

Cryptanalysis of the EPBC authenticated encryption mode

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Agenda

- Introduction
- Simultaneous confidentiality and integrity
- Attacking EPBC
- Completing the attack

Simultaneous encryption and integrity

- Both confidentiality and integrity are often required.
- Indeed, encrypting without integrity protection is now known to be dangerous (variety of attacks).
- One simple way to provide both services is the *encrypt-then-MAC* model where we encrypt the message and then compute a MAC, using two distinct keys.
- This is very effective (if used with care), but each block of data is processed twice.

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***Add-redundancy-and-encrypt* model**

- To avoid the extra work of double processing, one widely discussed alternative to *encrypt-then-MAC* is the *add-redundancy-and-encrypt* model.
- Here, predictable redundancy is added to the plaintext (e.g. a fixed block at the end) prior to encryption, and the receiver checks for the presence of the redundancy after decryption.

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Shortcomings of model

- The encryption method needs to be chosen carefully (e.g., a stream cipher is bad news)!
- So does the method of adding redundancy.
 - Suppose the 'fixed block at the end' method is used.
 - Obvious dangers arise if the fixed block arises by chance in the middle of the plaintext!
- Despite these dangers, the technique has often been advocated.

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EPBC mode

- One major problem with the add-redundancy-then-encrypt approach is that commonly used encryption modes are not appropriate.
- That is, if a mode like CBC is used, then relatively simple forgery attacks are possible (as we show).
- We consider a mode specially designed for use with add-redundancy-then-encrypt, namely EPBC, and show that this mode too is subject to forgery attacks.

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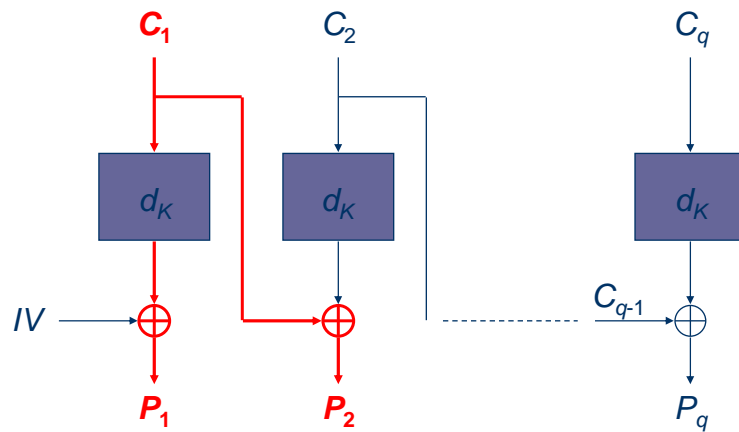
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CBC mode = no good!

- Having decided to use *add-redundancy-and-encrypt*, the encryption method needs to be chosen.
- It is not hard to see that CBC mode is completely inappropriate.
- This is because ciphertext errors only propagate in a very limited way.
- That is, changing ciphertext block C_i only affects P_i and P_{i+1} .

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CBC decryption – error propagation



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EPBC mode

- EPBC (Efficient error-Propagating Block Chaining) was proposed by Zúquete and Guedes in 1997.
- It is a mode of operation in which ciphertext errors **propagate in an unlimited way**.
- Designed as an improvement of a mode called IOBC (Recacha, 1996).
- Uses an n -bit block cipher where n is even (assume $n=2m$).

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EPBC mode operation

- Uses two n -bit secret IVs: F_0, G_0 .
 - To encrypt plaintext P_1, P_2, \dots, P_t :
 - perform the following for $i = 1, 2, \dots, t$:
 - $G_i = P_i \oplus F_{i-1}$
 - $F_i = e_K(G_i)$
 - $C_i = F_i \oplus g(G_{i-1})$ [except for $i=1$: $C_1 = F_1 \oplus G_0$]
- where \oplus denotes bit-wise exclusive or, and g is a function mapping an n -bit block to an n -bit block.

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The function g

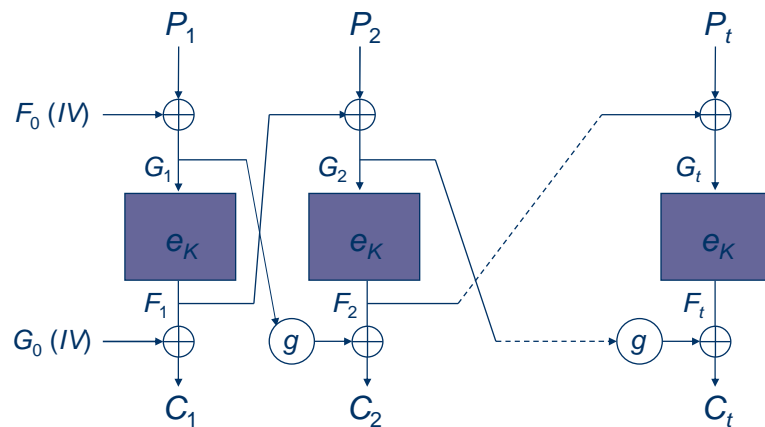
- Suppose X is an n -bit block, where $X = L || R$, and L and R are m -bit blocks.
- Then:

$$g(X) = (L \vee \sim R) || (L \wedge \sim R)$$

where \vee denotes bit-wise inclusive or, \wedge denotes bit-wise logical and, and \sim denotes logical negation (changing every zero to one and vice versa).
- Note that g is not one-to-one. [This is the only change between OPBC to EPBC: IOBC uses a one-to-one function g].

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EPBC encryption (also IOBC)



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An observation

- To launch a forgery attack, it would appear to be necessary to have knowledge of the 'internal' values of F_i and G_i .
- However, since these values are never transmitted (and F_0 and G_0 are assumed to be secret), attacking this mode would appear to be difficult.
- Moreover, g is deliberately chosen to be not one-to-one to thwart known-plaintext based forgery attacks which apply to long messages encrypted using IOBC.

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Objective of attack

- We assume that the *add-redundancy-and-encrypt* model is being used with EPBC.
- We also assume that the method of adding redundancy is to add a fixed block to the end of the message.
- The objective is to take a valid ciphertext and use this to construct another 'forged' ciphertext which will have the correct redundancy when decrypted.

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Observation regarding g

- Suppose $g(X) = L' || R'$, where $L' = (\lambda'_1, \lambda'_2, \dots, \lambda'_m)$ and $R' = (r'_1, r'_2, \dots, r'_m)$.
- Then, for every i , if $\lambda'_i = 0$, then $r'_i = 0$.
- To see this, suppose $X = L || R$, where $L = (\lambda_1, \lambda_2, \dots, \lambda_m)$ and $R = (r_1, r_2, \dots, r_m)$.
- If $\lambda'_i = 0$ for some i , then, since $\lambda'_i = \lambda_i \vee \sim r_i$, we know immediately that $\lambda_i = 0$ and $r_i = 1$. Hence $r'_i = \lambda_i \wedge \sim r_i = 0$.
- That is, pairs (λ'_i, r'_i) can never equal $(0, 1)$.

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A more general observation

- Using the same notation, if (λ_i, r_i) is in the set A , then (λ'_i, r'_i) must be a member of the set B , where the possibilities for the sets A and B are now given.
- Unless $|A| = 1$, given a random set A of a certain size, the expected size of B is always smaller than $|A|$.

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The sets A and B

A (set of input pairs)	B (set of output pairs)
$\{00, 01, 10, 11\}$	$\{00, 10, 11\}$
$\{01, 10, 11\}$ $\{00, 10, 11\}$ $\{00, 01, 11\}$ $\{00, 01, 10\}$	$\{00, 10, 11\}$ $\{10, 11\}$ $\{00, 10\}$ $\{00, 10, 11\}$
$\{10, 11\}$ $\{01, 11\}$ $\{01, 10\}$ $\{00, 11\}$ $\{00, 10\}$ $\{00, 01\}$	$\{10, 11\}$ $\{01, 11\}$ $\{00, 11\}$ $\{10\}$ $\{10, 11\}$ $\{00, 10\}$
$\{11\}$ $\{10\}$ $\{01\}$ $\{00\}$	$\{10\}$ $\{11\}$ $\{00\}$ $\{10\}$

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Using the observation I

- Our objective is to use knowledge of known plaintext/ciphertext pairs (P_i, C_i) to learn pairs (F_i, G_i) .
- Suppose we know s consecutive pairs, i.e. we know:

$$(P_j, C_j), (P_{j+1}, C_{j+1}), \dots, (P_{j+s-1}, C_{j+s-1}).$$

where we suppose $j > 1$.

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Using the observation II

- We know:

$$C_j = F_j \oplus g(G_{j-1})$$

- We also know that if $g(G_{j-1}) = L' || R'$, where $L' = (\lambda'_1, \lambda'_2, \dots, \lambda'_m)$ and $R' = (r'_1, r'_2, \dots, r'_m)$, then (λ'_i, r'_i) can never equal $(0, 1)$ for any i .
- Hence, knowledge of C_j gives some knowledge about F_j .
- Specifically we know that certain bit pairs cannot occur in F_j , where each bit pair contains a bit from the left half and the corresponding bit from the right half.

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Using the observation III

- We also know:

$$G_{j+1} = P_{j+1} \oplus F_j$$

- Hence knowledge of forbidden bit pairs in F_j , combined with knowledge of P_{j+1} , gives us knowledge of forbidden bit pairs in G_{j+1} .
- This means we know of even more (potentially) forbidden bit pairs in $g(G_{j+1})$.

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Using the observation IV

- Since we know:

$$C_{j+2} = F_{j+2} \oplus g(G_{j+1})$$

and we know C_{j+2} , this gives us even more forbidden bit pairs in F_{j+2} , and so on.

- For sufficiently large w , we hope that we know F_{j+2w} for certain.
- This immediately gives complete knowledge of G_{j+2w+1} , using knowledge of P_{j+2w+1} .
- I.e. we have complete knowledge of all F_{j+2w} and G_{j+2w+1} for all sufficiently large w .

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A side remark

- In our discussion we have not used all the available knowledge.
- In fact we only use knowledge of $C_j, C_{j+2}, C_{j+4}, \dots$ and $P_{j+1}, P_{j+3}, P_{j+5}, \dots$
- We also only learn information about $F_j, F_{j+2}, F_{j+4}, \dots$ and $G_{j+1}, G_{j+3}, G_{j+5}, \dots$
- However, we now repeat the process starting with F_{j+1} , using all the rest of the information we have.

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How big is sufficiently large?

- Consider any pair of bit positions: $(i, i+m)$.
- Returning to our previous argument, we know that $g(G_{j-1})$ cannot have $(0, 1)$ in these two bit positions.
- Hence, we know that the pair of bit positions in $F_j = C_j \oplus g(G_{j-1})$ can only take three of the possible four values.
- Precisely which three possibilities will depend on C_j , which should look random.

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How big II?

- Hence we know that the two bit positions in G_{j+1} can only take three of the possible four values.
- The possibilities for the two bit positions in $g(G_{j+1})$ will depend on which three pairs are possible (using our table for the sets A and B).
- That is, there is a 50% chance that we will know that the two bit positions in $g(G_{j+1})$ have only two possible values, and a 50% chance that there are 3 possible values.

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How big III?

- Using standard probabilistic arguments for stochastic processes, the probability that there will only be a single possibility for the bit pair after v iterations of the above process is equal to the top right entry in the v th power of the following 4 by 4 matrix:

$$\begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 1/2 & 1/2 & 0 \\ 0 & 0 & 5/6 & 1/6 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

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How big IV?

- For $v = 10$, this is 0.710.
- For $v = 20$, this is 0.953.
- That is, after 20 iterations, i.e., if we know 40 consecutive plaintext/ciphertext pairs, we will know for certain around 95% of the bit pairs.
- I.e., if $m=64$, we will know for certain around 120 of the 128 bits.
- There will only be a small number of possibilities for the other bit pairs.

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What else needs to be done?

- Once we know some values of F_i and G_i , we need to use these values to construct a forgery.
- This seems likely to be straightforward, although the details have yet to be worked out (this is work in progress!).
- Any thoughts?

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***Encrypt-then-MAC* model**

- There seem to be too many problems with the *add-redundancy-and-encrypt* model to be able to recommend it.
- *Encrypt-then-MAC* seems much safer, and is provably secure.
- However even this approach needs to be implemented with care.

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Combined encryption/integrity modes

- There are alternatives to *encrypt-then-MAC*.
- Of particular interest is the Offset CodeBook (OCB) mode, due to Rogaway, Bellare, Black and Krovetz (2001), and a revised OCB v2.0 more recently released.
- These block-cipher-based modes only require each plaintext block to be processed once, and have a complexity-theoretic 'proof of security' (based on the assumption that the block cipher is a pseudo-random permutation family).

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Standards

- OCB v2.0, together with other carefully specified ways of combining encryption and MACing, are in the process of being standardised.
- One such standard will be ISO/IEC 19772 (currently at Committee Draft stage).

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Further reading

- For more information on cryptography standards (including MACs, modes, etc.) see:
 - A. Dent and C. Mitchell, *User's guide to cryptography and standards*. Artech House, 2005.
- The standard reference for much of crypto (even though it is now 8 years old) remains:
 - A. Menezes, P. van Oorschot and S. Vanstone, *Handbook of Applied Cryptography*, CRC Press, 1997.

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