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History of message integrity techniques

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1

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Contents of talk

2

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Scope of talk

- We are concerned in this talk with message integrity techniques based on shared secret keys, i.e. the class of symmetric cryptosystems known as **MACs**.
- Digital signatures (examples of asymmetric cryptography) can also be used to provide message integrity, but we do not discuss them.

3

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Purpose of MACs

- Used to protect integrity and guarantee origin of data strings.
- Sender and verifier share a secret key (of k bits).
- Sender inputs data and key to MAC algorithm – output is MAC (short string of bits) which is sent/stored with data.
- Verifier recomputes MAC using received message and secret key and compares.

4

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CBC-MACs

- A CBC-MAC is a particular (very popular) type of MAC. CBC-MACs are the main focus of this talk.
- Computed using a block cipher in CBC (Cipher Block Chaining) mode.
- Write $e_K(P)$ for block cipher encryption of block P (n bits) using secret key K (k bits).
- Similarly, write $d_K(C)$ for block cipher decryption of block C using key K.

5

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Simple CBC-MAC operation

- Divide and **pad** data to be MACed into n-bit blocks D_1, D_2, …, D_q (n is block length of block cipher, e.g. n = 64 for DES).
- The MAC is computed by:
  - put $H_1 = e_K(D_1)$,
  - for i = 2, 3, ..., q: put $H_i = e_K(D_i \oplus H_{i-1})$.
- H_q is then truncated to m bits to give the MAC.

6

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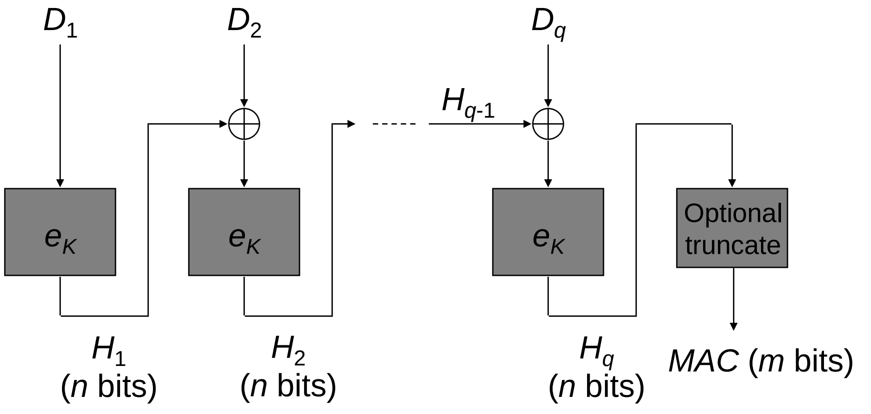
Simple CBC-MAC calculation



7

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Background

- Idea dates (at least) back to 1970s.
- Simple CBC-MACs have been used since that time, most widely with DES and (more recently) triple DES.
- First appeared in a standard in 1980.
- Padding method needed – originally done simply by adding the minimum number of zeros necessary.

8

Attack types

- There are two main types of attack on a MAC scheme:
  - **Forgery attacks**, in which an attacker is able to generate a new valid (message, MAC) pair;
  - **Key recovery attacks**, where an attacker can learn the secret key in use (of course, a successful key recovery attack enables arbitrary numbers of forgeries).
- There are also variants of the basic attacks, including **chosen message forgery attacks**.

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Contents of talk

1. CBC-MACs
2. **Standardised CBC-MACs**
3. EMAC and ARMAC
4. New CBC-MAC schemes
5. RMAC
6. The XCBC family
7. Other schemes
8. Conclusions

Evolution of CBC-MACs

- The Simple CBC-MAC (SMAC) was the first used MAC scheme, and is still in use today.
- SMACs are provably secure if the message length is fixed.
- However, there are problems both with the method used to generate the MAC and also with the padding method if message lengths are variable.

Enhanced CBC-MAC operation

- Divide and pad data to be MACed into n-bit blocks $D_1, D_2, \ldots, D_q$ (n is block length of block cipher, e.g. n = 64 for DES).
- The MAC is computed by:
  - put $H_1 = e_K(D_1)$,
  - for $i = 2, 3, \ldots, q$: put $H_i = e_K(D_i \oplus H_{i-1})$.
- H_q **is then subject to an 'optional process'** and truncated to m bits to give the MAC.

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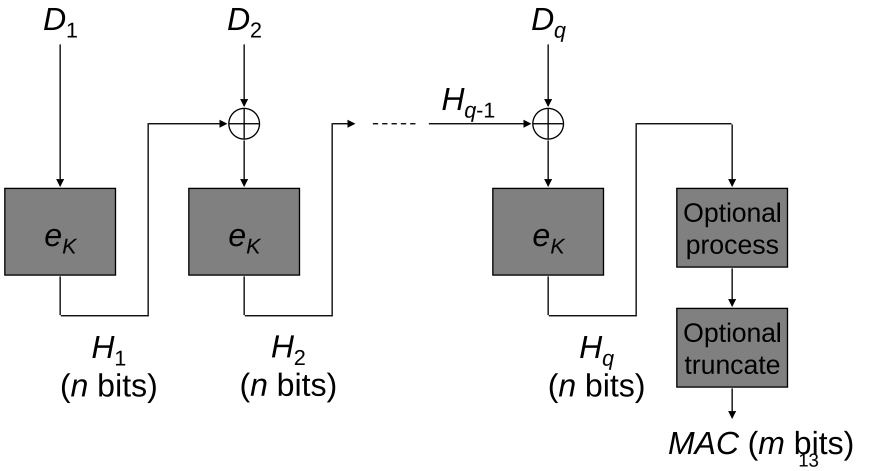
CBC-MAC calculation



13

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Padding

- Three well known padding methods:
  - Method 1: add minimum no. of zeros to make a whole number of blocks.
  - Method 2: add single one followed by zeros to make a whole number of blocks.
  - Method 3: right-pad with zeros as necessary. Left-pad with extra *n*-bit block containing binary representation of bit-length of unpadded string.
- Padding not sent with MACed message.

14

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Trailing zeros forgeries

- Padding Method 1 allows attacker to add or delete trailing zeros from a message without changing the MAC. A forgery attack.
- Arises from fact that Padding Method 1 is not a one-to-one function, i.e. up to *n* unpadded messages map to the same padded message.
- Motive for introduction of Method 2.

15

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Need for optional process

- Suppose a CBC-MAC is computed with no optional process and no truncation (SMAC).
- Suppose we have the MACs for two one-block messages:

  $\mathrm{MAC}_1 = e_K(D_1)$, $\mathrm{MAC}_2 = e_K(D_2)$.
- Then MAC_2 is a valid MAC on the two block message: $D_1 \,||\, D_2 \oplus \mathrm{MAC}_1$.
- Need to add optional process (or padding method 3) to avoid this ‘cut and paste’ Forgery attack.

16

Contents of talk

Optional processes

- Two well-known optional processes:
  - choose a key K_1 and compute:

    $H_q'' = e_K(d_{K_1}(H_q))$,
  - choose a key K_1 and compute:

    $H_q' = e_{K_1}(H_q)$.
- First method results in ANSI Retail MAC (ARMAC) when block cipher = DES
- Second method often called EMAC.

Standard CBC-MACs (1999)

- ISO/IEC standard for CBC-MACs (ISO/IEC 9797-1: 1999) contains 6 schemes.
- First three are as follows:
  – Alg. 1 = CBC-MAC with no optional process (SMAC).
  – Alg. 2 = CBC-MAC with optional process as single extra encryption (EMAC).
  – Alg. 3 = CBC-MAC with optional process as extra decryption and encryption (i.e., triple encrypt last block) (ARMAC).

EMAC security

- EMAC has a proof of security (Petrank & Rackoff, 2000).
- For block ciphers with large enough n and k (128 or more), EMAC is sound choice – with padding method 2 or 3.
- For block ciphers with small k (e.g. DES: k=56), EMAC insecure, because of simple meet-in-the-middle key recovery attack.
- Attack complexity: $O(2^k)$ encryptions with 1 known MAC.

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ARMAC security

- Problems with EMAC (and SMAC), combined with desire to use DES, motivates design of ARMAC.
- ARMAC seems much more resistant to key recovery attacks than EMAC (no proof however).
- Key recovery attack either requires triple DES break (2^k encryptions + 2^k storage) or large number ($2^{n/2}$) of known MACs combined with single DES break (2^k encryptions).

21

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Forgery attacks

- Both EMAC and ARMAC are subject to possible forgery attacks if the attacker has access to $2^{n/2}$ (message, MAC) pairs.
- Relies on the fact that it is likely that two of these pairs will have the same MAC.
- This will arise because of a 'birthday probability' internal collision.
- A pair of messages with the same MAC can then be used to construct forgeries.

22

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Contents of talk

1. CBC-MACs
2. Standardised CBC-MACs
3. EMAC and ARMAC
4. **New CBC-MAC schemes**
5. RMAC
6. The XCBC family
7. Other schemes
8. Conclusions

23

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Rationale

- The standardisation of a block cipher (AES) with larger n and k, means that it seems appropriate to re-examine ways in which we use block ciphers.
- Modes of operation and commonly used CBC-MAC schemes are quite ‘old’ designs.
- Can we do better?

24

New standards

- NIST has recently produced three new ‘modes’ standards for AES.
  A. Encryption modes standard (NIST Special Publication: SP800-38A, December 2001).
  B. CBC-MAC standard (SP800-38B, May 2005).
  C. Combined encryption + integrity mode (SP800-38C, May 2004) – contains CCM.
- NIST activity mirrored in ISO, where:
  A. ISO/IEC 10116 (encryption modes) new version just completed,
  B. ISO/IEC 9797-1 (CBC-MACs) currently being revised, and
  C. ISO/IEC 19772 (Authenticated encryption) being developed.

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Candidate schemes

- A number of candidate CBC-MAC schemes were proposed for inclusion in SP800-38B, including:
  – RMAC (Jaulmes, Joux and Valette, 2002),
  – XCBC (Black and Rogaway, 2000), and
  – TMAC and OMAC (Iwata and Kurosawa, 2003).

Contents of talk

1. CBC-MACs
2. Standardised CBC-MACs
3. EMAC and ARMAC
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5. **RMAC**
6. The XCBC family
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8. Conclusions

RMAC

- RMAC operates as follows.
- Two block cipher keys required (K, K_1).
- To generate a MAC first generate a random salt R (of k bits).
- Then, using the model previously described, RMAC involves the optional process:

$$H_q' = e_{K_1 \oplus R}(H_q).$$

Rationale of RMAC

- Typically, a CBC-MAC scheme will be subject to forgery attacks requiring $O(2^{n/2})$ known/chosen MACs (based on 'birthday paradox' probability).
- For 'short block' block ciphers (e.g. 3DES, IDEA, … with n = 64) this is sometimes a little 'close' to what is possible.
- RMAC objective is to offer greater resistance to 'birthday' forgery attacks.

The 2002 draft of SP800-38B

- RMAC was included in the first draft of NIST special publication 800-38B (published in November 2002).
- At that time RMAC was clearly the leading candidate for standardisation.

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Reaction to draft SP800-38B

- The release of the 2002 draft of NIST SP 800-38B provoked a large number of negative comments.
- The result was that RMAC was no longer seriously considered for NIST adoption.

31

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A simple observation

- Suppose know one RMAC (*M* say) for data *D* (using salt *R*, say).
- Request another MAC (*M′* say) for the same data *D* (uses salt *R′* say).
- Then immediately know that:

  $d_{K_1 \oplus R}(M) = d_{K_1 \oplus R'}(M')$.
- Enables exhaustive search for K_1 with complexity 2^k (and just 2 known MACs).
- This contradicts claims in the 2002 draft of SP 800-38B.

32

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Some attacks on RMAC

- In (Knudsen & Mitchell, 2005) a series of *partial key recovery* attacks on RMAC are presented.
- Enable one of the two RMAC keys (K_1) to be recovered with much less than 2^k work.
- Once K_1 is known, very simple forgery attacks become possible (based on ‘cut and paste’ attack).

33

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Contents of talk

34

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XCBC

- XCBC, another CBC-MAC scheme, was proposed by Black & Rogaway in 2000.
- Objective was to define a provably secure CBC-MAC which minimises number of block cipher encryptions/decryptions.
- Address fact that EMAC + pad method 2 can involve 2 'extra' encryptions by comparison with SMAC + padding method 1.

35

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XCBC operation I

- XCBC does not quite fit the general CBC-MAC model presented earlier.
- Use padding method 2 if data string needs padding; otherwise do not pad.
- Avoid ambiguity problems by computing MAC differently depending on whether or not padding was performed.
- Three keys: K, K_1 and K_2 (K has k bits, & K_1, K_2 have n bits).

36

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XCBC operation II

- If no padding then exor K_1 with D_q (last data block).
- If padding used then exor K_2 with D_q.
- Then compute SMAC on (modified) data using key K.

37

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XCBC properties

- Same number of encryptions as SMAC with padding method 1, yet forgery problems removed.
- Proof of security exists.
- Hence optimally efficient with respect to block cipher operations, BUT largish key (384 bits for AES).

38

TMAC

- To reduce key size, Kurosawa and Iwata (2003) proposed TMAC (T for 'two key') using keys K (of k bits) and K' of n bits.
- Derive K_1 and K_2 from K' by putting $K_2 = K'$ and $K_1 = u.K'$ where multiplication takes place in GF(2^n).
- Compute MAC as for XCBC.
- TMAC still has a proof of security.

OMAC

- Iwata and Kurosawa (2003) proposed OMAC (O for 'one-key') using just one key K (of k bits).
- Derive K' from K by setting $K' = e_K(0^n)$.
- Then derive K_1 and K_2 from K' as for TMAC.
- Finally, compute MAC as for XCBC.
- OMAC again has a proof of security.

NIST standardisation

- In May 2005 NIST published the final version of SP 800-38B.
- This standardises OMAC (which, rather confusingly, NIST calls CMAC).

Partial key recovery attack on TMAC

- Sung, Hong & Lee (2003) described an attack against TMAC which allows recovery of K' given $O(2^{n/2})$ known/chosen MACs and trivial computation (no key search).
- Recovering K still requires 2^k work, and proof of security not challenged.
- However, knowing K' does make very trivial forgeries possible.

OMAC attacks

- The TMAC attack works against OMAC, as does a further (different) attack, both allowing recovery of *K′* given $O(2^{n/2})$ known/chosen MACs.
- As Iwata has pointed out, (and depending on the definition of the term) this is no longer a partial key recovery attack, since *K′* is not part of the key (but is derived from it) – unlike in TMAC.
- Nevertheless, recovery of *K′* would allow very trivial forgeries.

What does it mean?

- These attacks do not contradict proofs of security for OMAC and TMAC.
- None of the proofs say anything about security once an attacker has $O(2^{n/2})$ known MACs.
- However, it is arguable that one should still be concerned about what happens at the ‘boundaries’ of the security proof.
- OMAC (and TMAC) are clearly weaker than EMAC at the ‘proof boundary’, since OMAC (and TMAC) fail catastrophically to trivial forgery attacks.

Modified EMAC I

- We also note that there is a modified version of EMAC which is almost as efficient as OMAC.
- In EMAC the final message block is encrypted twice, once with K and then with a second key K'.
- This can be replaced by a single encryption using K'.

Modified EMAC II

- This is still provably secure.
- It requires the same number of encryption operations as OMAC unless the message is a multiple of the block length (in which case the padding means that one extra encryption is needed).
- Included in the draft revised version of ISO/IEC 9797-1, along with OMAC, EMAC, ARMAC, SMAC (and a modified version of ARMAC called MacDES).

Contents of talk

Hash-based MACs

- We have considered only CBC-MACs.
- There are other ways of building MACs.
- With development of credible hash-functions, in 1990s HMAC (a MAC derived from a hash-function) emerged and became popular.
- Note that hashing a concatenation of a key and a message is NOT a good way to generate a MAC – message extension forgeries may be possible.

Novel MAC schemes

- More recently, a new family of MAC functions has emerged with apparently very desirable properties.
- These are based on a family of functions called *universal hash-functions*.
- A random nonce is needed, which must be different for every message for which a MAC is computed.
- As long as nonces are generated correctly, the schemes are provably secure and also highly efficient.
- Being standardised in ISO/IEC 9797-3.

Contents of talk

Where next?

- The main choice right now (for users of CBC-MACs) would appear to be between EMAC and OMAC.
- Both have similar provable security properties.
- OMAC is slightly more efficient.
- However EMAC appears stronger just outside envelope of security proof.
- This may be significant for n=64 case, where $2^{n/2}$ is a realisable number of MAC computations.