CSE 3400 - Introduction to Computer & Network Security
(aka: Introduction to Cybersecurity)

Lecture 9
Shared Key Protocols – Part II

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From Textbook Slides by Prof. Amir Herzberg
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Outline

- Handshake protocol extensions.
- Key distribution centers.
- Improving resilence to key exposure.

Handshake Protocols Extensions

Authenticated Request-Response Protocols

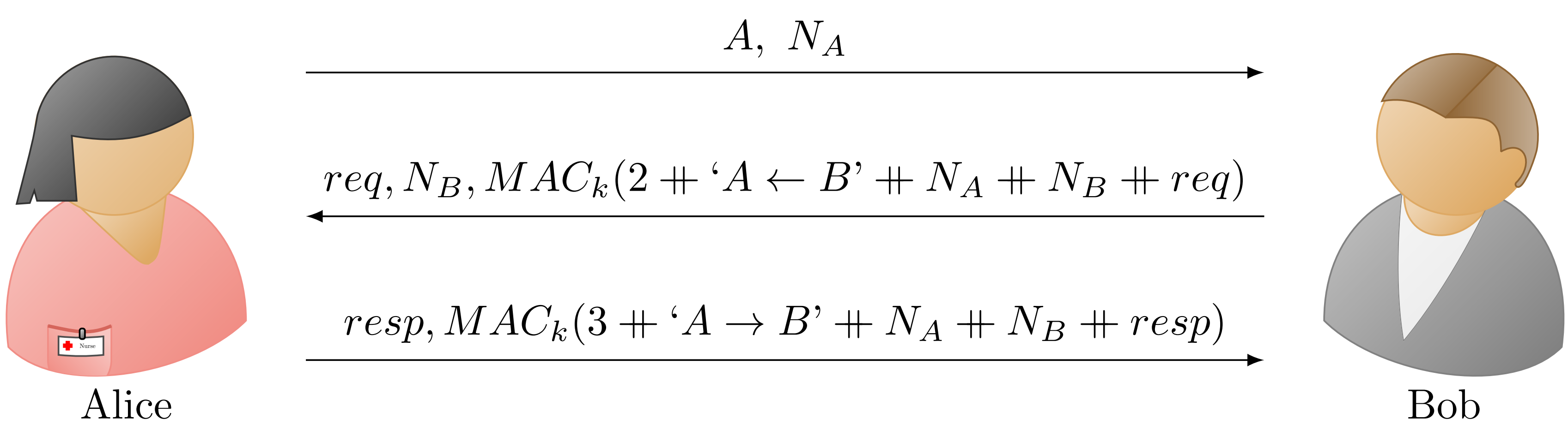
- Beside authenticating entities, these protocols authenticate the exchange of a request and a response between the entities.
- Required properties:
  - **Request authentication.**
    - The request was indeed sent by the peer.
  - **Response authentication**
    - The response was indeed sent by the peer.
  - **No replay.**
    - Every request/response was received at most the number of times it was sent by the peer.

Authenticated Request-Response Protocols

- Five variants:
  - 2PP-RR
  - 2RT-2PP
  - Counter-based-RR
  - Time-based-RR.
  - Key-exchange.

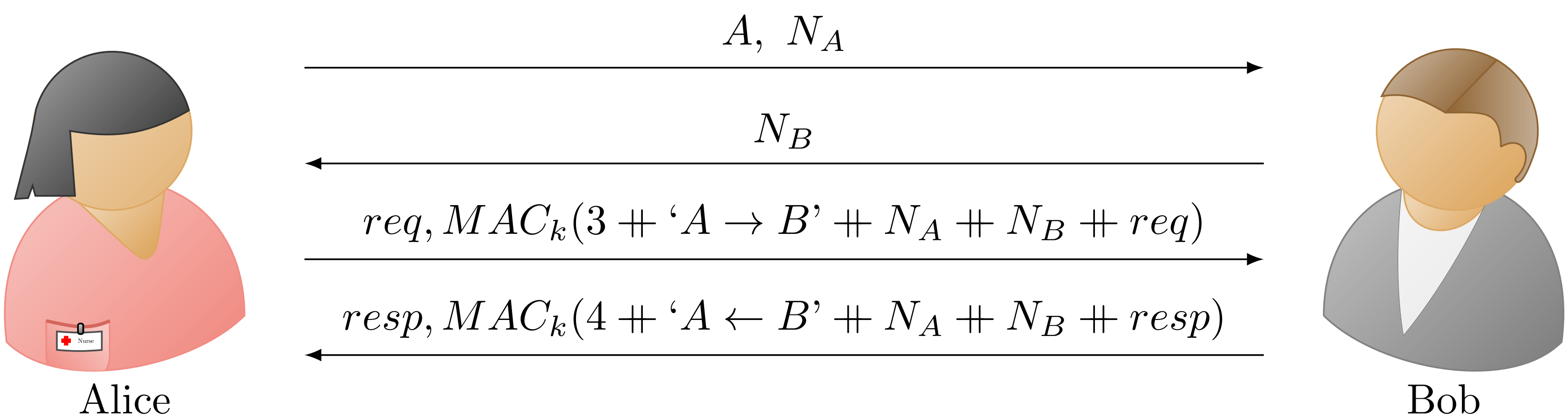
2PP-RR

- A three-flow nonce-based protocol.
- Significant drawback:
  - The request is sent by the responder and the initiator sends the response.
  - So initiator has to wait for a request rather sending it!!



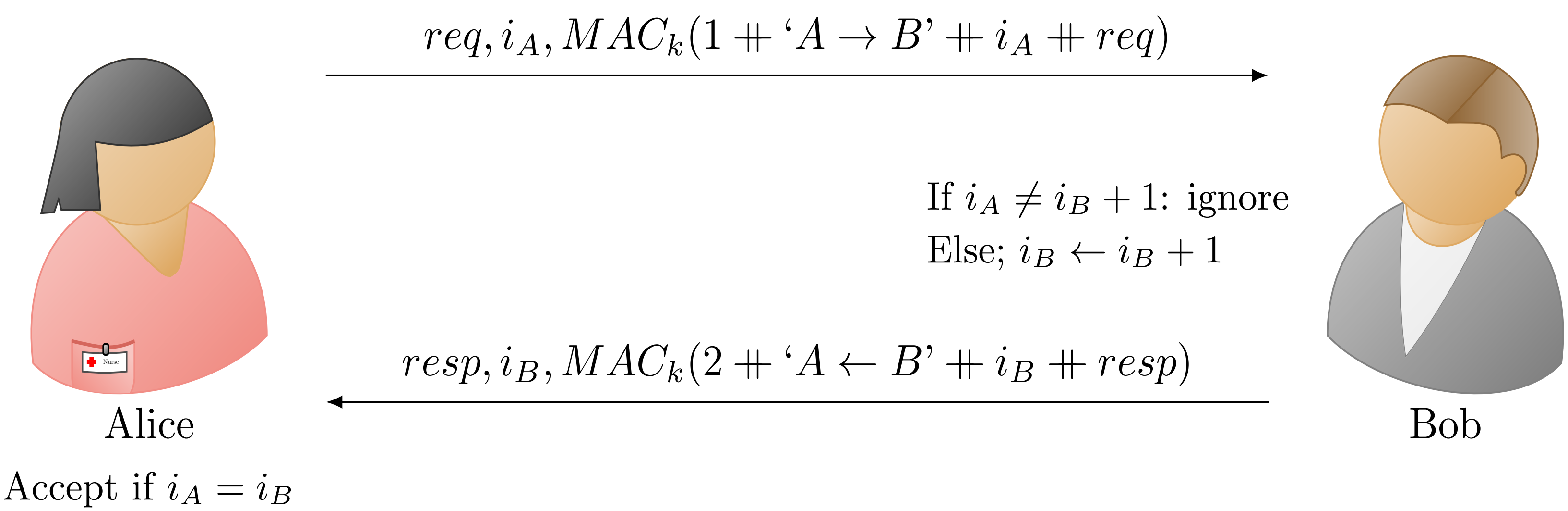
2RT-2PP

- A four-flow nonce-based protocol.
- Mainly fixes the drawback of 2PP-RR (see previous slide).



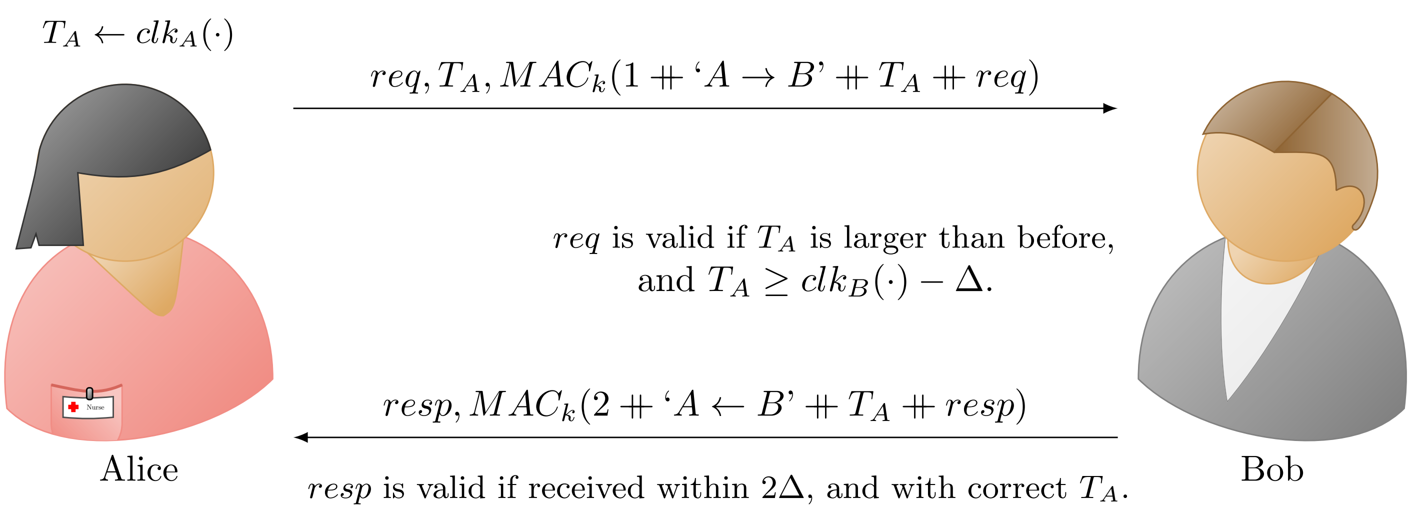
Counter-Based Authenticated RR

- **Simple stateful (counter) solution, requiring only one round:**
  - Unidirectional (run once for each direction if both are needed).
  - Parties maintain synchronized counter i of requests (and responses) to avoid replay attacks.
  - Recipient (e.g. Bob) validates counter received is $i + 1$
  - Both parties must remember counter



Time-Based Authenticated RR

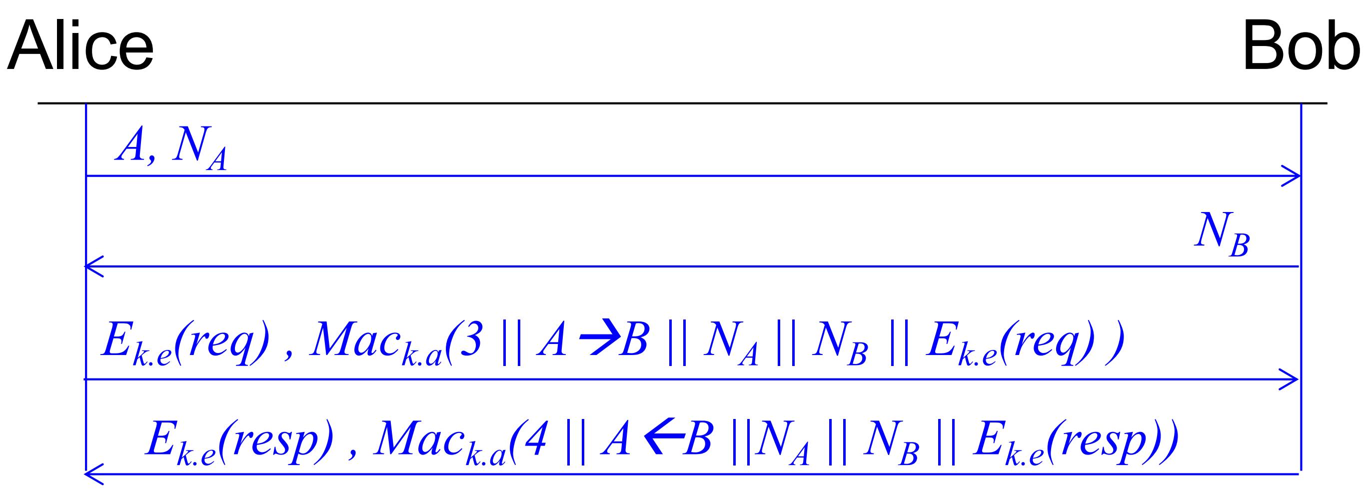
- **Simple stateful (time) solution, requiring only one round:**
  - Use local clocks T_A, T_B instead of counters with two assumptions: bounded delays and bounded clock skews.
  - Responder (Bob):
    - Rejects request if: $T_B > T_A + \Delta$ where $\Delta \equiv \Delta_{skew} + \Delta_{delay}$
    - Or if he received larger T_A already
    - Maintains last T_A received, until $T_A + \Delta$
  - Initiator (Alice) does not need **any** state, when can Bob discard his?



Remember T_A

2RT-2PP with Confidentiality

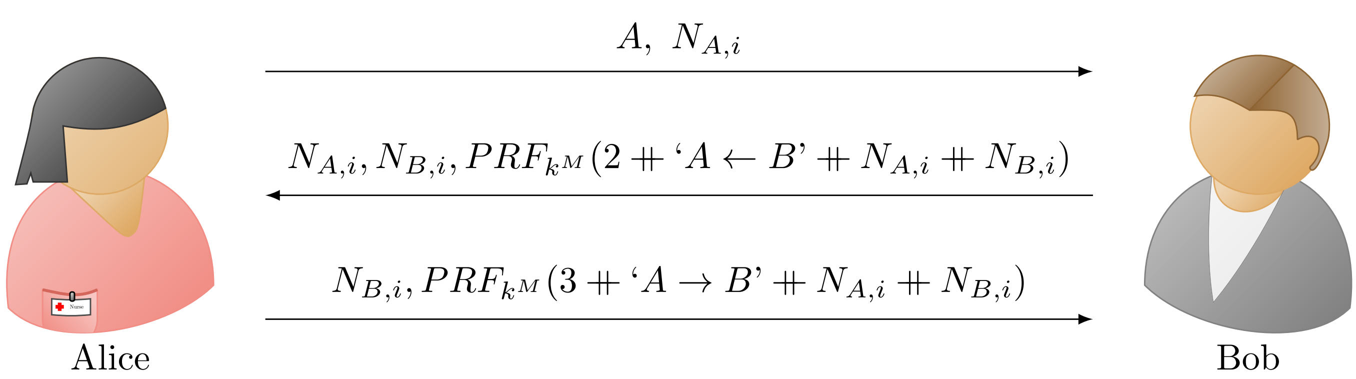
- **Secure connection: authentication, freshness, secrecy**
  - Independent keys: for encryption $k.e$, for authentication: $k.a$
  - How can we derive them both from a single key k ?
  - $k.e=PRP_k(\text{"Encrypt"}),\ k.a=PRP_k(\text{"MAC"})$
  - Hmm… same key encrypts all messages, in all sessions ☹
- Can we improve security, by changing keys, e.g., btw sessions ?



2PP Key Exchange Protocol

- Independent session keys, e.g. $k=PRF_{MK}(N_A,N_B)$
- Or, `directly' for authentication and for encryption:
  $k.e=PRF_{MK}(\text{“}Encrypt\text{”}, N_A,N_B)$, $k.a=PRF_{MK}(\text{“}MAC\text{”}, N_A,N_B)$
- Improves security:
  - Exposure of session key does not expose (long-term) ‘master key’ MK
  - And does not expose keys of other sessions
  - Limited amount of ciphertext exposed with each session key k
- Later: reduce risk also from exposure of Master Key MK

Why a PRF is used instead of the MAC as before?



$k_i^S = PRF_{k^M}(N_{A,i} + N_{B,i})$ $k_i^S = PRF_{k^M}(N_{A,i} + N_{B,i})$

Key Distribution Centers (KDCs)

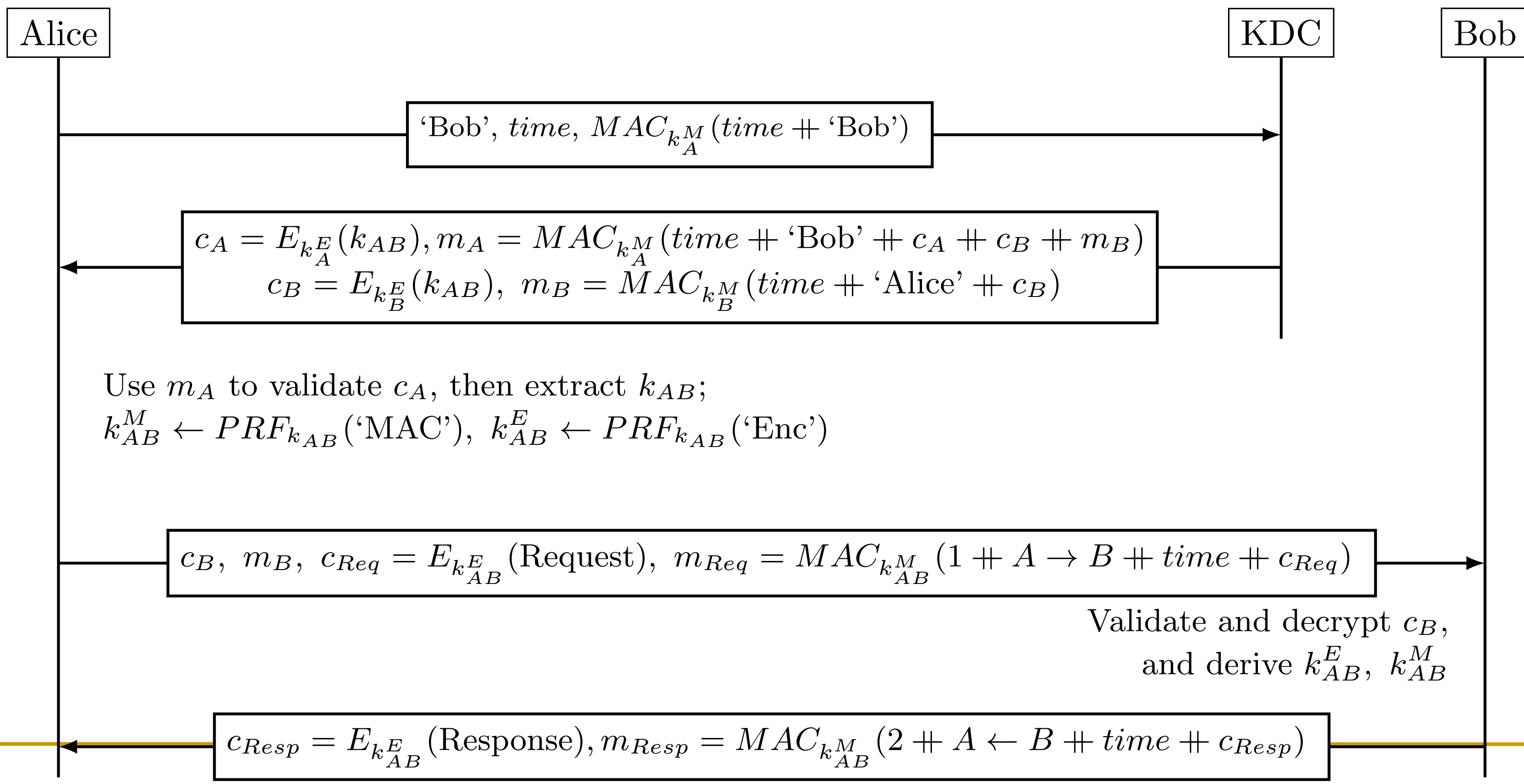
Establish a shared key between two or more entities, usually with the help of a trusted third party referred to as KDC

Key Distribution Center (KDC)

- Will focus on three party protocols; Alice, Bob, and KDC.
- KDC: shares keys with all parties (k_A, k_B…)
- Goal: help parties (A, B) establish k_{AB}
- We will study two protocols; simplified versions of:
  - The Kerberos protocol (secure) widely used in computer networks.
  - The GSM protocol (insecure) used by cellular networks.

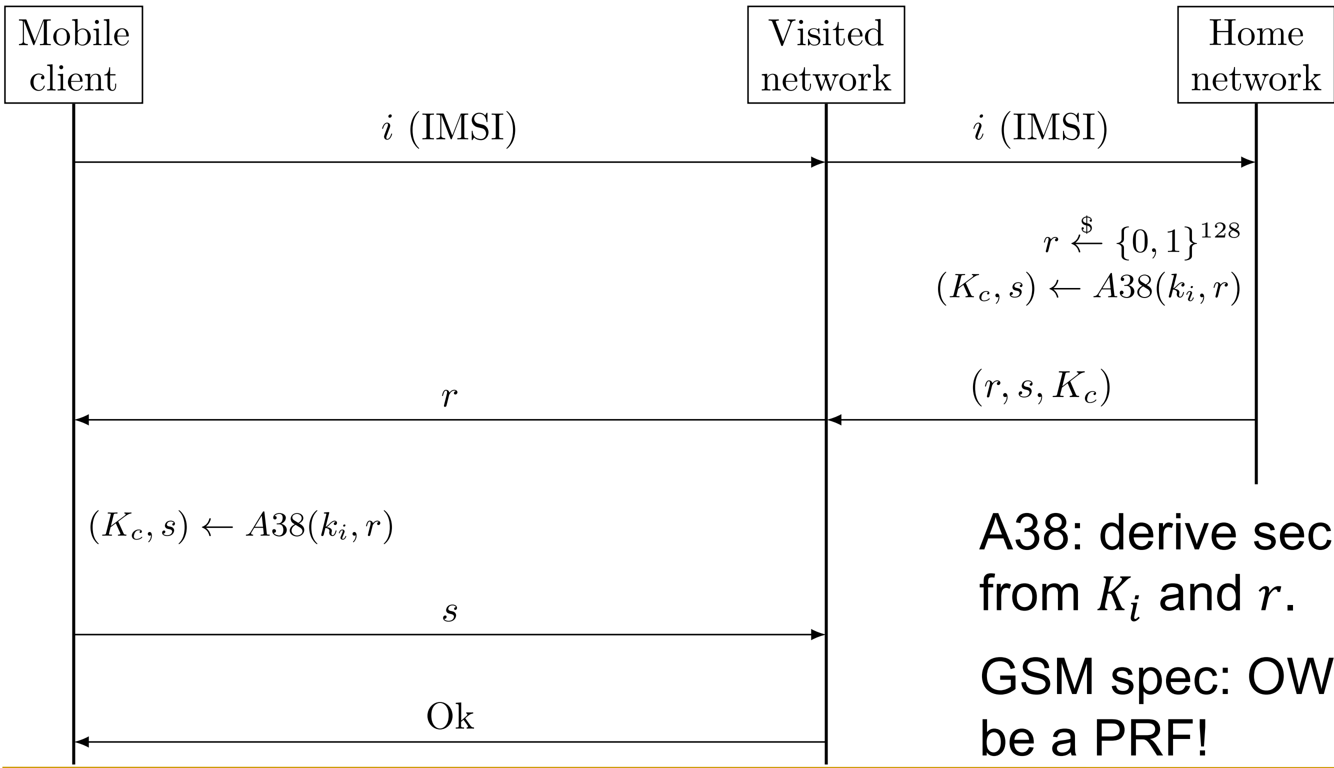
The Kerberos KDC Protocol

- KDC shares keys k_A^E (enc.), k_A^M (MAC) with Alice and k_B^E, k_B^M with Bob
- Goal: Alice and Bob share k_{AB}, then derive: k_{AB}^E, k_{AB}^M
- KDC performs access control as well; controlling whom Alice can contact.



The GSM Handshake Protocol

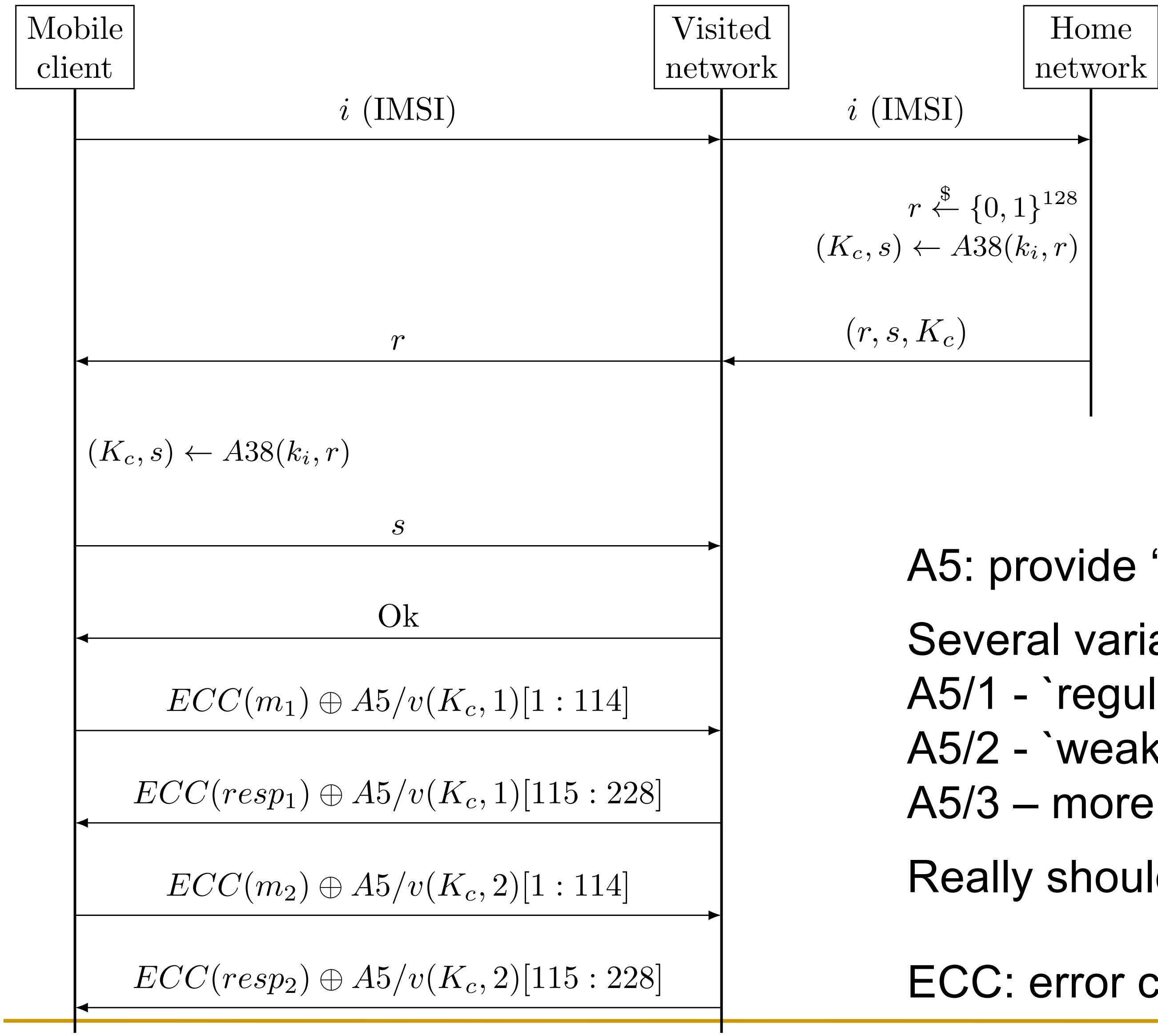
- Mobile client
  - Identified by i (IMSI: International Mobile Subscriber Identifier)
- Visited network (aka Base station); not fully trusted !
- Home network; trusted, shares key k_i with client i



A38: derive secret, random K_c, s , from K_i and r.

GSM spec: OWF, but really should be a PRF!

Example – Sending two messages



A5: provide 'pad' for encryption

Several variants:
A5/1 - `regular'
A5/2 - `weak'
A5/3 – more secure

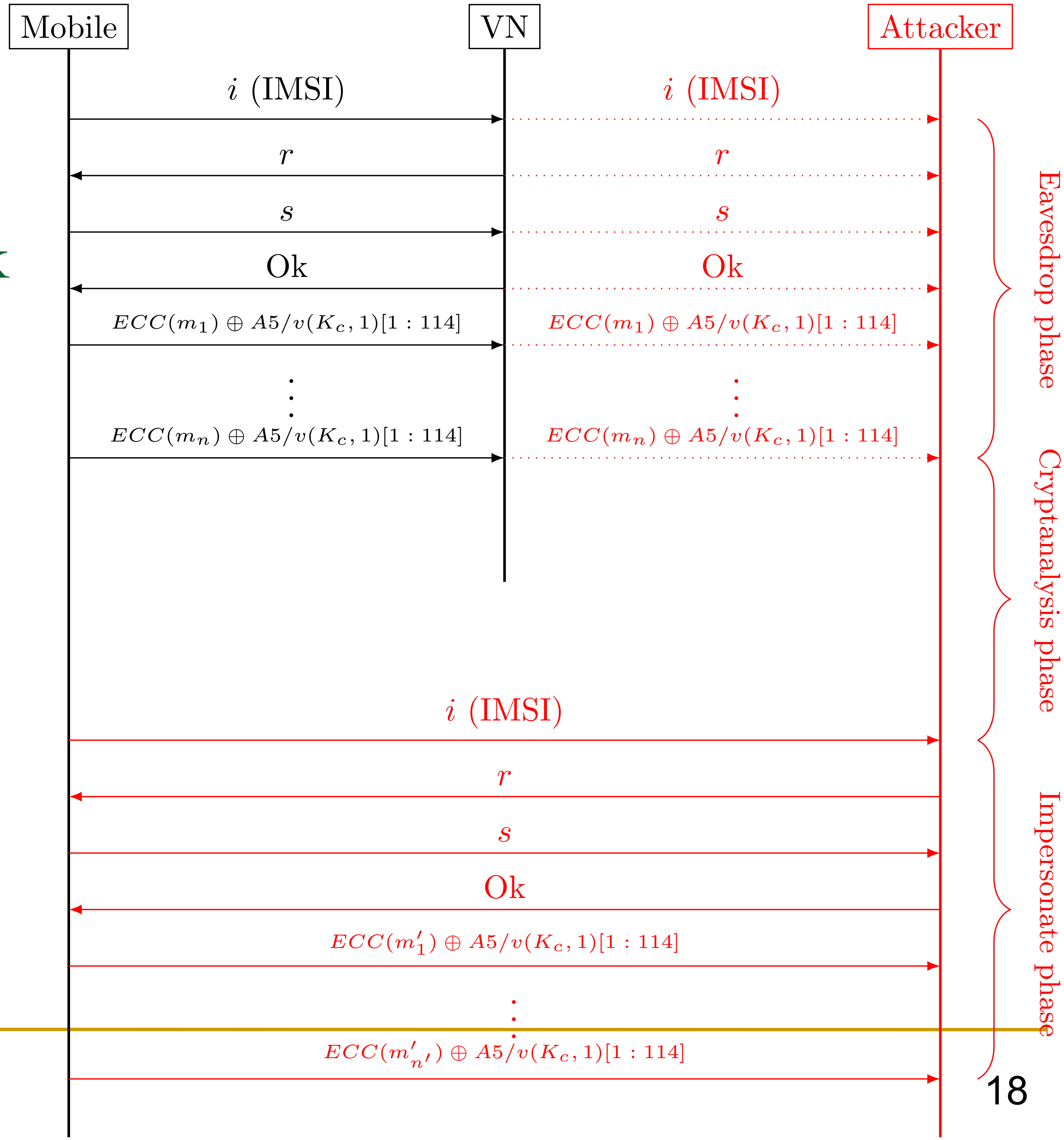
Really should be a PRF!

ECC: error correcting code.

Attacks on GSM

- We will explore two such attacks:
  - Visited network impersonation replay attack.
  - Downgrade attack.

Visited-network Impersonation Attack

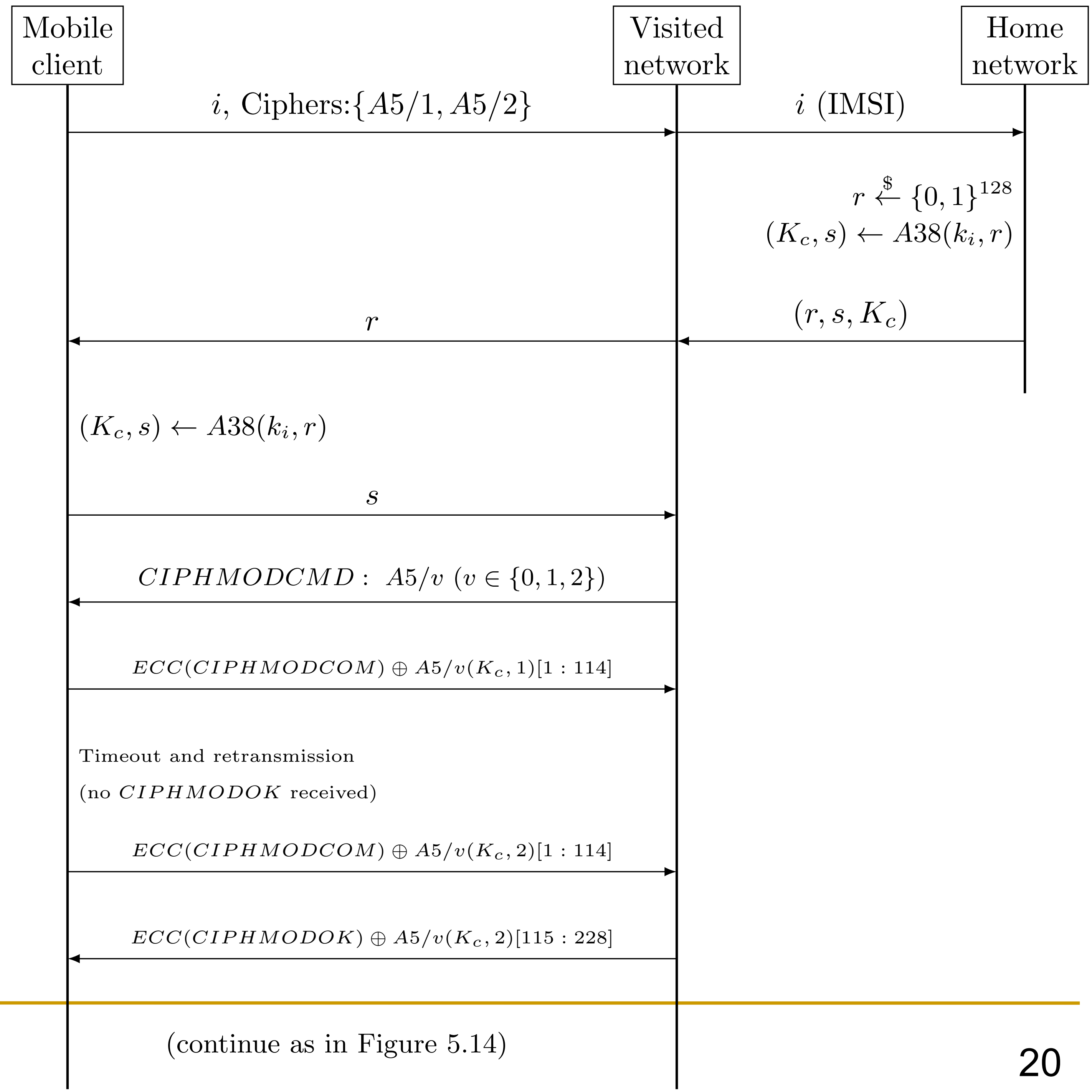


Note: does NOT Impersonate **mobile,** only Visited network.

GSM Ciphersuites Downgrade Attack

- A ciphersuite is the set of cryptographic schemes used in a protocol execution.
- Ciphersuite negotiation:
  - Mobile sends list of cipher-suites it supports
  - Visited-net selects best one that it also supports
- GSM encryption algorithms E_k:
  - A5/0: none, A5/1: broken, A5/2: useless (break with only 1sec of ciphertext!), A5/3: ‘other’
- A MitM attacker may trick these parties to use a weak suite although the parties can support a stronger one.
- Let’s first see how ciphersuite negotiation happened in GSM.

GSM Handshake, With Cipher-negotiation.



Cipher mode messages, negotiation

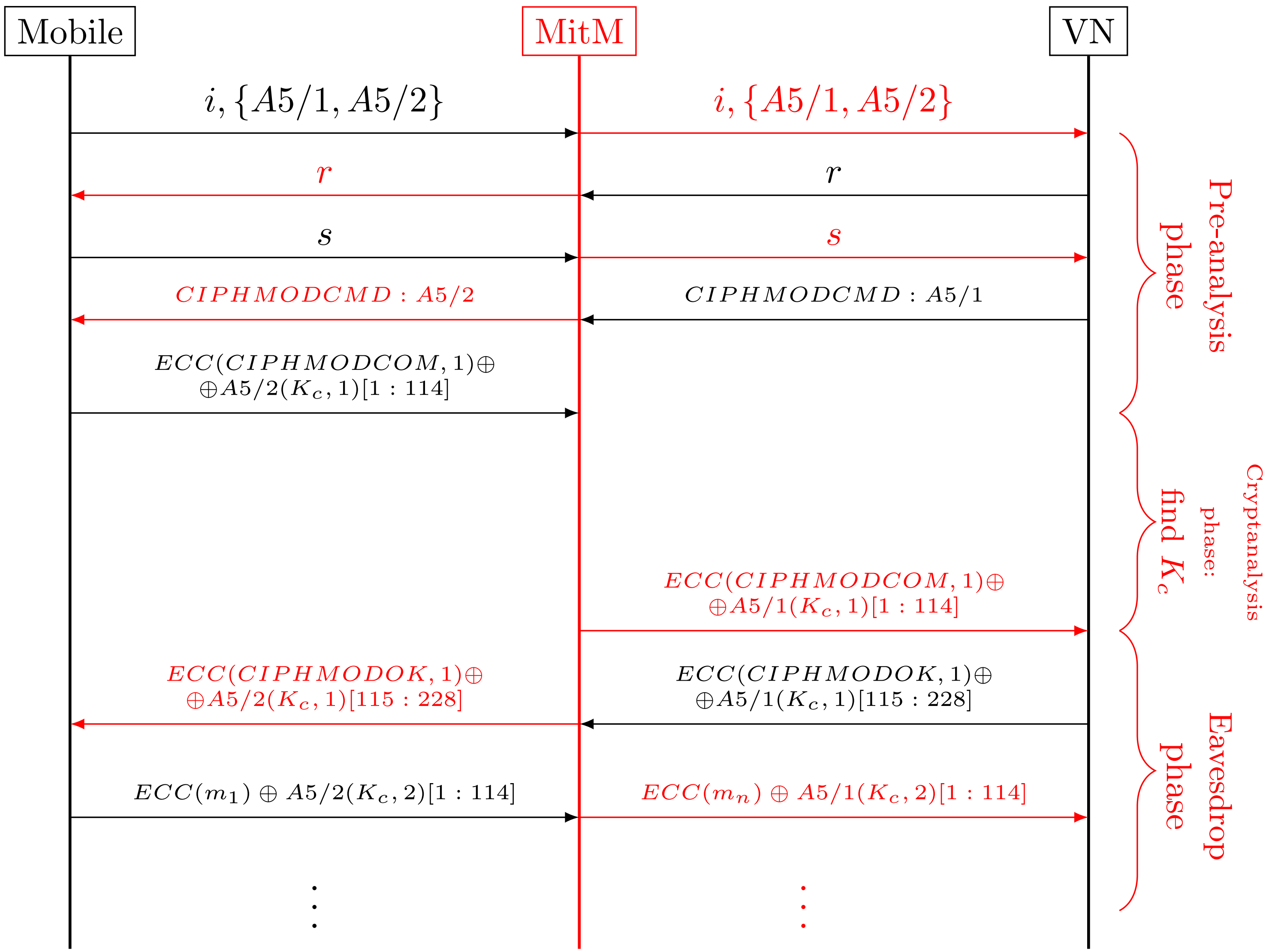
- Mobile sends list of supported ciphers
- VN sends choice in: CIPHMOD**CMD**
  - **Cipher Mode Command**
- Mobile confirms by sending encrypted: CIPHMOD**COM: cipher mode complete**
  - If not received (in few msecs), VN disconnects
- VN Acks: CIPHMOD**OK: cipher mode Ok**
  - If not received, mobile resends CIPHMOD**COM**

GSM ciphersuite facts: for fun and profit

- GSM uses same K_c for all ciphers
- CTO attack on A5/2 requires 900 bits, 1 sec
  - If ciphertext is after GSM's ECC, of course
  - Lots of redundancy
- Visited networks don't downgrade to A5/2
- Mobile encrypts, sends CIPHMOD**COM**
  - Resends (in few msecs) if no CIPHMOD**OK**
  - New encryption each time (counter)
  - 456bit message (after ECC)
- Allow 12s delay for the s message

Simplified Downgrade Attack

Efficient attack known only for A5/2; Client, Visited-net normally prefers A5/3 or A5/1, which are harder to break. Attack forces use of A5/2 !!

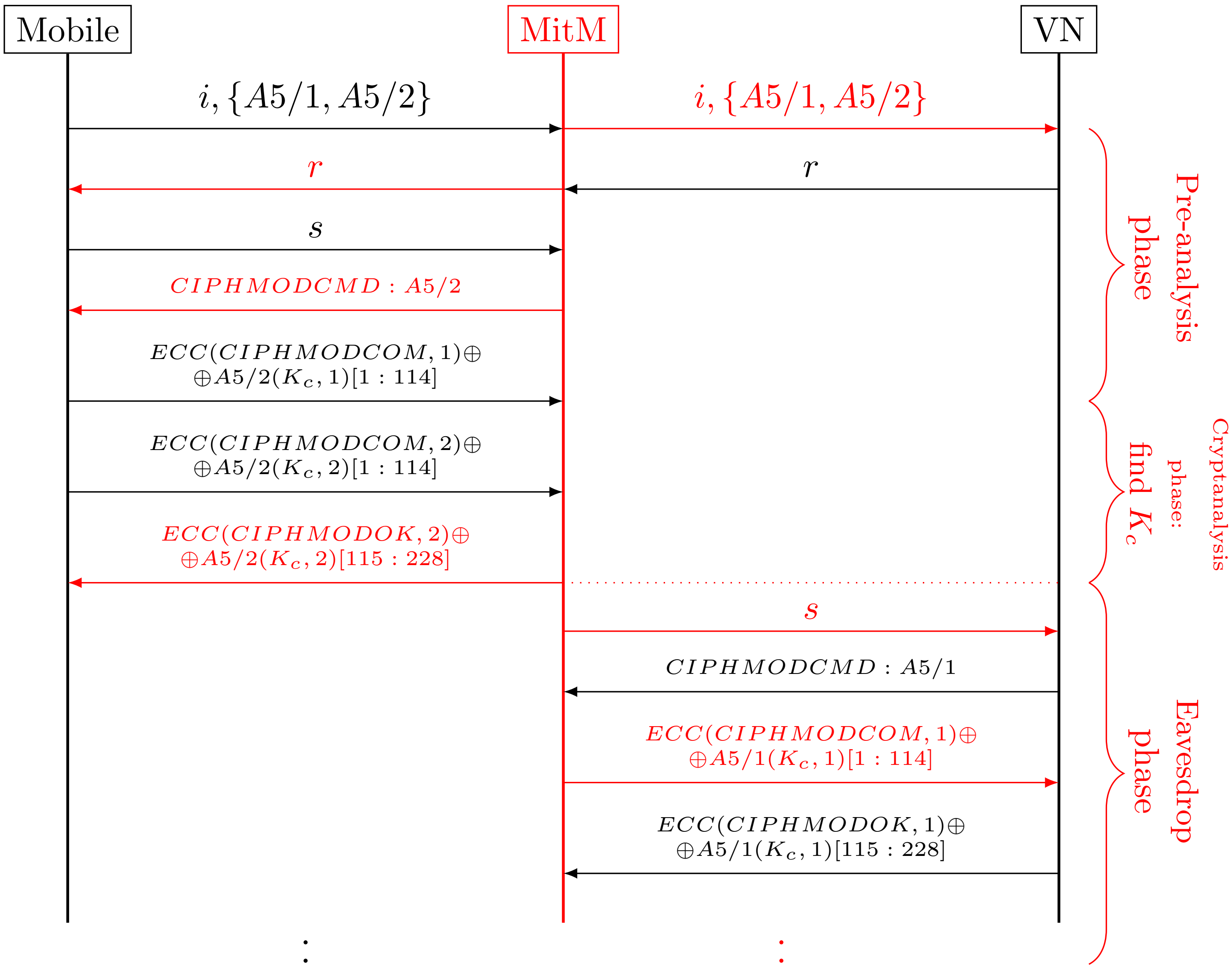


Simplified downgrade attack - Fails

- Fails in practice due to two reasons:
  - VN would time-out since CIPHMOD**COM is** not received in few milliseconds
    - A5/2 CTO attacker requires a second to reveal the key.
  - And CIPHMOD**COM** is only 456 bits
    - A5/2 CTO attacker requires 900 bits.

Real Downgrade Attack

Works even if VN insists to use A5/1; attacker tricks client to use A5/2. That suffices, since GSM uses same key for all cryptosystems!



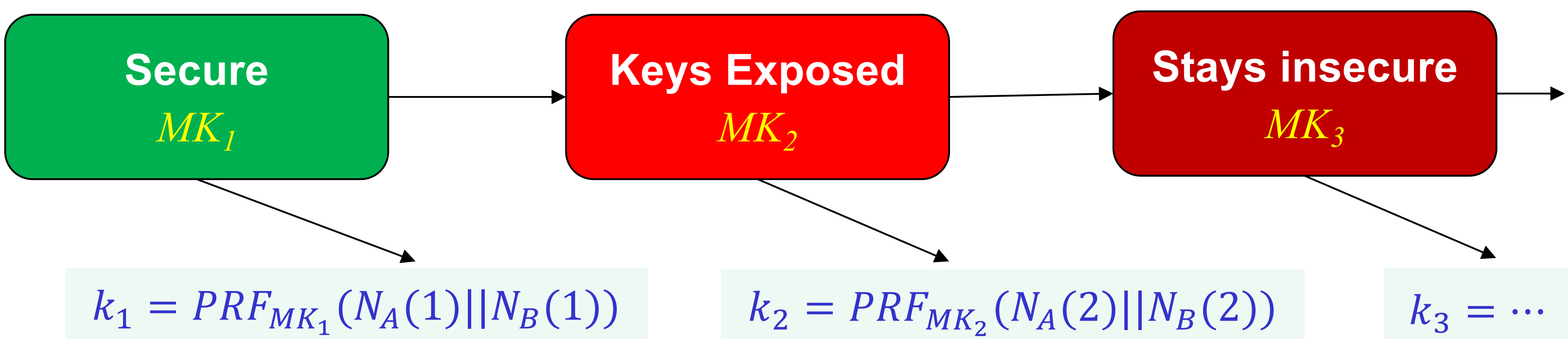
The 12 sec delay allows that!

Retransmissions of CIPHERMODCOM provides the attacker with more than 900 bits of ciphertext!

Improving Resiliency to Key Exposure

Forward Secrecy I

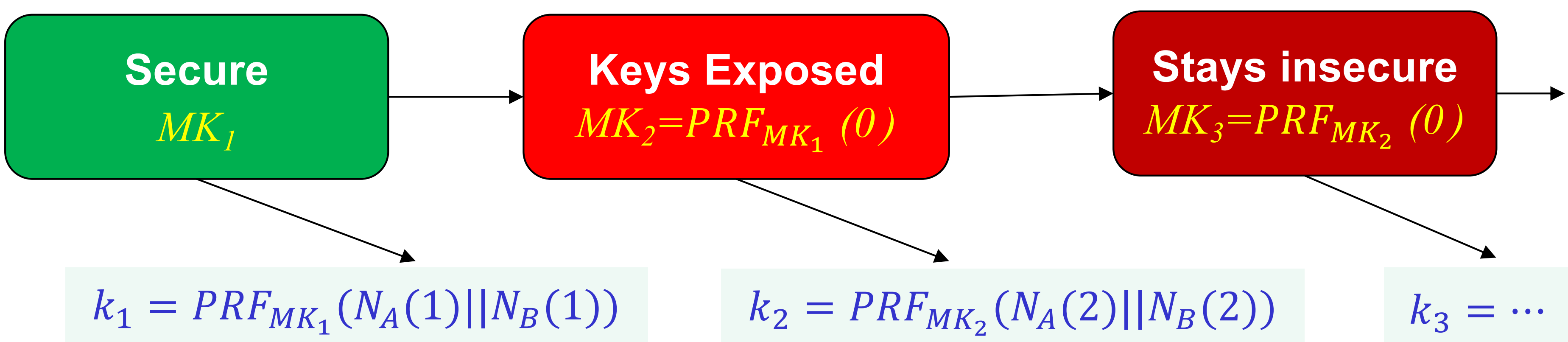
- **So far:** session key $k_i \nRightarrow k_j$ (expose no other keys)
  - And master key was fixed for all sessions
- Idea: we can do better!
  - Change the master key each session: $MK_1, MK_2, \ldots$
- Forward Secrecy (FS): <u>master</u> key $MK_i \nRightarrow k_j (j < i)$
  - I.e., MK_i (and k_i) don't expose keys, communication of <u>previous</u> sessions $(j < i)$



Forward Secrecy II

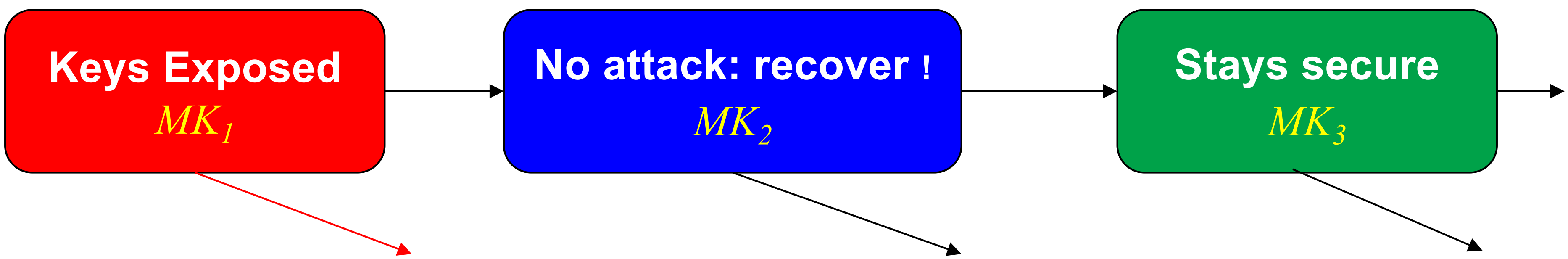
- Forward Secrecy (FS): master key $MK_j \nRightarrow k_i (j > i)$
  - Session i is secret even if any state of later sessions is exposed.
  - Uni-directional: $MK_i \rightarrow MK_{i+1}$, but $MK_{i+1} \nrightarrow MK_i$
  - **How?** Solution: PRF!

$$MK_i = PRF_{MK_{i-1}}(0)$$



Recover Security

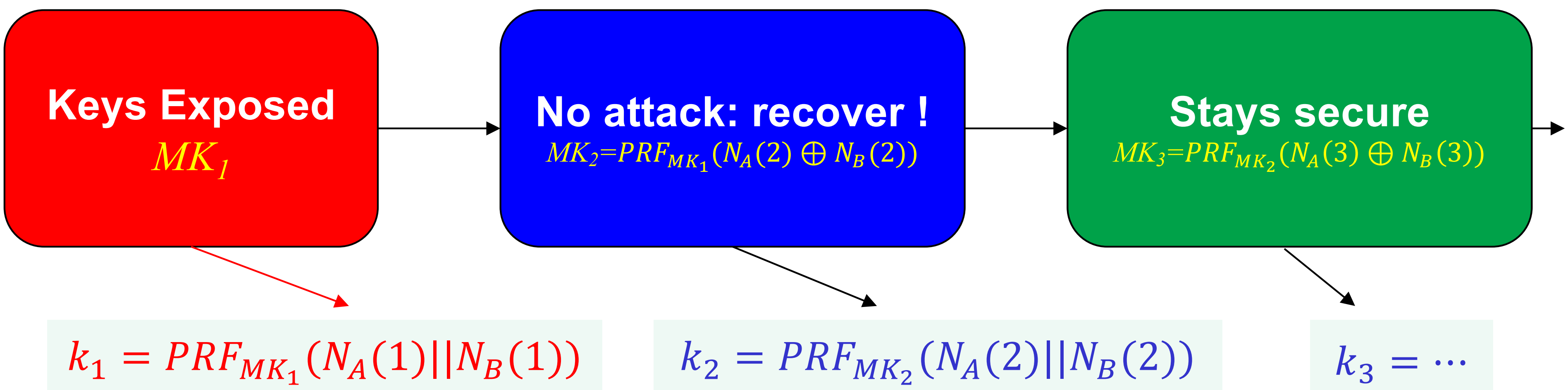
- Can we also **recover** security?
  - MK_{i_R-1} exposed, yet MK_{i_R}, $MK_{i_{R+1}}$ … secure ?
  - Idea: assume **no attack** during 'recovery session' i_R



$k_1 = PRF_{MK_1}(N_A||N_B)$ $k_2 = PRF_{MK_2}(N_A||N_B)$ $k_3 = \cdots$

Recover Security (RS)

- Recover security: session i secure if :
  - session i is secure if it's keys are not given to attacker, and either session $i-1$ is secure, or there is no attack during session i
  - How? The RS-Ratchet Protocol:
    - Let $N_A(i), N_B(i)$ denote session's i nonces
    - Then: $MK_i = PRF_{MK_{i-1}}(N_A(i) \oplus N_B(i))$



Stronger Notion of Resiliency

- **Perfect** Forward Secrecy (PFS): session i is secure even if attacker is given, only **after** session i ends, all keys of **all** other sessions, **and** Master Key of session i
  - *All include future and past sessions.*

- **Perfect** Recover Security (PRS): session i is secure if it's keys are not given to attacker, and either session $i-1$ is secure, or there is no MitM attack during session i

- How? **public-key** (key exchange) protocols – next topic!

Resiliency Notions: Shared + Public Key

Notion	*Session i is secure, if keys are not expose and...*	Crypto
Secure key-setup	... attacker is given *session keys* k_j, for $j \neq i$, and master-key is not exposed.	Shared key
Forward Secrecy (FS)	... attacker is given *all* keys of sessions $> i$.	Shared key
Perfect forward Secrecy (PFS)	... attacker given all master keys, but only *after* session i ends	Public key
Recover Security (RS)	... no attack during session i, or previous session, $i-1$, was secure	Shared key
Perfect Recover Security (PRS)	... no *MitM* attack during session i, or previous session, $i-1$, was secure	Public key

MitM is an active attacker, not like an eavesdropper!

Covered Material From the Textbook

- Chapter 5
  - Sections 5.3, 5.4, 5.5, and 5.6

Thank You!