

A SUBMISSION TO CAESAR COMPETITION FOR
AUTHENTICATED ENCRYPTION

CBA Mode (v1)

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Abstract. This paper presents the Code-Book Authentication mode (CBA), a submission to the CAESAR competition for authenticated encryption. CBA is a blockcipher mode of encryption that provides confidentiality and authenticity for plaintexts and authenticity for associated data. The proposed mode improves the OCB mode in the sense that, on average, it requires up to one less blockcipher call to encrypt and authenticate the input message. The improvement is achieved by merging the last two blocks into one block and also using the fact that most applications need relatively small or moderate amount of data to be encrypted, per key. The trade off is that the last block in the encryption algorithm loses its parallelizability and the decryption algorithm has to wait one block before processing the received block. The CBA mode possesses other attractive features of the OCB; it is one pass, uses one-key for encryption and authentication and employs a fixed-length arbitrary nonce.

Keywords: Authenticated Encryption, Blockcipher Mode, CBA, OCB.

1 Introduction

Authenticated encryption (AE) is a shared-key encryption scheme which provides confidentiality and authenticity simultaneously. A straightforward approach for constructing an authenticated-encryption scheme is to combine an encryption scheme and a message authentication code (MAC), appropriately. However, composition methods are slow, require at least two keys, and in practice are more likely to be misused. Therefore, designing a mode of operation for blockciphers has become a popular approach to achieve AE. In recent years, several modes have been proposed, such as CCM [9], GCM [6], EAX [1], IAPM [3], OCB [8,7,4] and CCFB [5].

This submission presents a new blockcipher-based mode of operation, called Code-Book Authentication (CBA). CBA inherits many features from the OCB, which in turn was a refinement of the IAPM. It is one-pass, uses a single key for both the encryption and authentication processes, and employs a fixed-length arbitrary nonce.

However, CBA improves the OCB mode in the sense that, on average, it requires up to one less blockcipher call to encrypt and authenticate the input message. The improvement is achieved by merging the last two blocks into one block and also using the fact that most applications need relatively small or moderate amount of data to be encrypted, per key. The trade off is that the last block in the encryption algorithm loses its parallelizability and the decryption algorithm has to wait one block before processing the received block.

2 Notation

A string is a finite sequence of symbols over alphabet $\{0, 1\}$. Let $\{0, 1\}^*$ denote the set of all strings and $A, B \in \{0, 1\}^*$. Let i be a non-negative integer. Let $\{0, 1\}^i$ denote the set of all strings of length i . The following notations and operations are used in the description of the CBA mode:

- AB : concatenation of the two strings A and B .
- 0^i : string of i 0s.
- $|A|$: bit-length of A .
- $\text{pad}_i(A) = \begin{cases} A10^{i-|A|-1} & \text{if } |A| < i \\ A & \text{if } |A| = i \end{cases}$.
- $\text{pad}(A) = \text{pad}_{128}(A)$
- $\text{MSB}_i(A)$: first i bits of A , where $i \leq |A|$.
- $\text{LSB}_i(A)$: last i bits of A , where $i \leq |A|$.
- $A \oplus B$: bitwise exclusive-or of two equal-length strings A and B .
- $\lceil x \rceil$: smallest integer not less than x .
- $A \ll i$: a string with the same bit-length as A , which is a left shift of A by i bits, where $i \leq |A|$ and the first i bits are discarded.
- $[i]_8$: the 8-bit string that encodes i as a binary number, where $i \in \{0, \dots, 255\}$.

3 Specification

3.1 Parameters

The CBA mode uses a blockcipher E (whose inverse is denoted by D), with n -bit blocksize and k -bit key, along with a ν -bit nonce.

Parameter space: CBA is parametrized with a tag-length τ and usage-capacity b , where $0 \leq \tau \leq n$ and $b \leq n/2 - 16$. By usage-capacity b we mean that CBA can be used to encrypt and authenticate at most 2^b message blocks, including associated data, per key. There is no secret message number; i.e., the secret message number is empty.

- From here on, we fix $n = 128$ and $\nu = 96$.
- All over the paper, we let $\ell = \min(n - 2b - 32, \tau)$.

Recommended parameter sets Our recommended parameters are as follows:

	E	k	τ	b
(1)	AES	128	32	16
(2)	AES	128	32	32
(3)	AES	128	64	16
(4)	AES	128	64	32
(5)	AES	128	64	48
(6)	AES	128	96	16
(7)	AES	128	96	32
(8)	AES	128	96	48
(9)	AES	192	64	32
(10)	AES	256	96	48

The Scheme The CBA mode consists of the algorithm ENC for the encryption and authentication process and the algorithm DEC for the decryption and verification process. These algorithms use H for authenticating the associated data, and F and F* for updating the offset values.

The encryption process takes a key $K \in \{0, 1\}^k$, a public message number (nonce) $N \in \{0, 1\}^\nu$, a message $M \in \{0, 1\}^*$ and an associated data $A \in \{0, 1\}^*$. The output is the ciphertext $C \in \{0, 1\}^*$, with the same size as the plaintext, plus τ extra bits to authenticate C . The decryption process takes a key, a ciphertext, and a nonce, and it returns either a plaintext or a special symbol \perp , indicating that the decrypted plaintext is invalid.

The algorithm H takes a key $K \in \{0, 1\}^k$ and the associated data A to compute the tag value $T_A = H(K, A)$. The value T_A will be used in the process of message encryption and authentication.

Figures 1-5 illustrate the functionality of the CBA encryption algorithm. In the figures, we show the offset values by Δ_i 's and Δ^* for clarity. The decryption algorithm is straightforward.

CBA Definition In the following, we provide the details of the CBA ENC and DEC algorithms and the three subroutines H, F and F*.

[assumes: $K \in \{0, 1\}^k$, $A \in \{0, 1\}^*$, $\ell = \min(n - 2b - 32, \tau)$]

function H(K, A)

$A_1 \cdots A_a \leftarrow A$ where $|A_i| = n$ for $1 \leq i \leq a - 1$, $|A_a| \leq n$

$S \leftarrow 0^n$

$L \leftarrow E_K([\tau]_s[b]_s 0^{n-16})$

$\Delta \leftarrow L$

for $i = 1$ **to** $a - 1$ **do**

$\Delta \leftarrow F(\Delta)$

$S \leftarrow S \oplus E_K(A_i \oplus \Delta)$

if $|A_a| < n$ **then**

$\Delta \leftarrow F^*(\Delta)$

else

$\Delta \leftarrow F(\Delta)$

$S \leftarrow S \oplus E_K(\text{pad}(A_a) \oplus \Delta)$

$T_A \leftarrow \text{MSB}_\tau(S)$

return T_A

[assumes: $\Delta \in \{0, 1\}^{128}$]

function F(Δ)

$(A, B) \leftarrow \Delta$ where $|A| = |B| = 64$

$(A, B) \leftarrow (B, (A \ll 1) \oplus \text{MSB}_1(A) \cdot 0^2 10^{26} 10^{24} 10^8 1 \oplus B)$

function F*(Δ)

$(A, B) \leftarrow \Delta$ where $|A| = |B| = 64$

$(A, B) \leftarrow (B, A \oplus (A \ll 1) \oplus \text{MSB}_1(A) \cdot 0^2 10^{26} 10^{24} 10^8 1 \oplus B)$

The details of the encryption and decryption algorithms are given below.

```

[assumes:  $E : \{0, 1\}^k \times \{0, 1\}^n \rightarrow \{0, 1\}^n$  is a blockcipher,
 $0 \leq \tau \leq n$ ,  $b \leq n/2 - 16$  and  $\ell = \min(n - 2b - 32, \tau)$ ,
 $K \in \{0, 1\}^k, N \in \{0, 1\}^\nu$ ,  $A, M \in \{0, 1\}^*$ .]
function ENC( $K, N, A, M$ )
   $T_A \leftarrow H(K, A)$ 
   $R \leftarrow E_K([\tau]_s[b]_s 0^{n-\nu-16} N)$ 
   $L \leftarrow E_K([\tau]_s[b]_s 0^{n-16})$ 
   $\Delta \leftarrow 1\text{MSB}_{n-\ell}(R) 0^{\ell-2} 1$ 
  if  $|M| \leq \ell$  then
     $C_0 \leftarrow M \oplus \text{LSB}_{|M|}(R)$ 
     $T \leftarrow T_A \oplus \text{pad}_\tau(C_0)$ 
     $\Delta \leftarrow F^*(\Delta)$ 
     $C_1 \leftarrow \text{MSB}_\tau(E_K(0^{n-\tau} T \oplus \Delta))$ 
    return  $C_0 C_1$ 
  else
     $M_0 M' \leftarrow M$  where  $|M_0| = \ell$ 
     $C_0 \leftarrow M_0 \oplus \text{LSB}_\ell(R)$ 
     $T \leftarrow T_A \oplus 0^{\tau-\ell} C_0$ 
     $M_1 \cdots M_m \leftarrow M'$  where  $|M_i| = n$  for  $1 \leq i \leq m-1$ ,  $1 \leq |M_m| \leq n$ 
     $S \leftarrow 0^n$ 
    for  $i = 1$  to  $m-2$  do
       $S \leftarrow S \oplus M_i$ 
       $\Delta \leftarrow F(\Delta)$ 
       $C_i \leftarrow E_K(M_i \oplus \Delta) \oplus \Delta$ 
     $S \leftarrow S \oplus M_{m-1}$ 
     $\Delta \leftarrow F(\Delta)$ 
     $\text{Temp} \leftarrow E_K(M_{m-1} \oplus \Delta)$ 
    if  $|M_m| \leq n - \tau$  then
       $C_{m-1} \leftarrow \text{MSB}_{|M_m|+\tau}(\text{Temp}) \oplus M_m T$ 
       $\Delta \leftarrow F^*(L) \oplus \Delta$ 
       $C_m \leftarrow S \oplus E_K(\text{pad}(C_{m-1}) \oplus \Delta)$ 
      return  $C_0 C_1 \cdots C_m$ 
    else
       $C_{m-1} \leftarrow \text{Temp} \oplus \Delta$ 
       $S \leftarrow S \oplus \text{pad}(M_m)$ 
       $\Delta \leftarrow F(\Delta)$ 
       $C_m \leftarrow M_m \oplus \text{MSB}_{|M_m|}(E_K(0^{n-\tau} T \oplus \Delta))$ 
       $\Delta \leftarrow F^*(\Delta)$ 
       $C_{m+1} \leftarrow \text{MSB}_\tau(E_K(S \oplus 0^{n-\tau} T \oplus \Delta))$ 
      return  $C_0 C_1 \cdots C_m C_{m+1}$ 

```

[assumes: $E : \{0, 1\}^k \times \{0, 1\}^n \rightarrow \{0, 1\}^n$ is a blockcipher with inverse D ,
 $0 \leq \tau \leq n$, $b \leq n/2 - 16$ and $\ell = \min(n - 2b - 32, \tau)$
 $K \in \{0, 1\}^k, N \in \{0, 1\}^\nu$, $A, C \in \{0, 1\}^*$.]

function DEC(K, N, A, C)

$T_A \leftarrow H(K, A)$

$R \leftarrow E_K([\tau]_8[b]_8 0^{n-\nu-16} N)$

$\Delta \leftarrow 1\text{MSB}_{n-\ell}(R) 0^{\ell-2} 1$

if $|C| \leq \ell + \tau$ **then**

$C_0 C_1 \leftarrow C$ where $|C_1| = \tau$

$M \leftarrow C_0 \oplus \text{LSB}_{|C_0|}(R)$

$T \leftarrow T_A \oplus \text{pad}_\tau(C_0)$

$\Delta \leftarrow F^*(\Delta)$

if $C_1 = \text{MSB}_\tau(E_K(0^{n-\tau} T \oplus \Delta))$ **then**

return M

else

return \perp

else

$C_0 C' \leftarrow C$ where $|C_0| = \ell$

$M_0 \leftarrow C_0 \oplus \text{LSB}_\ell(R)$

$T \leftarrow T_A \oplus 0^{\tau-\ell} C_0$

$C_1 \cdots C_m C'' \leftarrow C'$ where $|C_i| = n$ for $1 \leq i \leq m$, $n < |C''| \leq 2n$

$S \leftarrow 0^n$

for $i = 1$ **to** m **do**

$\Delta \leftarrow F(\Delta)$

$M_i \leftarrow D_K(C_i \oplus \Delta) \oplus \Delta$

$S \leftarrow S \oplus M_i$

if $|C''| > n + \tau$ **then**

$C_1'' C_2'' \leftarrow C''$ where $|C_2''| = n$

$\Delta \leftarrow F^*(L) \oplus F(\Delta)$

$M_1'' \leftarrow C_2'' \oplus S \oplus E_K(\text{pad}(C_1'') \oplus \Delta)$

$\Delta \leftarrow F^*(L) \oplus \Delta$

$\text{Temp} \leftarrow E_K(M_1'' \oplus \Delta)$

$M_2'' T' \leftarrow \text{MSB}_{|C_1''|}(\text{Temp}) \oplus C_1''$ where $|T'| = \tau$

if $T = T'$ **then**

return $M_0 M_1 \cdots M_m M_1'' M_2''$

else

return \perp

else

$C_1'' C_2'' \leftarrow C''$ where $|C_2''| = \tau$

$\Delta \leftarrow F(\Delta)$

$M'' \leftarrow C_1'' \oplus \text{MSB}_{|C_1''|}(E_K(0^{n-\tau} T \oplus \Delta))$

$S \leftarrow S \oplus \text{pad}(M'')$

$\Delta \leftarrow F^*(\Delta)$

if $C_2'' = \text{MSB}_\tau(E_K(S \oplus 0^{n-\tau} T \oplus \Delta))$ **then**

return $M_0 M_1 \cdots M_m M''$

else

return \perp

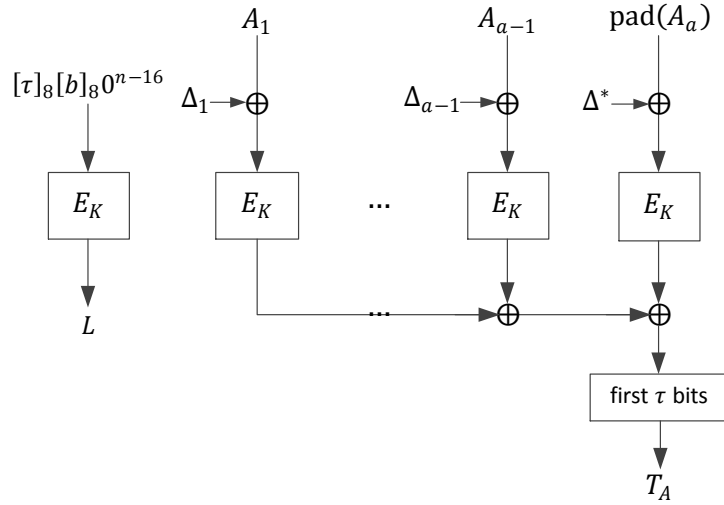


Fig. 1: **CBA Encryption-associated data processing.** Case $|A_a| < n$. In the figure, we have $\Delta_i = F(\Delta_{i-1})$ where $\Delta_0 = L$, and $\Delta^* = F^*(\Delta_{a-1})$.

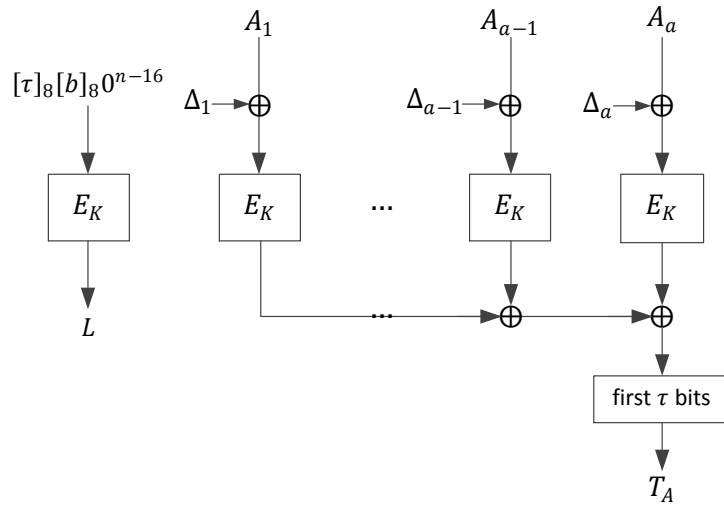


Fig. 2: **CBA Encryption-associated data processing.** Case $|A_a| = n$. In the figure, we have $\Delta_i = F(\Delta_{i-1})$ where $\Delta_0 = L$.

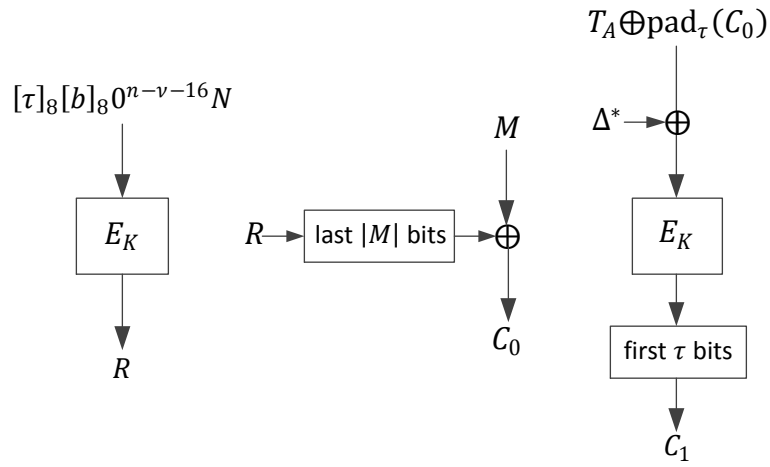


Fig. 3: **CBA Encryption—message processing.** Case $|M| \leq \ell$. In the figure, we have $\Delta^* = F^*(\Delta_0)$ where $\Delta_0 = 1\text{MSB}_{n-\ell}(R)0^{\ell-2}1$.

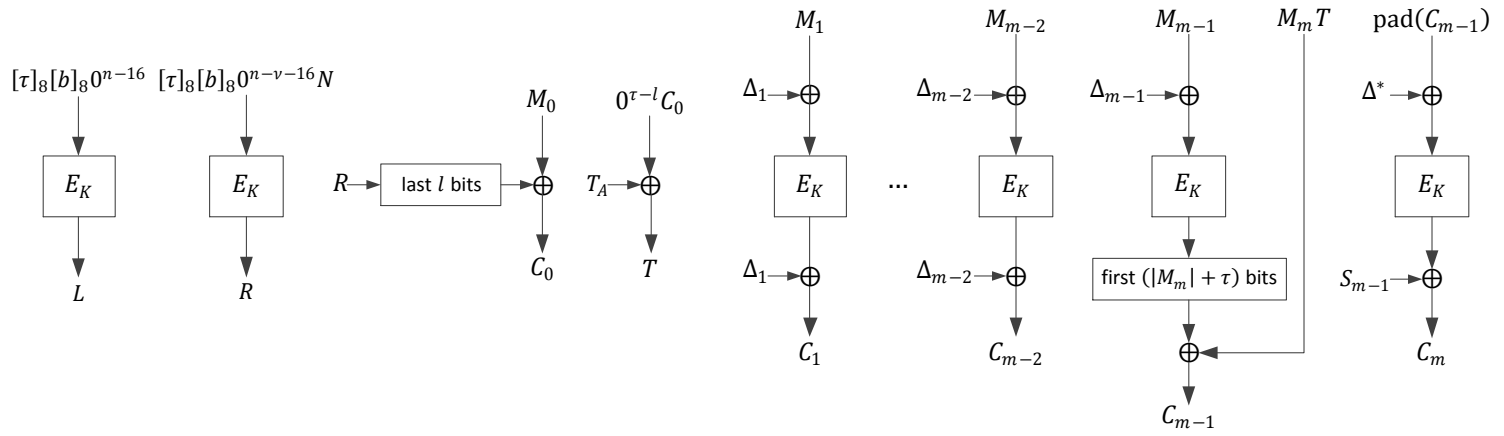


Fig. 4: **CBA Encryption—message processing.** Case $|M_m| \leq n - \tau$. In the figure, we have $\Delta_i = F(\Delta_{i-1})$ where $\Delta_0 = 1\text{MSB}_{n-l}(R)0^{\ell-2}1$, and $\Delta^* = F^*(L) \oplus \Delta_{m-1}$ and $S_{m-1} = M_1 \oplus \dots \oplus M_{m-1}$.

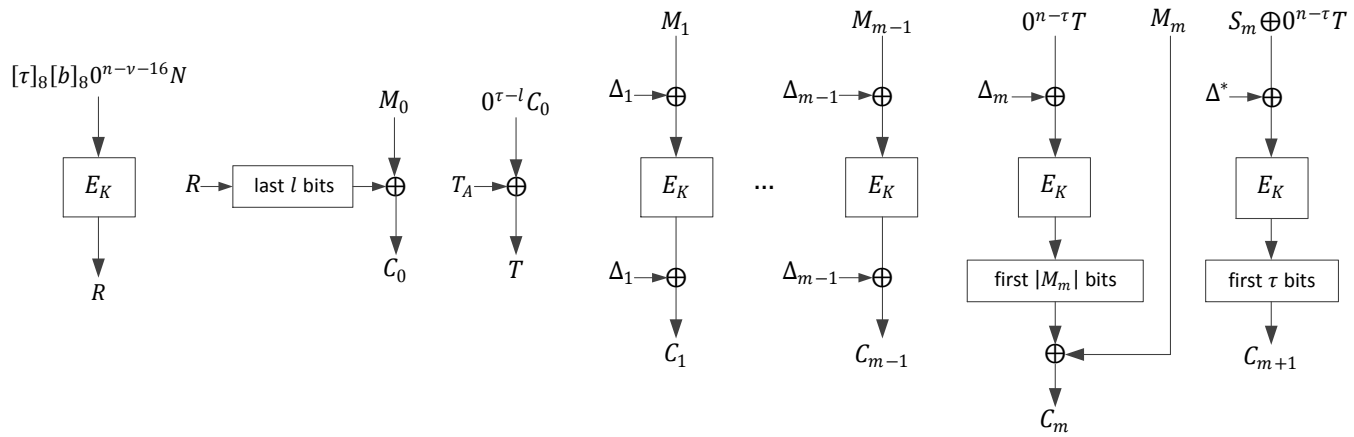


Fig. 5: **CBA Encryption—message processing.** Case $|M_m| > n - \tau$. In the figure, we have $\Delta_i = F(\Delta_{i-1})$ where $\Delta_0 = 1\text{MSB}_{n-l}(R)0^{\ell-2}1$, and $\Delta^* = F^*(\Delta_m)$ and $S = M_1 \oplus \dots \oplus M_{m-1} \oplus \text{pad}(M_m)$.

4 Security goals and analysis

CBA has been designed to support the strongest notions of security for both confidentiality and authenticity. This can be formalized using the standard indistinguishability games for confidentiality and unforgeability games for authenticity. However, the security of the CBA mode is not yet proved and is a work on progress.

The following requirements should be satisfied in order to use CBA securely:

1. Each key should be randomly generated.
2. Each key and nonce pair should not be used to encrypt more than one message.
3. If the decryption algorithm returns \perp , the decrypted plaintext and the wrong authentication tag should not be given as output.
4. For each key, the CBA should not be used to encrypt more than a total of 2^b message blocks including associated data.
5. The CBA message capacity parameter is required to satisfy $b \leq n/2 - 16$.

If the above requirements are satisfied, we have the following claims:

Claim 1. Claim 2. Confidentiality of CBA degrades as per $q^2 \times 2^{n-\ell}$, where q is the total number of blocks that the adversary acquires.

Claim 2. Authenticity of CBA degrades as per $q^2 \times 2^{n-\ell}$, where q is the total number of blocks that the adversary acquires.

The consequences of above claims is that the security guarantees of CBA reasonably holds as long as q is smaller than 2^b . However, security vanishes when q becomes as large as let say 2^{16+b} . Thus the user should never use a key to generate an amount of ciphertext that exceeds 2^b blocks.

5 Features

CBA inherits most of the desirable properties of OCB. However, it refines OCB in the sense that, on average, it requires up to one less blockcipher call for both encryption and decryption. Thus, CBA performs better specifically for short length messages. We specify the CBA features in the following:

- CBA protects the confidentiality of M and the authenticity of A , N , and M . It does this using, on average, $\lceil \frac{|A|}{n} \rceil + \lceil \frac{|M|}{n} \rceil + 1 + \frac{\tau - \ell}{n}$ blockcipher calls.
- For a given message, the CBA returns a ciphertext of minimal length.
- CBA requires a single blockcipher key for both encryption and authentication.
- It achieves AE using only a single pass over the message M .
- The nonce need not be random or secret.
- CBA is on-line: one does not need to know the length of the M or A to proceed with encryption, nor need one know the length of A or C to proceed with decryption. However, the decryption algorithm has to wait one block before processing the received block.

- If the associated data is fixed during a session, then it can be pre-processed so that there is effectively no per-message cost to providing the authenticity of associated data.
- OCB is parallelizable: the bulk of its blockcipher calls can be performed simultaneously, except for the last block of the decryption process.

Recommended parameters: Since we are using ASE, as the underlying blockcipher, we have three parameters to take into account.

- **key-length.** AES supports 128, 192 and 256-bit keys. Our parameter sets consider all key-lengths with an emphasize on the 128-bit key, because it is believed to be enough for many applications. However, other key-lengths maybe chosen if higher levels of security are required.
- **tag-length.** We consider different tag lengths of 32, 64 and 96, which are appropriate for different applications.
- **usage-capacity.** To increase the efficiency, we suggest different settings for the maximum number of allowed message and associated data blocks. We consider three categories, low, moderate and high amount of data, corresponding to at most 2^{16} , 2^{32} and 2^{48} blocks of data.

In comparison with AES-GCM, we expect that the CBA is at least two times faster than the AES-GCM. Moreover, CBA is more flexible in terms of the parameters' selection.

6 Design rationale

CBA is designed such that it requires up to one less blockcipher call, compared to the OCB mode, when the nonce is random. The improvement is achieved by two contribution to the OCB. The first is that if the maximum number of message blocks is to be lower than 2^b , then ℓ bits of R can be used to encrypt ℓ bits of the message in a stream cipher fashion, and yet preserve the security. Recall that R is an encryption of a nonce-dependent block. This means that the message length, needed to be encrypted, is decreased by ℓ bits. Note that this decrease does not necessarily result in one less blockcipher call. In fact, on average, we need ℓ/n less blockcipher calls. This improvement is particularly important for very short-length messages, which is the case in many applications.

The second improvement is originated from the fact that OCB truncates more than n bits in the encryption process when $|M_m| + \tau \leq n$. Thus, in this case, it is possible to make an improvement by merging the last two blocks and, therefore, omit one blockcipher call. Assuming that the length of the last message block is a uniform variable between 1 and n , we need, on average, $(n - \tau)/n$ less blockcipher calls.

Let g denote the gain of the CBA mode with respect to the OCB, i.e., the average number of blockcipher call reductions. We have:

$$g = \frac{n - \tau}{n} + \frac{\ell}{n} = 1 - \frac{\tau - \ell}{n} .$$

Since $0 \leq \ell \leq \tau$, we have:

$$1 - \frac{\tau}{n} \leq g \leq 1.$$

This shows that CBA saves a number of blockcipher calls between $1 - \tau/n$ and 1. To evaluate the improvement of the CBA with respect to the OCB, in the case of random nonce, the CBA gain for the recommended parameter sets of the Section 3 is provided in the following:

parameter set	1	2	3	4	5	6	7	8	9	10
gain g	1	1	1	3/4	1/2	3/4	1/2	1/4	3/4	1/4

Moreover, we suggest a simpler offset generation, compared to the OCB. The idea of the *stretch-then-shift* hash, propose in [4] is also applicable to the CBA for further reduction of, on average, 0.98 blockcipher calls in case that the nonce is counter. But for CBA, we seek for solutions, which are efficient for various applications and platforms, without increasing in the internal state or going for the table look-up. There are many approaches for updating the offset strings to guarantee the maximum period for them [2]. However, we mention that since the message size is at most 2^{48} bytes, it is of no use for the offsets to have the maximum period of 2^{128} . Therefore, we suggest an updating function which provides the period of 2^{64} . The function is $(A, B) \leftarrow (B, 2 \cdot A \oplus B)$, where A and B are 64-bit strings and the multiplication is done in $\text{GF}(2^{64})$. We found that this function performs reasonably well on 32, 64 or 128-bit processors.

The last point is to prevent the algorithm from misusing with different lengths of tag or usage capacity. For this, we pad the tag-length and usage capacity to the 96-bit nonce, so that their integrity will be protected along with nonce.

The designers have not hidden any weaknesses in this cipher. CBA is a refinement over OCB, which has received years of in-depth analysis in the cryptography society and enjoys provable security.

7 Intellectual property

The authors have largely been influenced by the OCB mode, which in turn was a refinement of the IAPM mode. There are US patents 7046802, 7200227, 7949129, and 8321675 on OCB. In addition, there are patents 6963976, 6973187, 7093126, and 8107620 on IAPM.

The authors are not aware of any other patents related to the CBA mode. If any of this information changes, the submitters will promptly (and within at most one month) announce these changes on the crypto-competitions mailing list.

8 Consent

The submitter hereby consents to all decisions of the CAESAR selection committee regarding the selection or non-selection of this submission as a second-round candidate,

a third-round candidate, a finalist, a member of the final portfolio, or any other designation provided by the committee. The submitter understands that the committee will not comment on the algorithms, except that for each selected algorithm the committee will simply cite the previously published analyses that led to the selection of the algorithm. The submitter understands that the selection of some algorithms is not a negative comment regarding other algorithms, and that an excellent algorithm might fail to be selected simply because not enough analysis was available at the time of the committee decision. The submitter acknowledges that the committee decisions reflect the collective expert judgments of the committee members and are not subject to appeal. The submitter understands that if he disagrees with published analyses then he is expected to promptly and publicly respond to those analyses, not to wait for subsequent committee decisions. The submitter understands that this statement is required as a condition of consideration of this submission by the CAESAR selection committee.

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