On the (In)Security of IPsec in MAC-then-Encrypt Configurations

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Outline

1 Motivation

2 Security of MAC-then-Encrypt in IPsec
- Preliminaries
- Using an ESP Trailer Oracle to Recover Plaintext
- An Oracle Based on IP Fragmentation

3 Concluding Remarks

IPsec

- IPsec is a suite of protocols that provide security at the IP layer.
- Three main protocols – AH, ESP, IKE that can be combined in various ways, giving higher configurability.
- Encryption is provided by ESP, normally using a block cipher in CBC mode.
- Data origin authentication can be provided either by AH or ESP.
- Keys can be set manually or automatically through IKE.

Configuring IPsec

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- An admin who wants to use IPsec to ensure the confidentiality of network traffic, has to make a number of choices:
  - Encryption-only, Encrypt-then-MAC, MAC-then-encrypt.
  - Each of AH or ESP can be operated in Transport or Tunnel mode.
  - Is replay protection necessary to achieve confidentiality?
  - Should AH or ESP be used for authentication.
- The RFCs provide very little guidance on this matter.
- There exists no systematic security analysis of the resulting configurations.

Why Use MAC-then-Encrypt?

- SSL uses MAC-then-encrypt, and is widely perceived to be secure.
- A popular textbook by Stallings discusses several benefits that accrue from MAC-then-encrypt in IPsec.
- Ferguson and Schneier claim that encrypt-then-MAC as applied in ESP is **wrong**, and in their book ‘Practical Cryptography’ they recommend MAC-then-encrypt for constructing secure channels.
- Horton principle: *‘Authenticate what is meant not what is said’*.
- Krawczyk’s proof that MAC-then-encrypt in CBC mode is secure.

Why NOT MAC-then-Encrypt?

- Our paper presents practical attacks against **ALL** possible MAC-then-encrypt IPsec configurations:
  - AH in Transport mode followed by ESP in Transport mode
  - AH in Transport mode followed by ESP in Tunnel mode
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CBC encryption

$$C_i = \mathcal{E}_k(P_i \oplus C_{i-1});\ C_0 = IV$$

CBC decryption

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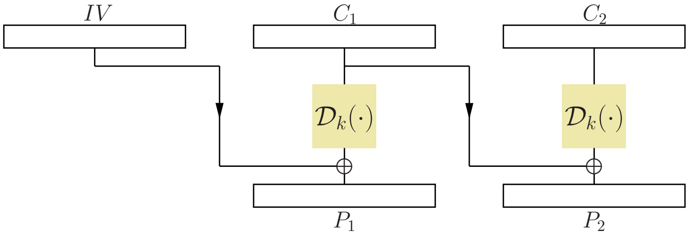

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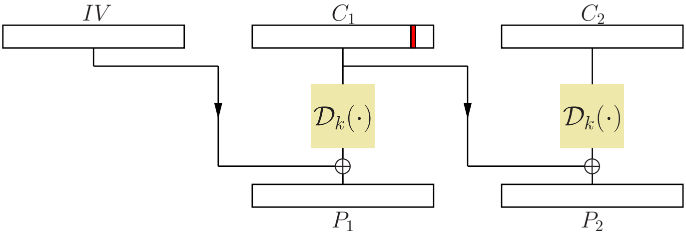

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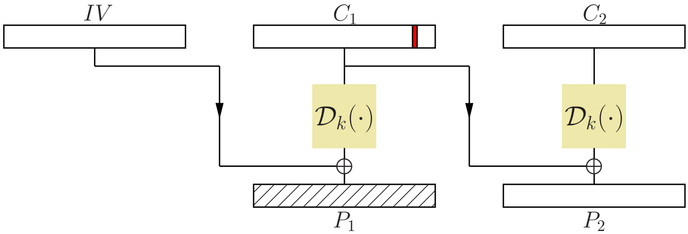

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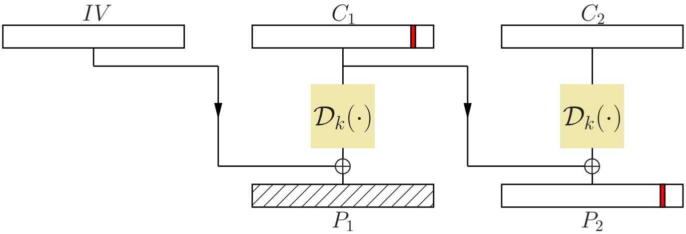

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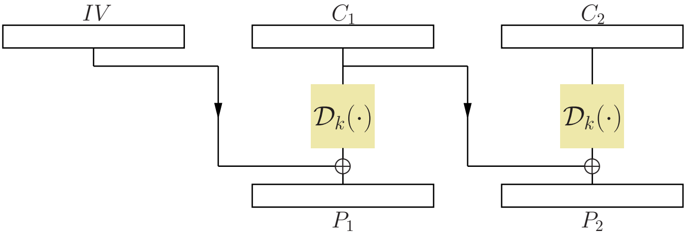

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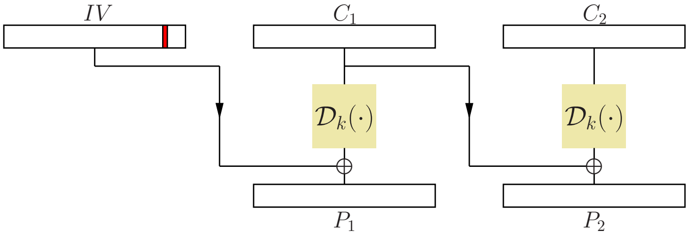

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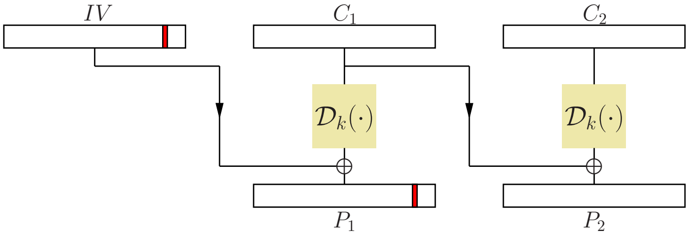

The ESP Trailer Format

- Prior to encryption an *ESP trailer* is appended to the plaintext, extending its length to an integer multiple of the blocksize.

Plaintext

- PL = Padding Length
  NH = Next Header
- In Tunnel mode NH = 4

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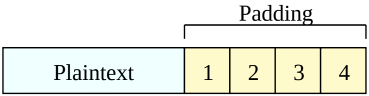

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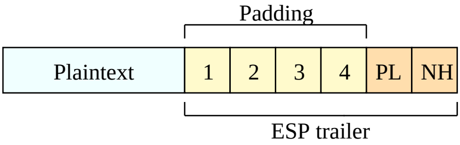

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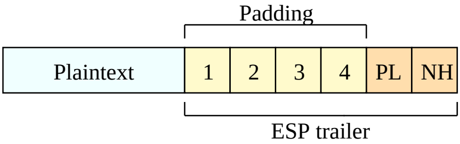

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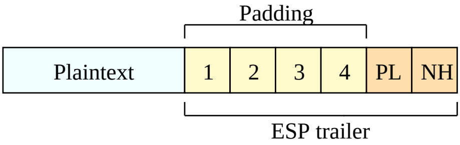

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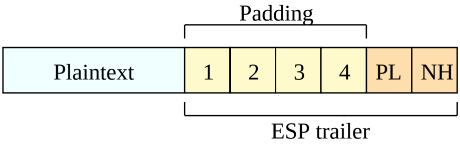

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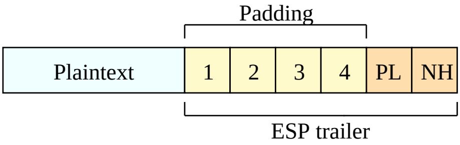

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An ESP Trailer Oracle

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An ESP Trailer Oracle is an oracle that when presented with an ESP-protected IP packet, outputs 1 if the underlying plaintext ends in a **valid ESP trailer**, and outputs 0 otherwise.

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A Decryption Algorithm

From an ESP Trailer Oracle

- Choose a ciphertext block from an ESP-protected IP packet that we want to decrypt.

IP $\text{header}^*_{\text{out}}$	ESP header^*	$C^*_0, C^*_1, \ldots, \mathbf{C^*_i}, \ldots, C^*_n$

- Arbitrarily pick another packet – call it the *carrier packet*.

- Append a random block R and block C^*_i to the carrier packet and submit it to the oracle.

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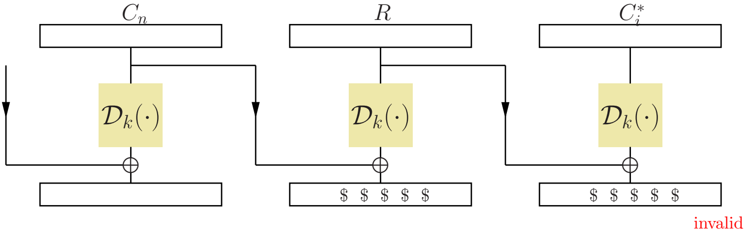

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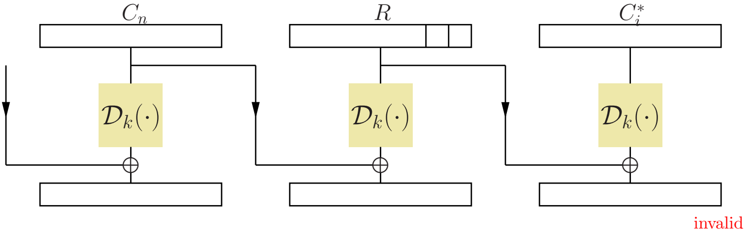

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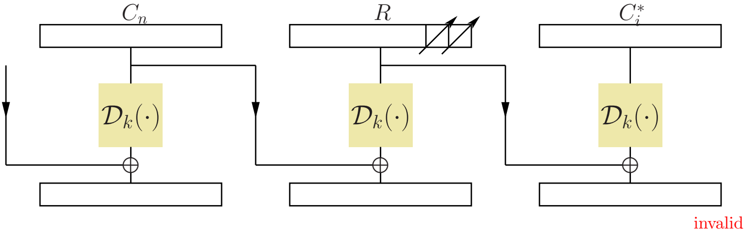

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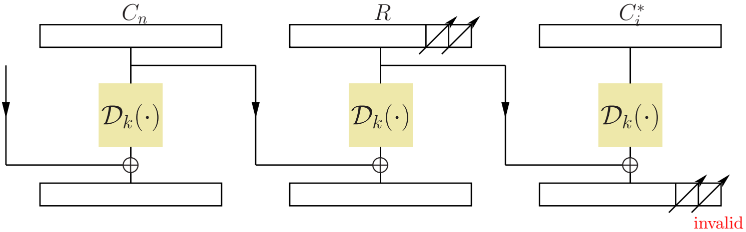

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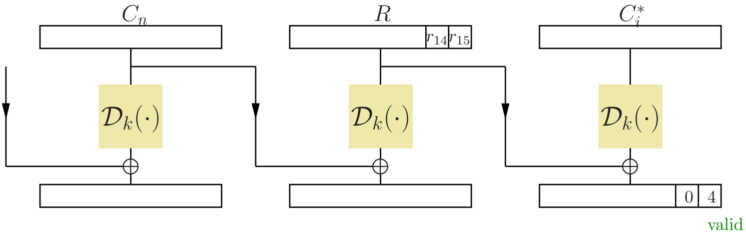

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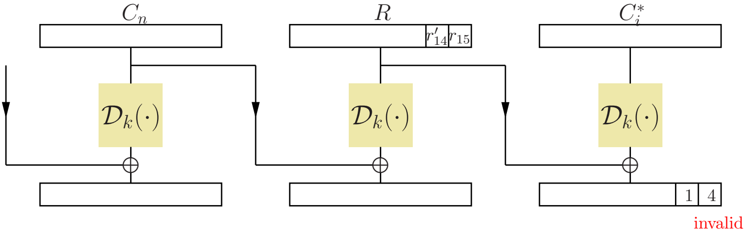

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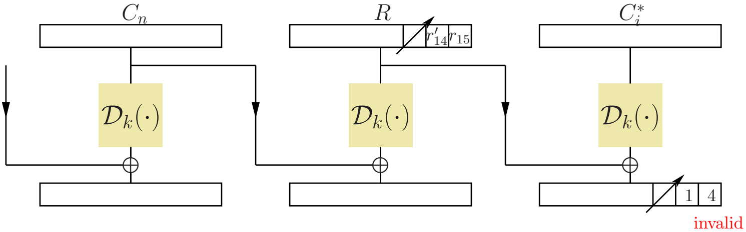

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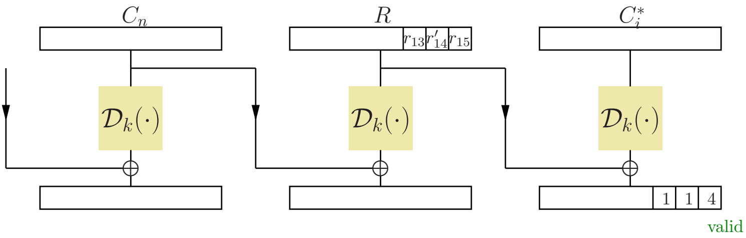

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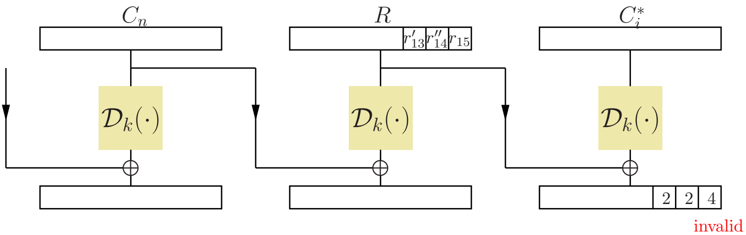

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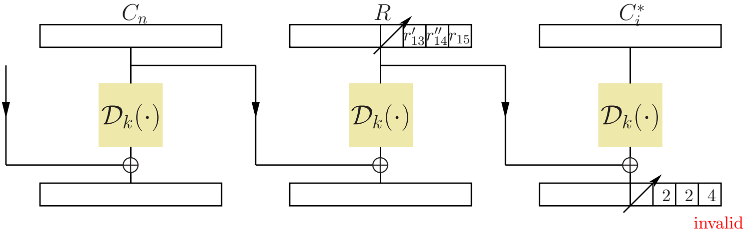

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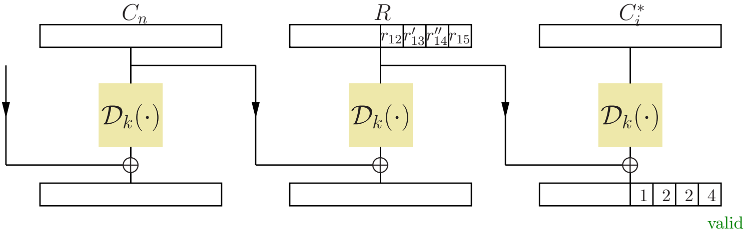

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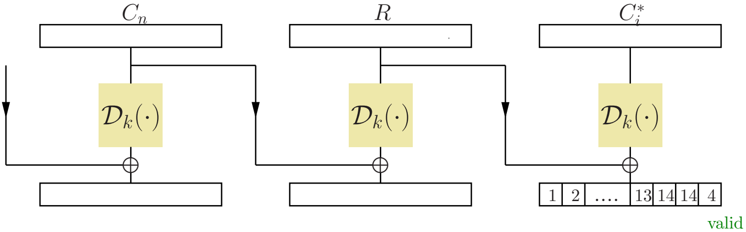

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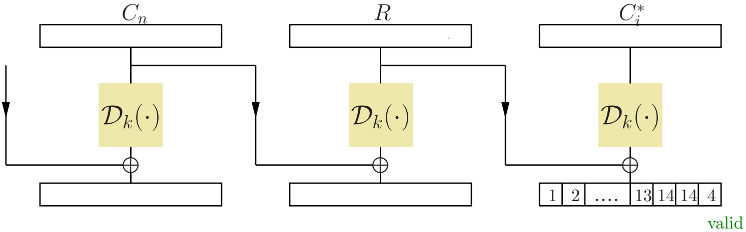

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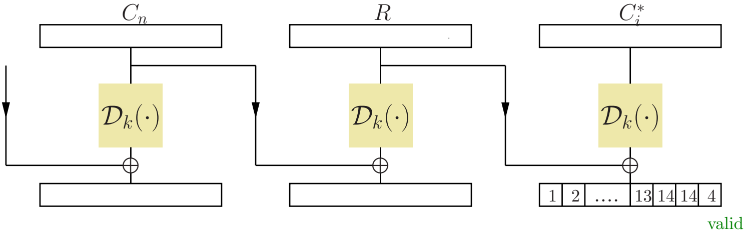

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Realising the Oracle

- An ESP trailer oracle can be realised by using a carrier packet that *always* generates a reply *after* IPsec processing.
- If the ESP trailer is invalid the packet is **discarded** and no reply is generated.
- Contrarily if the ESP trailer is valid a **reply** will be sent over the network.

Practical Complications

- A packet may be dropped for several other reasons – if this happens *the oracle is lost*.
- Flipping bits and appending blocks may invalidate the MAC.
- Replay protection prevents us from using the same carrier packet more than once.
- We need to preserve a valid internal structure of the IP packet.
- Our paper describes several ways to solve these problems – we will now present one approach.

Outline

MAC-then-Encrypt

Example Configuration

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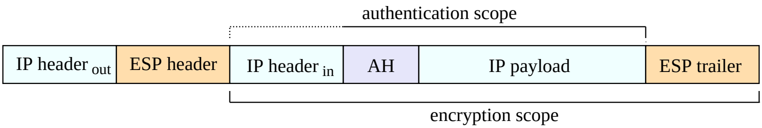
- In the following attack we will assume AH in Transport mode, followed by ESP in Tunnel mode.



IP Fragmentation

- An IP packet may be split into smaller autonomous *fragments* by an intermediate gateway.
- The **MF** bit is a flag in the IP header indicating that the IP packet is indeed a fragment and there are *More Fragments* to come.

An Oracle from IP Fragmentation

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- We flip bits in the IV to set the MF bit to 1 and correct the checksum in the inner IP header.
- The inner IP packet is not complete ⇒ cannot verify the MAC!
- The receiver enters a wait stage, waiting for more fragments.
- No other fragments exist, the wait stage will eventually timeout and an **ICMP Time Exceeded** message is sent.
- The packet is discarded and no further processing takes place.
- We realised the ESP trailer oracle, and completely bypassed AH processing!

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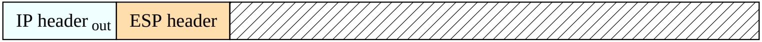

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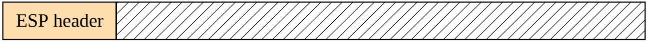

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ESP header	IP header $_{in}$	AH	IP payload	?

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An Oracle from IP Fragmentation

Royal Holloway University of London Information Security Group

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Implementing the Attacks

- We implemented and verified the validity of our attacks against the OpenSolaris IPsec implementation.
- The fragmentation attack takes around 10 mins to recover a 128 bit block of plaintext due to the timeout overhead.
- On a 10Mb Hub our alternative attacks take roughly 70 seconds to recover a 128 bit block of plaintext.

Conclusions

From a Practical Perspective

- All MAC-then-encrypt IPsec configurations are vulnerable to one or more of our attacks.
- Encryption-only configurations of IPsec are already known to be insecure.
- Thus most of the flexibility provided by IPsec results in **insecure configurations** – only encrypt-then-MAC provides confidentiality in IPsec.
- Our attacks highlight the difficulty in designing a secure network protocol – its interaction with the upper and lower layer protocols has to be included in the picture.

Conclusions

From a Theoretical Perspective

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- Krawczyk's security model considers a very restricted case of MAC-then-encrypt.
- Security proofs normally assume the cryptographic processing to be atomic and do not consider distinct error messages or fragmentation.
- Care should be taken in interpreting security proofs with respect to secure protocols in practice.
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