Security of Symmetric Encryption in the Presence of Ciphertext Fragmentation

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Outline of this Talk

Ciphertext Fragmentation

Under *normal operation* the channel delivers ciphertexts in a fragmented fashion, where:

a) The fragmentation pattern is arbitrary.

b) But the order of the fragments is preserved.

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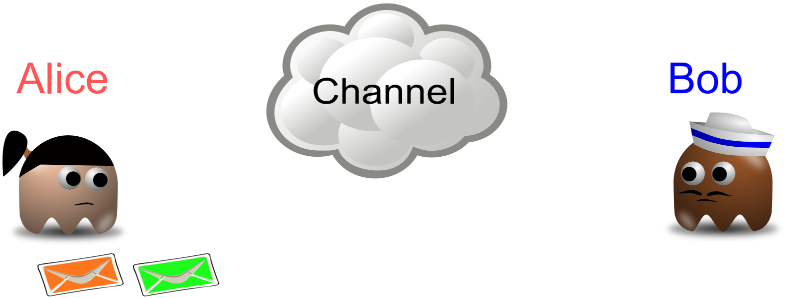

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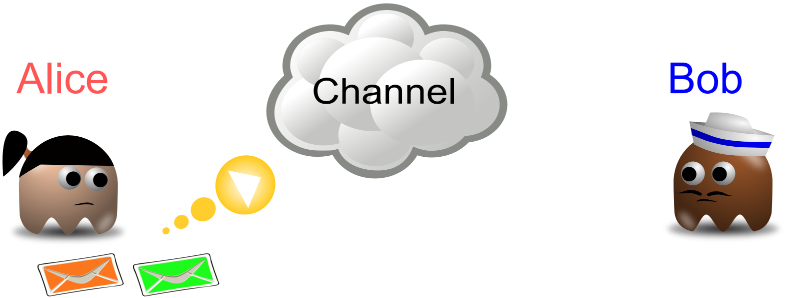

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Why Should We Care?

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- This setting emerges in practice, where encryption schemes have to operate under such conditions.
- One such instance is that of **secure network protocols**.
- However this is NOT captured by the security models currently used in cryptographic theory!
- Ciphertext fragmentation has given rise to a class of attacks that proved to be **fatal** in certain cases.
- This has left a **gap** between cryptographic theory and practice.

Ciphertext-Fragmentation Attacks

SSH:

- A proof of security (IND-sfCCA) for SSH was given in **[BKN 04]**.
- Yet **[APW 09]** presented plaintext-recovery attacks against SSH.

IPsec in MAC-then-encrypt (CBC):

- **[Kra 01]** proves that MAC-then-encrypt with CBC encryption is secure (secure channel [CK 01]).
- **[MT 10]** show that MAC-then-encode-then-encrypt (injective / CBC) is secure (secure channel [Mau 11]).
- **[DP 10]** present ciphertext-fragmentation attacks against such IPsec configurations.

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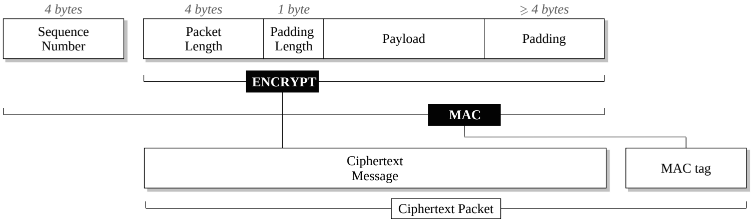
The SSH Attack (Main Idea)

- SSH encrypts messages in the following format:



- SSH commonly uses CBC mode for encryption.

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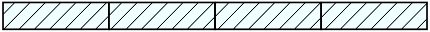

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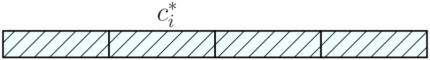

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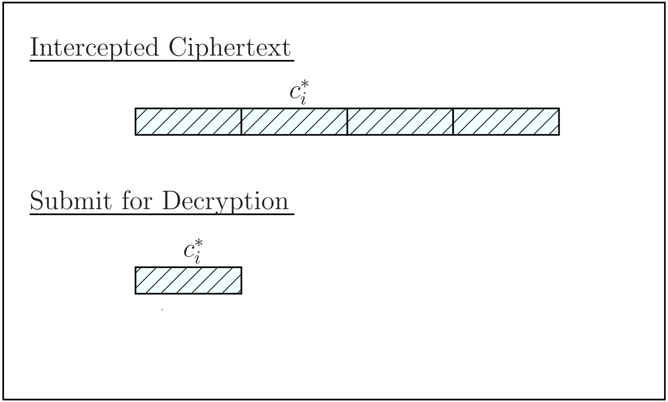

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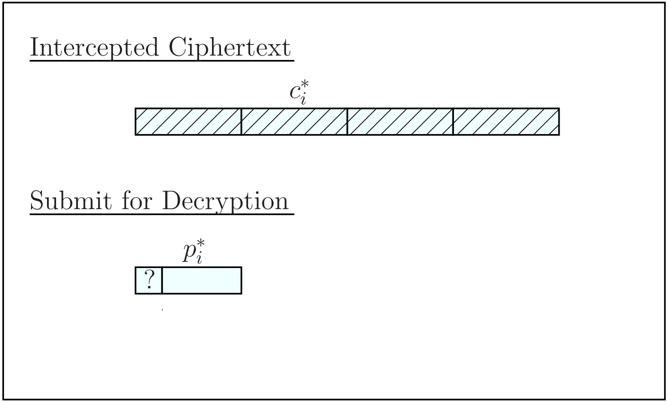

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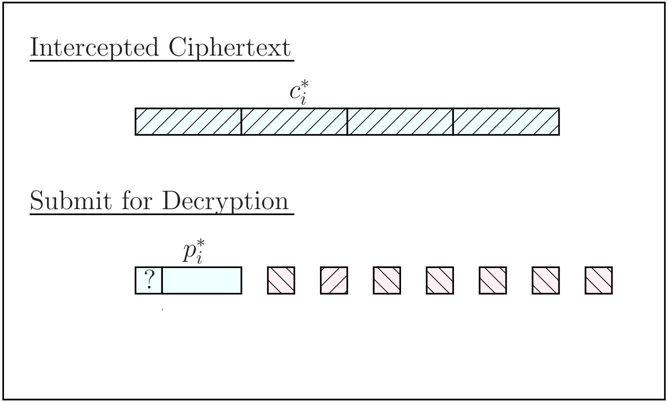

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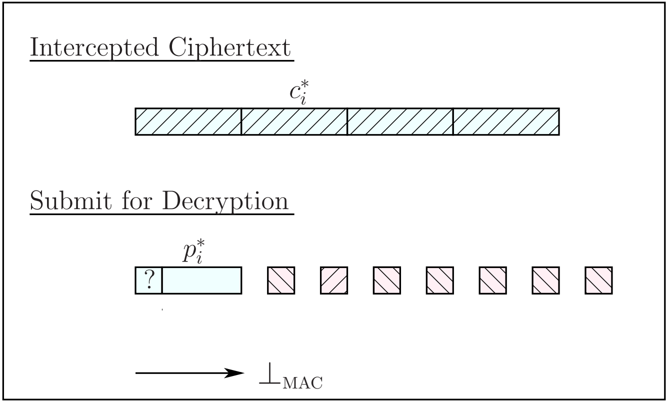

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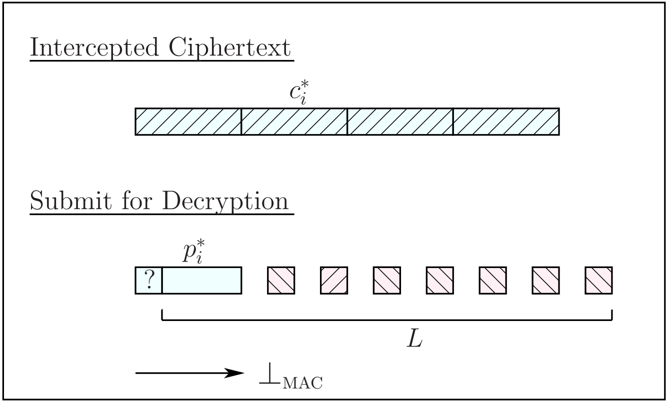

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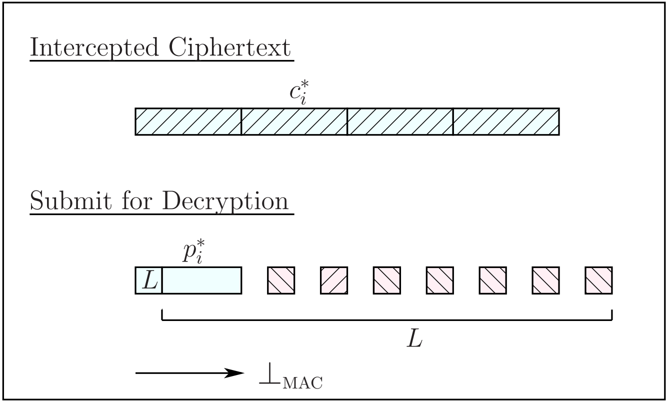

Related Work

- A first step towards analyzing security in the presence of ciphertext fragmentation was made by Paterson and Watson in 2010.
- They show that when CBC mode is replaced with (stateful) **counter mode** SSH is secure.
- However their security notion is closely tied to SSH, and hence it is not generally applicable to other schemes.
- At first glance, ciphertext fragmentation may show some resemblance to **online encryption**. We emphasize that there are some important differences, and the two settings are disjoint.

Our Contribution

- We define a **syntax** and **security notions** for encryption in the fragmented setting.
- We provide **generic constructions** of fragmented schemes that meet our security notions, from normal “atomic” schemes.
- We formalize other security goals that practical schemes commonly aim to achieve: **boundary-hiding** and robustness against **fragmentation-related DoS attacks**.
- We construct a scheme, **InterMAC**, that meets all three of our security notions.

Syntax

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A **fragmented symmetric encryption scheme** $\mathcal{SE} = (\mathcal{K}, \mathcal{E}, \mathcal{D})$ with associated message space $\mathcal{M} = \{0,1\}^*$ and ciphertext space $\mathcal{C} = \{0,1\}^*$, is a triple of algorithms such that:

- $(K, \sigma_0, \tau_0) \leftarrow \mathcal{K}$ where σ_0 and τ_0 are the respective initial states for encryption and decryption.
- $(c, \sigma_{i+1}) \leftarrow \mathcal{E}_K(m, \sigma_i)$ where $\mathcal{E}_K(\cdot)$ can be probabilistic, stateful, or both ($\sigma = \varepsilon$ for stateless); $m \in \mathcal{M}$, $c \in \mathcal{C}$.
- $(m, \tau_{i+1}) \leftarrow \mathcal{D}_K(f, \tau_i)$ where $\mathcal{D}_K(\cdot)$ is deterministic and stateful; $f \in \{0,1\}^*$ and $m \in (\{0,1\} \cup \mathcal{S}_\perp \cup \{\P\})^*$.

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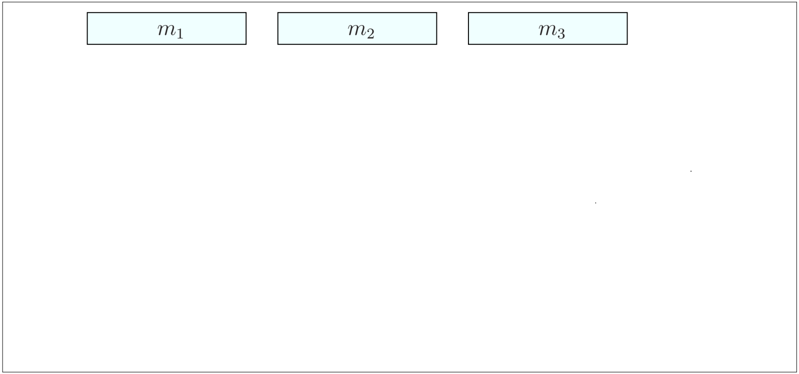
Correctness Requirement

(explained pictorially)



- Then $m_1 \,||\, ¶ \,||\, m_2 \,||\, ¶ \,||\, m_3 \,||\, ¶$ is a prefix of $m'_1 \,||\, m'_2 \,||\, m'_3 \,||\, m'_4 \,||\, m'_5$.

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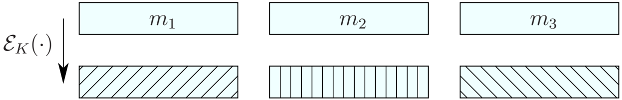

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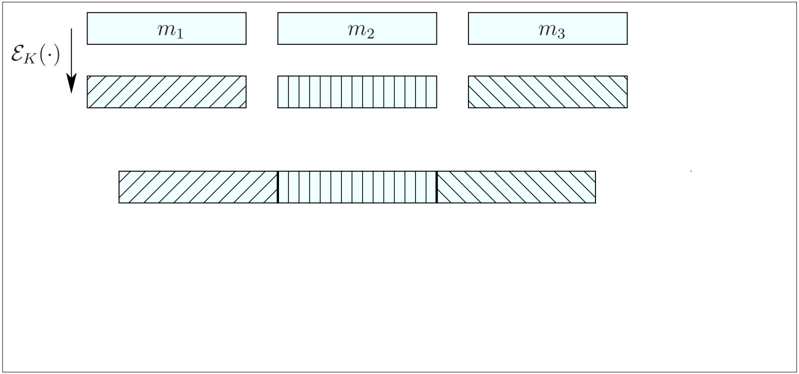

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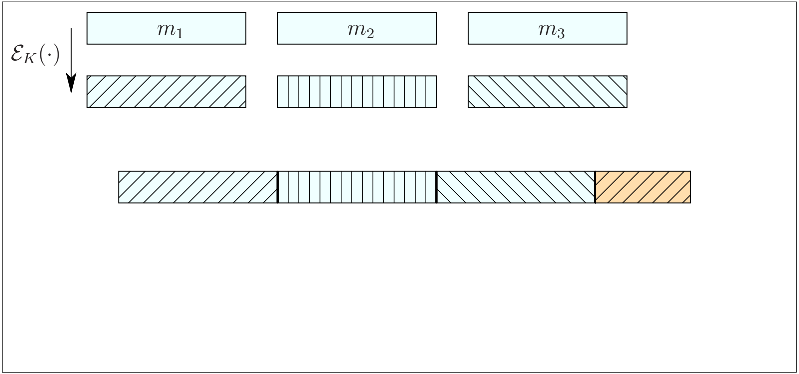

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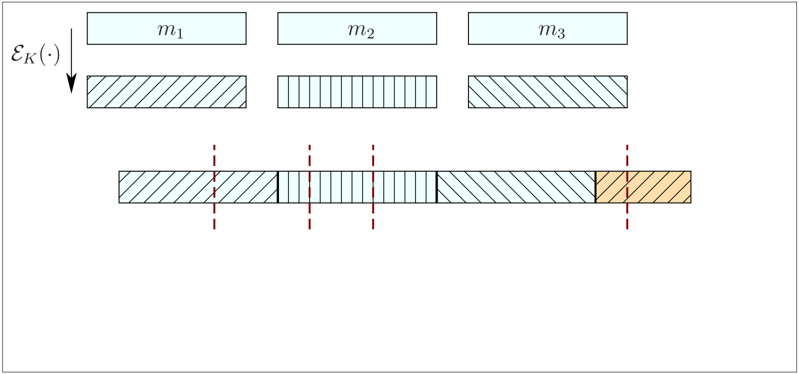

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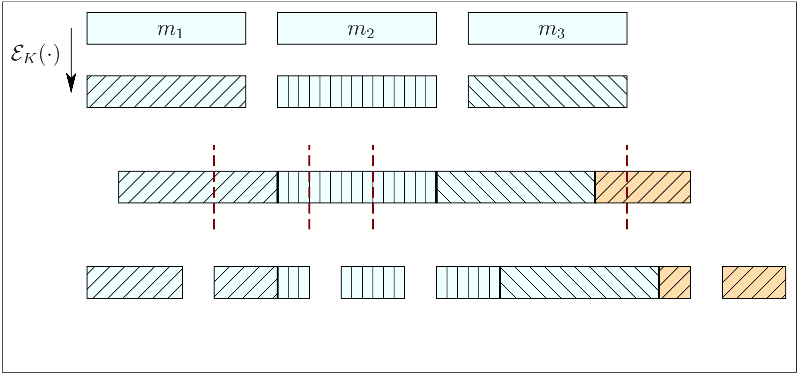

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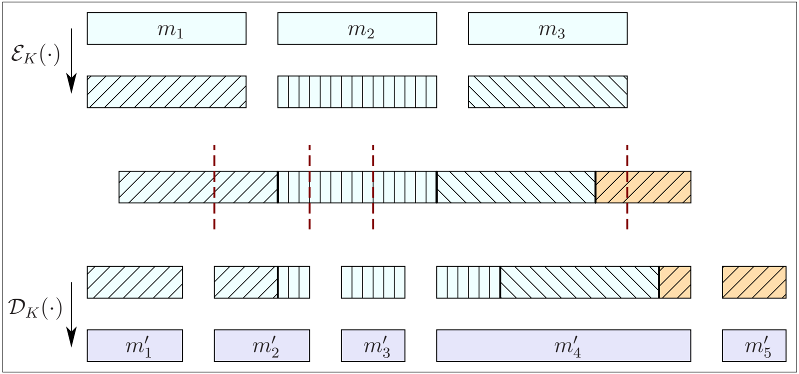

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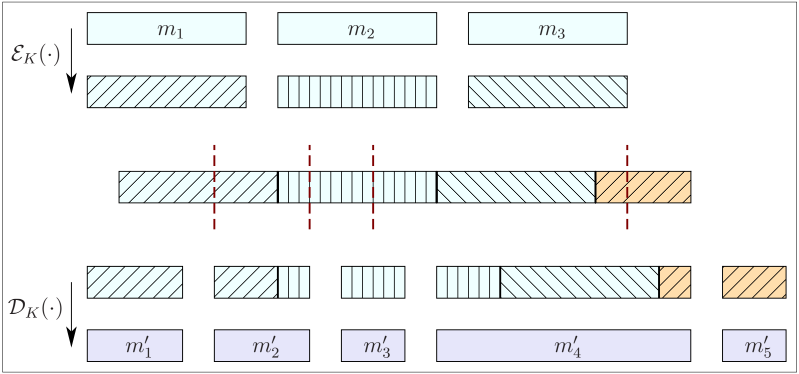

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Chosen-Fragment Security

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- IND-sfCCA **[BKN 04]** extends IND-CCA to protect against **replay** and **out-of-order delivery** attack.
- We extend IND-sfCCA to the fragmented setting, **IND-sfCFA** (Chosen Fragment Attack).
- We provide a **generic construction** for transforming an atomic scheme into a fragmented scheme.
- Starting from an atomic **IND-sfCCA** secure scheme, and a **prefix-free encoding**, the construction gives a fragmented scheme that is **IND-sfCFA** secure.

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End of the Story?

- Our construction shows that Chosen-Fragment Security is not that hard to achieve!
- A closer look at the SSH example, reveals that its designers were aiming for more than just confidentiality.
- We formalize these security goals as: **boundary-hiding** and robustness against **fragmentation-related DoS attacks**.
- Meeting such security goals without compromising confidentiality is more difficult! - as exemplified by the details of the SSH attack.

Boundary-Hiding

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- In the theoretical community it is often regarded as inevitable that a ciphertext leaks the message length. However in practice this is a real problem!
- Practical schemes employ some heuristic techniques in order to protect against **traffic analysis [TV 11]**, **[PRS 11]**, **[DCRS 12]**.
- As we saw earlier SSH encrypts the length field. This does not conceal the message length but can be seen as an attempt to hide ciphertext boundaries.

Boundary-Hiding

- **BH-CPA** (Informally): Given a concatenation of ciphertexts, no adversary can determine where the ciphertext boundaries lie.
- Correctness requires the decryption algorithm to determine ciphertext boundaries. Thus to achieve boundary-hiding, boundaries should be evident only if the secret key is known.
- We extend our earlier generic construction to also achieve **BH-CPA** by replacing the prefix-free encoding with a **keyed prefix-free encoding**.
- The notion is easily extended to the active setting: **BH-sfCFA**, but is more challenging to achieve.

Denial of Service

- The SSH standard (RFC 4253) suggests limiting the maximum value of the length field in order to mitigate against certain denial-of-service attacks.

- Otherwise an adversary could alter the contents of the length field to indicate a very large value. The receiver would then interpret all subsequent ciphertexts as part of this large ciphertext – **connection hang**.

- Such denial-of-service attacks are not specific to SSH, but to encryption schemes supporting fragmentation in general.

- Informally a scheme is **N-DOS-sfCFA** secure, if no adversary can produce an N-bit long sequence of ciphertext fragments (not output by the encryption oracle) such that the decryption algorithm returns ε throughout.

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Comparing Constructions

Scheme	IND-sfCFA	BH-CPA	BH-sfCFA	N-DOS-sfCFA $N < \max_{m \in \mathcal{M}}(\lvert m \rvert)$
SSH-CBC	✘	✔	✘	✘
SSH-CTR	✔	✔	✘	✘
PF	✔	✘	✘	✘
KPF	✔	✔	✘	✘
InterMAC	✔	✔	✔	✔

Concluding Remarks

- Our work provides a **general framework** for analyzing the security of symmetric encryption schemes over fragmented channels.
- We describe **practical constructions** using **standard primitives**, showing that security in the presence of ciphertext fragmentation can be achieved efficiently and from standard assumptions.
- A full version will be available soon on eprint.