-keying

Any mechanism described in Section 5 can be used with any mechanism described in Section 6.

## 8. Security Considerations

Re-keying should be used to increase "a priori" security properties of ciphers in hostile environments (e.g. with side-channel adversaries). If some non-negligible attacks are known for a cipher, it must not be used. So re-keying cannot be used as a patch for vulnerable ciphers. Base cipher properties must be well analyzed, because security of re-keying mechanisms is based on security of a block cipher as a pseudorandom function.

Re-keying is not intended to solve any post-quantum security issues for symmetric crypto since the reduction of security caused by Grover's algorithm is not connected with a size of plaintext transformed by a cipher - only a negligible (sufficient for key uniqueness) material is needed and the aim of re-keying is to limit a size of plaintext transformed on one key.



Re-keying can provide backward security only if the previous traffic keys are securely deleted by all parties that have the keys.

## 9. References

### 9.1. Normative References

- [GCM] McGrew, D. and J. Viega, "The Galois/Counter Mode of Operation (GCM)", Submission to NIST <http://csrc.nist.gov/CryptoToolkit/modes/proposedmodes/gcm/gcm-spec.pdf>, January 2004.
- [MODES] Dworkin, M., "Recommendation for Block Cipher Modes of Operation: Methods and Techniques", NIST Special Publication 800-38A, December 2001.
- [RFC2119] Bradner, S., "Key words for use in RFCs to Indicate Requirement Levels", BCP 14, RFC 2119, DOI 10.17487/RFC2119, March 1997, <<http://www.rfc-editor.org/info/rfc2119>>.
- [RFC3610] Whiting, D., Housley, R., and N. Ferguson, "Counter with CBC-MAC (CCM)", RFC 3610, DOI 10.17487/RFC3610, September 2003, <<http://www.rfc-editor.org/info/rfc3610>>.
- [RFC4493] Song, JH., Poovendran, R., Lee, J., and T. Iwata, "The AES-CMAC Algorithm", RFC 4493, DOI 10.17487/RFC4493, June 2006, <<http://www.rfc-editor.org/info/rfc4493>>.
- [RFC5869] Krawczyk, H. and P. Eronen, "HMAC-based Extract-and-Expand Key Derivation Function (HKDF)", RFC 5869, DOI 10.17487/RFC5869, May 2010, <<http://www.rfc-editor.org/info/rfc5869>>.
- [TLSDraft] Rescorla, E., "The Transport Layer Security (TLS) Protocol Version 1.3", 2017, <<https://tools.ietf.org/html/draft-ietf-tls-tls13-18>>.

### 9.2. Informative References

- [AbBell] Michel Abdalla and Mihir Bellare, "Increasing the Lifetime of a Key: A Comparative Analysis of the Security of Re-keying Techniques", ASIACRYPT2000, LNCS 1976, pp. 546-559, 2000.

- [LDC] Howard M. Heys, "A Tutorial on Linear and Differential Cryptanalysis", 2017,  
<<http://www.cs.bc.edu/~straubin/crypto2017/heys.pdf>>.
- [Sweet32] Karthikeyan Bhargavan, Gaetan Leurent, "On the Practical (In-)Security of 64-bit Block Ciphers. Collision Attacks on HTTP over TLS and OpenVPN", 2016,  
<[https://sweet32.info/SWEET32\\_CCS16.pdf](https://sweet32.info/SWEET32_CCS16.pdf)>.

## Appendix A. Test examples

CTR-ACPKM mode with AES-256

\*\*\*\*\*

c = 64  
k = 256  
N = 256  
n = 128

D\_1

80 81 82 83 84 85 86 87 88 89 8A 8B 8C 8D 8E 8F

D\_2

90 91 92 93 94 95 96 97 98 99 9A 9B 9C 9D 9E 9F

Key K:

88 99 AA BB CC DD EE FF 00 11 22 33 44 55 66 77  
FE DC BA 98 76 54 32 10 01 23 45 67 89 AB CD EF

Plain text P:

11 22 33 44 55 66 77 00 FF EE DD CC BB AA 99 88  
00 11 22 33 44 55 66 77 88 99 AA BB CC EE FF 0A  
11 22 33 44 55 66 77 88 99 AA BB CC EE FF 0A 00  
22 33 44 55 66 77 88 99 AA BB CC EE FF 0A 00 11  
33 44 55 66 77 88 99 AA BB CC EE FF 0A 00 11 22  
44 55 66 77 88 99 AA BB CC EE FF 0A 00 11 22 33  
55 66 77 88 99 AA BB CC EE FF 0A 00 11 22 33 44

ICN:

12 34 56 78 90 AB CE F0

ACPKM's iteration 1

Process block 1

Input block (ctr)

12 34 56 78 90 AB CE F0 00 00 00 00 00 00 00 00

Output block (ctr)

FD 7E F8 9A D9 7E A4 B8 8D B8 B5 1C 1C 9D 6D D0

Plain text

11 22 33 44 55 66 77 00 FF EE DD CC BB AA 99 88

Cipher text

EC 5C CB DE 8C 18 D3 B8 72 56 68 D0 A7 37 F4 58

Process block 2

Input block (ctr)

12 34 56 78 90 AB CE F0 00 00 00 00 00 00 01

Output block (ctr)

19 98 C5 71 76 37 FB 17 11 E4 48 F0 0C 0D 60 B2

Plain text

00 11 22 33 44 55 66 77 88 99 AA BB CC EE FF 0A

Cipher text

19 89 E7 42 32 62 9D 60 99 7D E2 4B C0 E3 9F B8

Input block (ctr)

80 81 82 83 84 85 86 87 88 89 8A 8B 8C 8D 8E 8F

Output block (ctr)

F6 80 D1 21 2F A4 3D F4 EC 3A 91 DE 2A B1 6F 1B

Input block (ctr)

90 91 92 93 94 95 96 97 98 99 9A 9B 9C 9D 9E 9F

Output block (ctr)

36 B0 48 8A 4F C1 2E 09 98 D2 E4 A8 88 E8 4F 3D

Updated key:

F6 80 D1 21 2F A4 3D F4 EC 3A 91 DE 2A B1 6F 1B

36 B0 48 8A 4F C1 2E 09 98 D2 E4 A8 88 E8 4F 3D

ACPKM's iteration 2

Process block 1

Input block (ctr)

12 34 56 78 90 AB CE F0 00 00 00 00 00 00 02

Output block (ctr)

E4 88 89 4F B6 02 87 DB 77 5A 07 D9 2C 89 46 EA

Plain text

11 22 33 44 55 66 77 88 99 AA BB CC EE FF 0A 00

Cipher text

F5 AA BA 0B E3 64 F0 53 EE F0 BC 15 C2 76 4C EA

Process block 2

Input block (ctr)

12 34 56 78 90 AB CE F0 00 00 00 00 00 00 03

Output block (ctr)

BC 4F 87 23 DB F0 91 50 DD B4 06 C3 1D A9 7C A4

Plain text

22 33 44 55 66 77 88 99 AA BB CC EE FF 0A 00 11

Cipher text

9E 7C C3 76 BD 87 19 C9 77 0F CA 2D E2 A3 7C B5

Input block (ctr)

80 81 82 83 84 85 86 87 88 89 8A 8B 8C 8D 8E 8F

Output block (ctr)

8E B9 7E 43 27 1A 42 F1 CA 8E E2 5F 5C C7 C8 3B

Input block (ctr)

90 91 92 93 94 95 96 97 98 99 9A 9B 9C 9D 9E 9F

Output block (ctr)

1A CE 9E 5E D0 6A A5 3B 57 B9 6A CF 36 5D 24 B8

Updated key:

8E B9 7E 43 27 1A 42 F1 CA 8E E2 5F 5C C7 C8 3B

1A CE 9E 5E D0 6A A5 3B 57 B9 6A CF 36 5D 24 B8

ACPKM's iteration 3

Process block 1

Input block (ctr)

12 34 56 78 90 AB CE F0 00 00 00 00 00 00 04

Output block (ctr)

68 6F 22 7D 8F B2 9C BD 05 C8 C3 7D 22 FE 3B B7

Plain text

33 44 55 66 77 88 99 AA BB CC EE FF 0A 00 11 22

Cipher text

5B 2B 77 1B F8 3A 05 17 BE 04 2D 82 28 FE 2A 95

Process block 2

Input block (ctr)

12 34 56 78 90 AB CE F0 00 00 00 00 00 00 05

Output block (ctr)

C0 1B F9 7F 75 6E 12 2F 80 59 55 BD DE 2D 45 87

Plain text

44 55 66 77 88 99 AA BB CC EE FF 0A 00 11 22 33

Cipher text

84 4E 9F 08 FD F7 B8 94 4C B7 AA B7 DE 3C 67 B4

Input block (ctr)

80 81 82 83 84 85 86 87 88 89 8A 8B 8C 8D 8E 8F

Output block (ctr)

C5 71 6C C9 67 98 BC 2D 4A 17 87 B7 8A DF 94 AC

Input block (ctr)

90 91 92 93 94 95 96 97 98 99 9A 9B 9C 9D 9E 9F

Output block (ctr)

E8 16 F8 0B DB BC AD 7D 60 78 12 9C 0C B4 02 F5

Updated key:

C5 71 6C C9 67 98 BC 2D 4A 17 87 B7 8A DF 94 AC

E8 16 F8 0B DB BC AD 7D 60 78 12 9C 0C B4 02 F5

ACPKM's iteration 4

Process block 1

Input block (ctr)

12 34 56 78 90 AB CE F0 00 00 00 00 00 00 06

Output block (ctr)

03 DE 34 74 AB 9B 65 8A 3B 54 1E F8 BD 2B F4 7D

Plain text

55 66 77 88 99 AA BB CC EE FF 0A 00 11 22 33 44

Cipher text

56 B8 43 FC 32 31 DE 46 D5 AB 14 F8 AC 09 C7 39

Input block (ctr)

80 81 82 83 84 85 86 87 88 89 8A 8B 8C 8D 8E 8F

Output block (ctr)

74 1E B5 88 D6 AB DA B6 89 AA FD BA A9 3E A2 46

Input block (ctr)

90 91 92 93 94 95 96 97 98 99 9A 9B 9C 9D 9E 9F

Output block (ctr)

16 3A A6 C2 3C E7 C3 74 CD 38 BF C6 FE 8C C5 FF

Updated key:

74 1E B5 88 D6 AB DA B6 89 AA FD BA A9 3E A2 46  
16 3A A6 C2 3C E7 C3 74 CD 38 BF C6 FE 8C C5 FF

Encrypted src

EC 5C CB DE 8C 18 D3 B8 72 56 68 D0 A7 37 F4 58  
19 89 E7 42 32 62 9D 60 99 7D E2 4B C0 E3 9F B8  
F5 AA BA 0B E3 64 F0 53 EE F0 BC 15 C2 76 4C EA  
9E 7C C3 76 BD 87 19 C9 77 0F CA 2D E2 A3 7C B5  
5B 2B 77 1B F8 3A 05 17 BE 04 2D 82 28 FE 2A 95  
84 4E 9F 08 FD F7 B8 94 4C B7 AA B7 DE 3C 67 B4  
56 B8 43 FC 32 31 DE 46 D5 AB 14 F8 AC 09 C7 39

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