GSM Security Overview

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Agenda

- GSM Security Objectives
  - Concerns, Goals, Requirements
- GSM Security Mechanisms
- SIM Anatomy
- Algorithms and Attacks
  - COMP128
  - Partitioning Attack on COMP128
    (J. Rao, P. Rohantgi, H. Scherzer, S. Tunguely)

GSM Security Concerns

- Operators
  - Bills right people
  - Avoid fraud
  - Protect Services
- Customers
  - Privacy
  - Anonymity
- Make a system at least secure as PSTN

GSM Security Goals

- Confidentiality and Anonymity on the radio path
- Strong client authentication to protect the operator against the billing fraud
- Prevention of operators from compromising of each others' security
  - Inadvertently
  - Competition pressure

GSM Security Design Requirements

- The security mechanism
  - MUST NOT
    - Add significant overhead on call set up
    - Increase bandwidth of the channel
    - Increase error rate
    - Add expensive complexity to the system
  - MUST
    - Cost effective scheme
  - Define security procedures
    - Generation and distribution of keys
    - Exchange information between operators
    - Confidentiality of algorithms

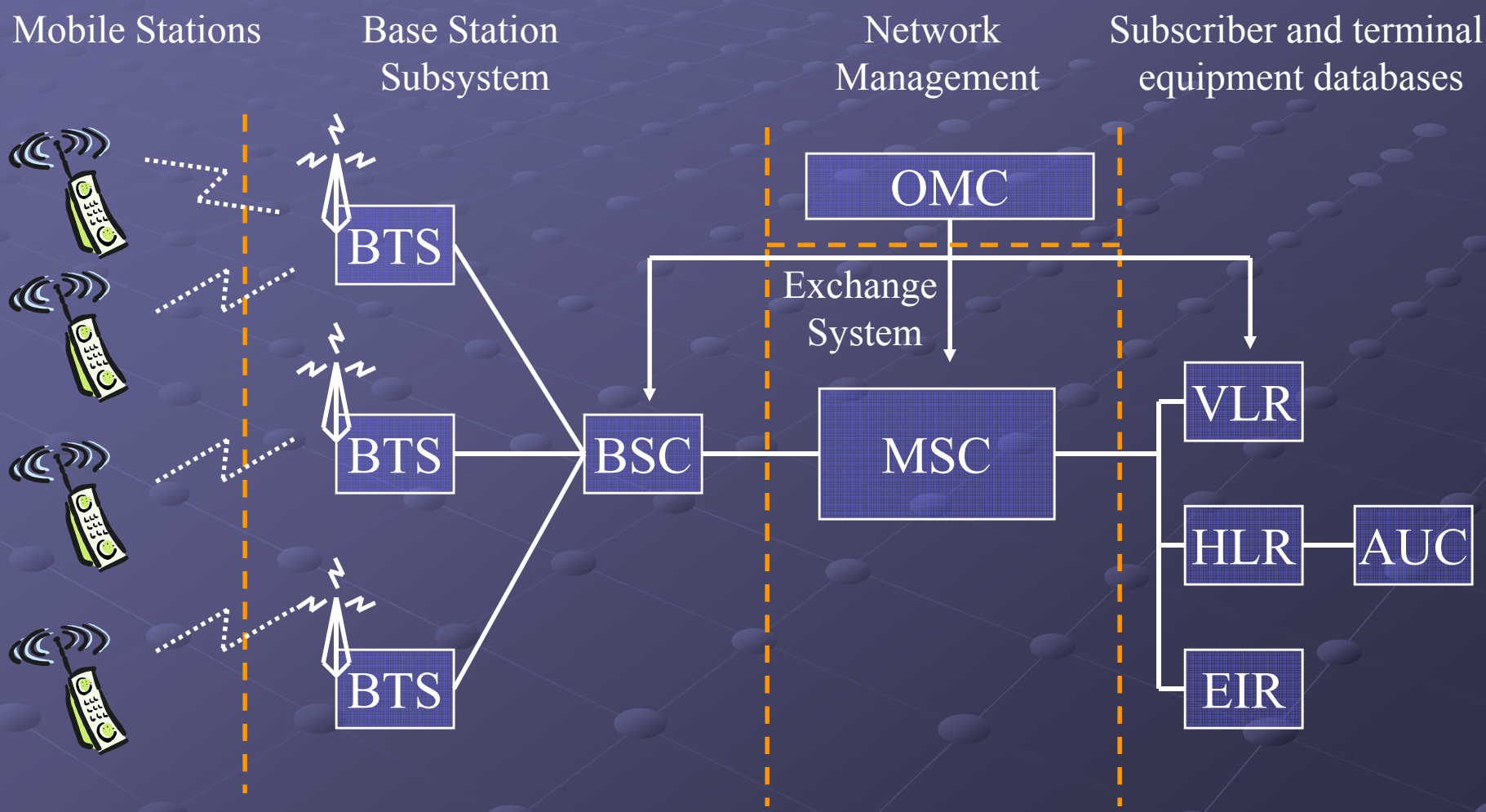
GSM Security Features

- ***Key management is independent of equipment***
  - Subscribers can change handsets without compromising security
- ***Subscriber identity protection***
  - not easy to identify the user of the system intercepting a user data
- ***Detection of compromised equipment***
  - Detection mechanism whether a mobile device was compromised or not
- ***Subscriber authentication***
  - The operator knows for billing purposes who is using the system
- ***Signaling and user data protection***
  - Signaling and data channels are protected over the radio path

GSM Mobile Station

- Mobile Station
  - Mobile Equipment (ME)
    - Physical mobile device
    - Identifiers
      - IMEI – International Mobile Equipment Identity
  - Subscriber Identity Module (SIM)
    - Smart Card containing keys, identifiers and algorithms
    - Identifiers
      - **K_i** – Subscriber Authentication Key
      - IMSI – International Mobile Subscriber Identity
      - TMSI – Temporary Mobile Subscriber Identity
      - MSISDN – Mobile Station International Service Digital Network
      - PIN – Personal Identity Number protecting a SIM
      - LAI – location area identity

GSM Architecture



Subscriber Identity Protection

- TMSI – Temporary Mobile Subscriber Identity
  - Goals
    - TMSI is used instead of IMSI as an a temporary subscriber identifier
    - TMSI prevents an eavesdropper from identifying of subscriber
  - Usage
    - TMSI is assigned when IMSI is transmitted to AuC on the first phone switch on
    - Every time a location update (new MSC) occur the networks assigns a new TMSI
    - TMSI is used by the MS to report to the network or during a call initialization
    - Network uses TMSI to communicate with MS
    - On MS switch off TMSI is stored on SIM card to be reused next time
  - The Visitor Location Register (VLR) performs assignment, administration and update of the TMSI

Key Management Scheme

- K_i – Subscriber Authentication Key
  - Shared 128 bit key used for authentication of subscriber by the operator
  - Key Storage
    - Subscriber's SIM (owned by operator, i.e. trusted)
    - Operator's Home Locator Register (HLR) of the subscriber's home network
- SIM can be used with different equipment

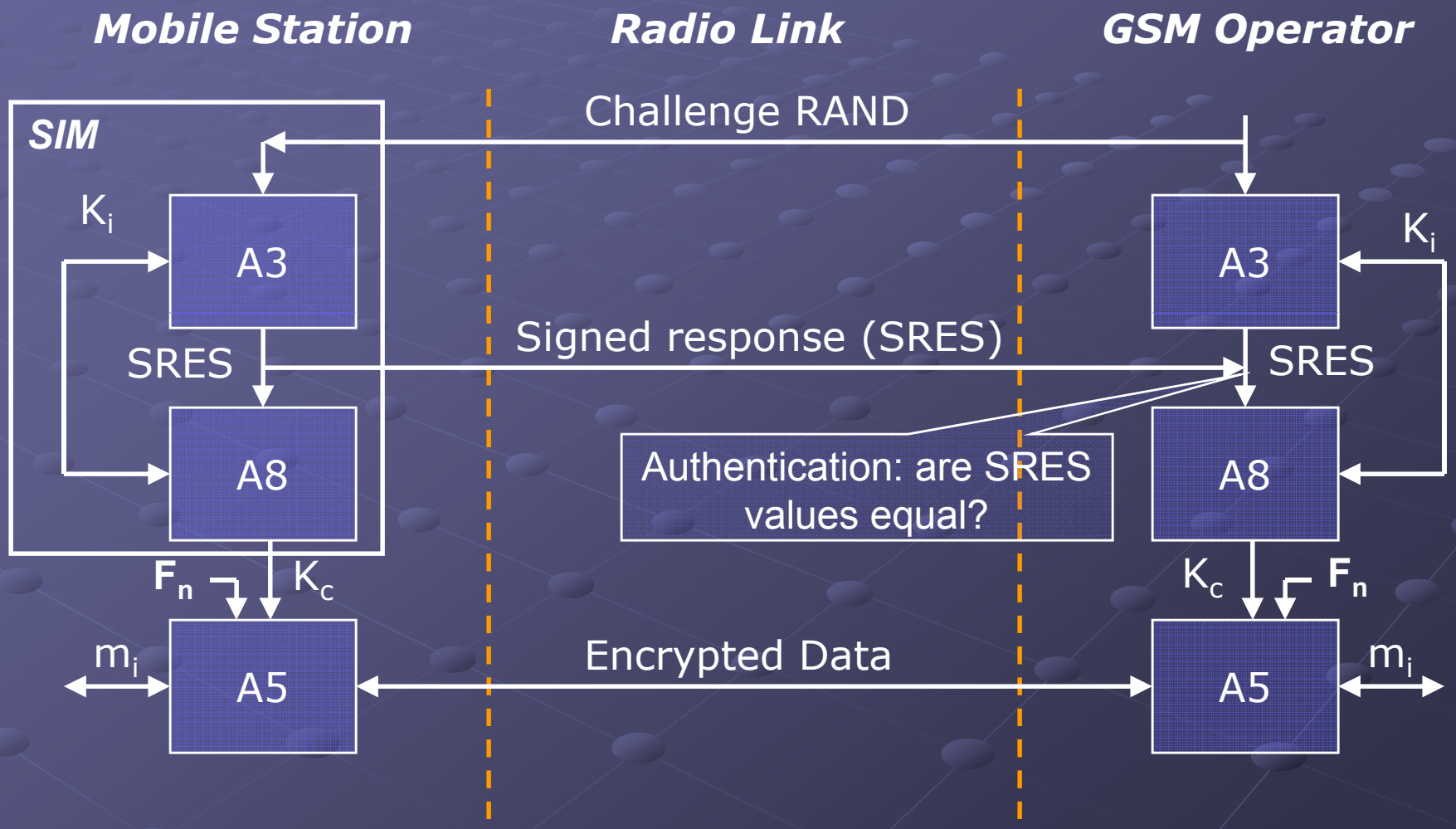
Detection of Compromised Equipment

- International Mobile Equipment Identifier (IMEI)
  - Identifier allowing to identify mobiles
  - IMEI is independent of SIM
  - Used to identify stolen or compromised equipment
- Equipment Identity Register (EIR)
  - Black list – stolen or non-type mobiles
  - White list - valid mobiles
  - Gray list – local tracking mobiles
- Central Equipment Identity Register (CEIR)
  - Approved mobile type (type approval authorities)
  - Consolidated black list (posted by operators)

Authentication

- Authentication Goals
  - Subscriber (SIM holder) authentication
  - Protection of the network against unauthorized use
  - Create a session key
- Authentication Scheme
  - Subscriber identification: IMSI or TMSI
  - Challenge-Response authentication of the subscriber by the operator

Authentication and Encryption Scheme

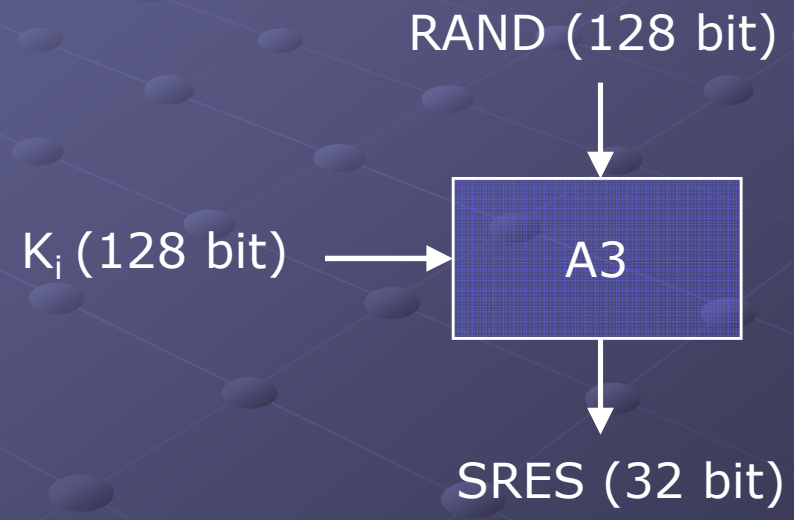


Authentication

- AuC – Authentication Center
  - Provides parameters for authentication and encryption functions (RAND, SRES, K_c)
- HLR – Home Location Register
  - Provides MSC (Mobile Switching Center) with triples (RAND, SRES, K_c)
  - Handles MS location
- VLR – Visitor Location Register
  - Stores generated triples by the HLR when a subscriber is not in his home network
  - One operator doesn’t have access to subscriber keys of the another operator.

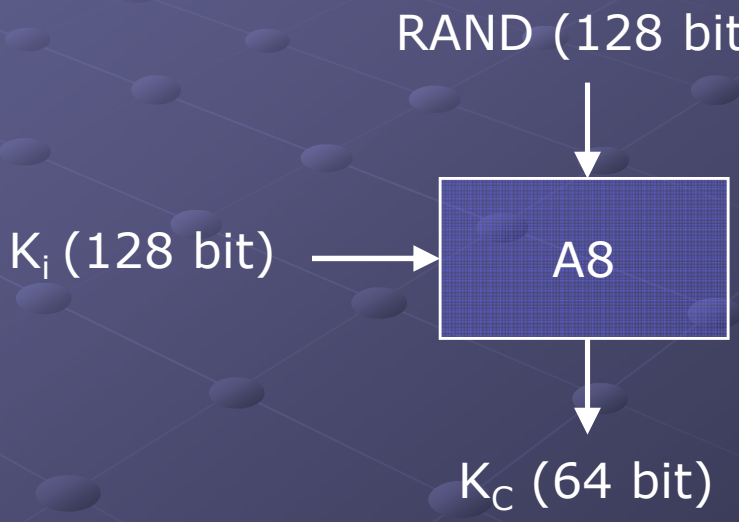
A3 – MS Authentication Algorithm

- Goal
  - Generation of SRES response to MSC's random challenge RAND



A8 – Voice Privacy Key Generation Algorithm

- Goal
  - Generation of session key K_s
    - A8 specification was never made public

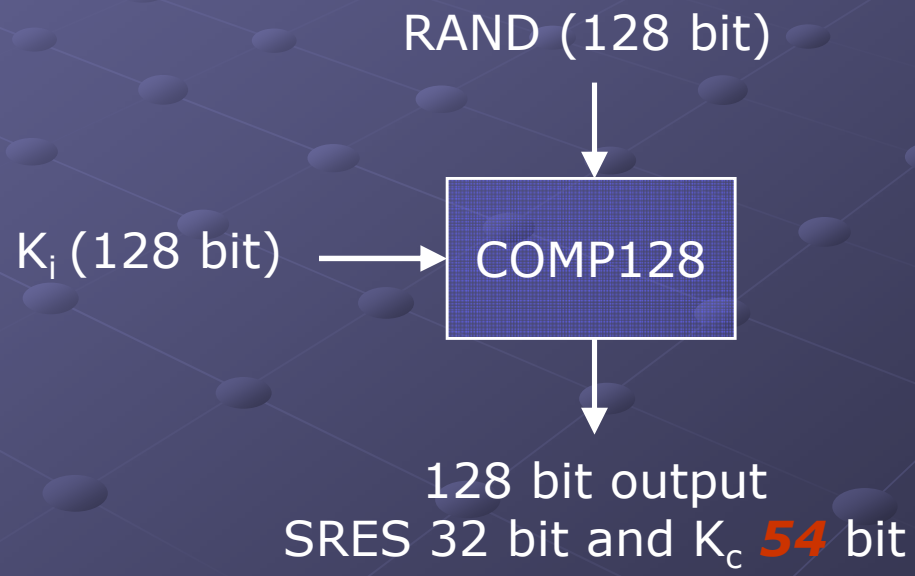


Logical Implementation of A3 and A8

- Both A3 and A8 algorithms are implemented on the SIM
  - Operator can decide, which algorithm to use.
  - Algorithms implementation is independent of hardware manufacturers and network operators.

Logical Implementation of A3 and A8

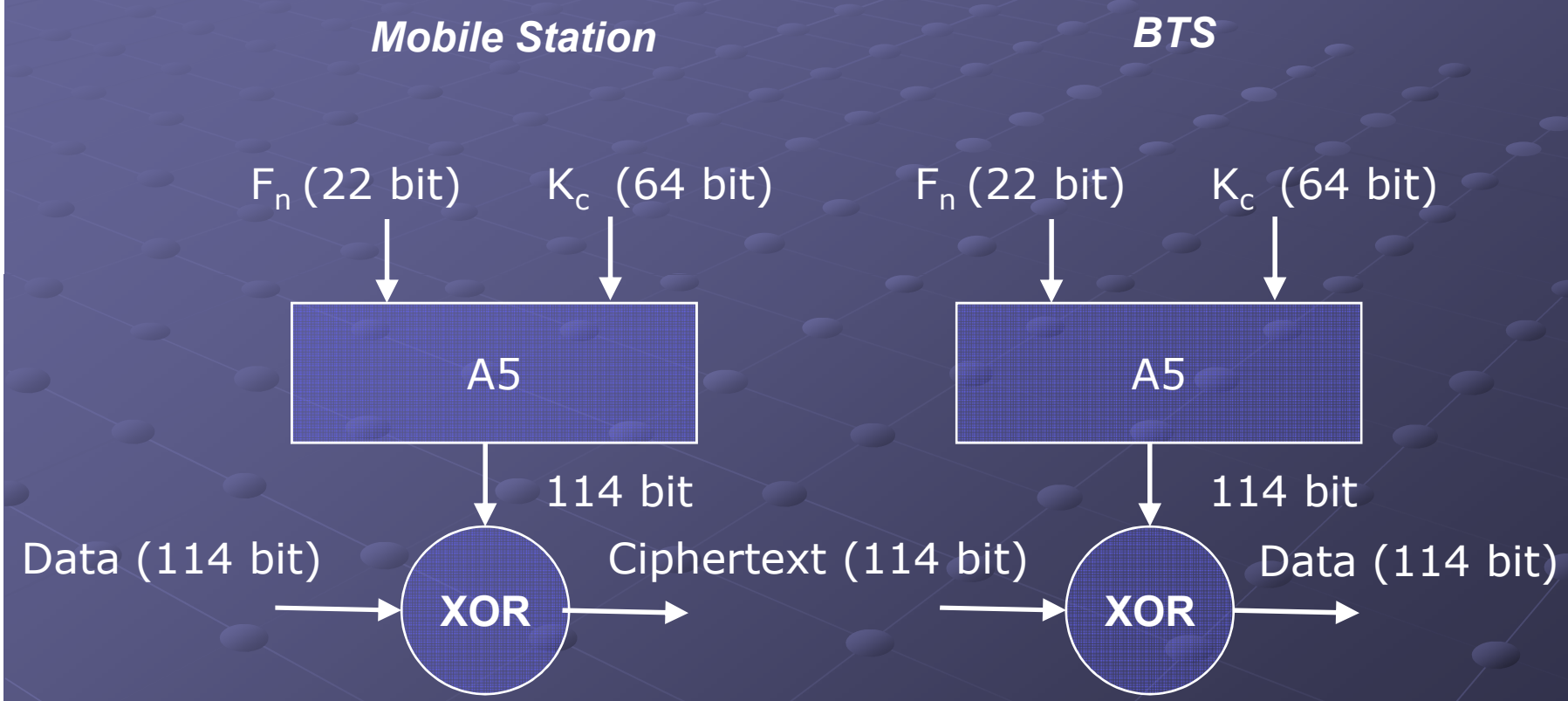
- COMP128 is used for both A3 and A8 in most GSM networks.
  - COMP128 is a keyed hash function



A5 – Encryption Algorithm

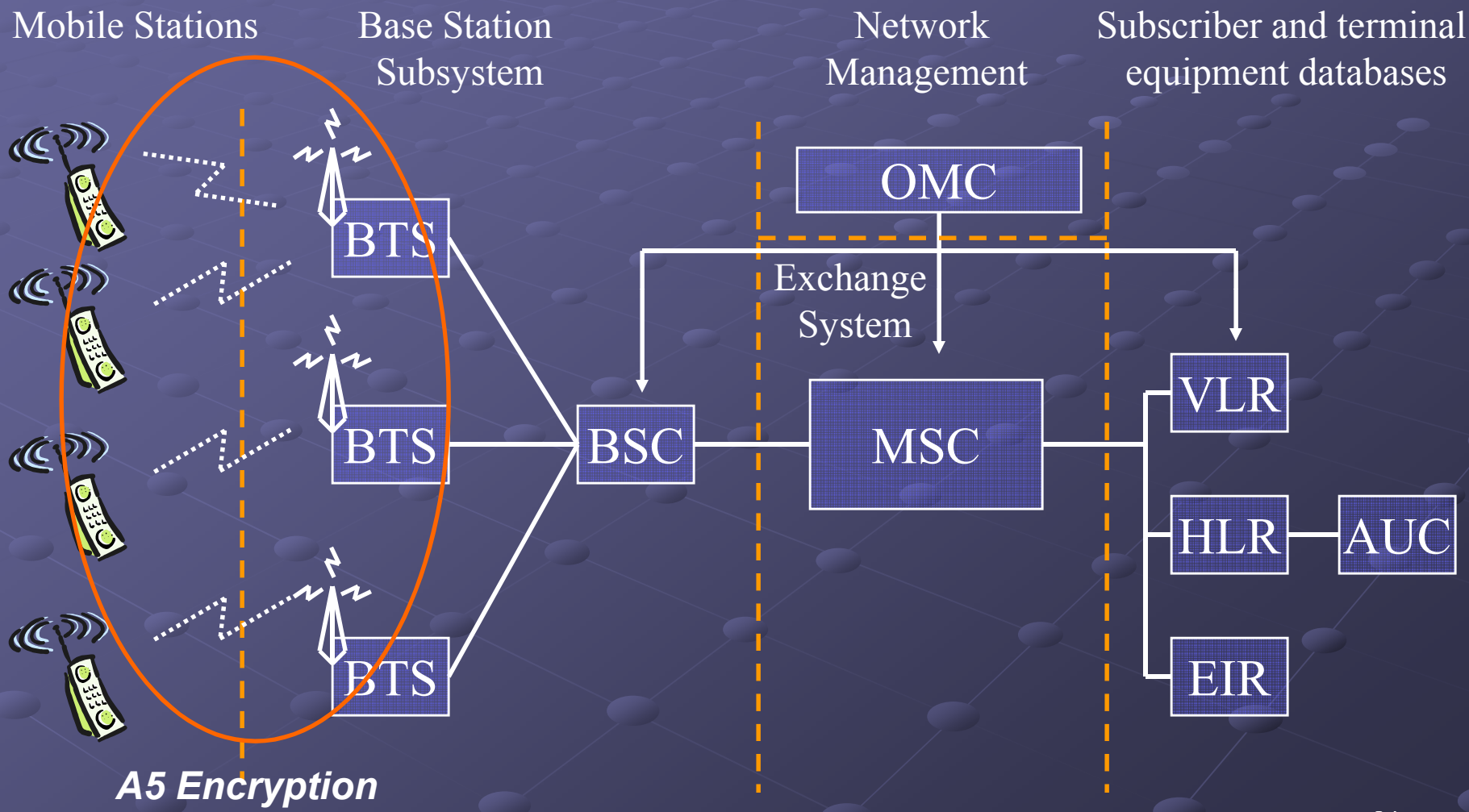
- A5 is a stream cipher
  - Implemented very efficiently on hardware
  - Design was never made public
  - Leaked to Ross Anderson and Bruce Schneier
- Variants
  - A5/1 – the strong version
  - A5/2 – the weak version
  - A5/3
    - GSM Association Security Group and 3GPP design
    - Based on Kasumi algorithm used in 3G mobile systems

Logical A5 Implementation



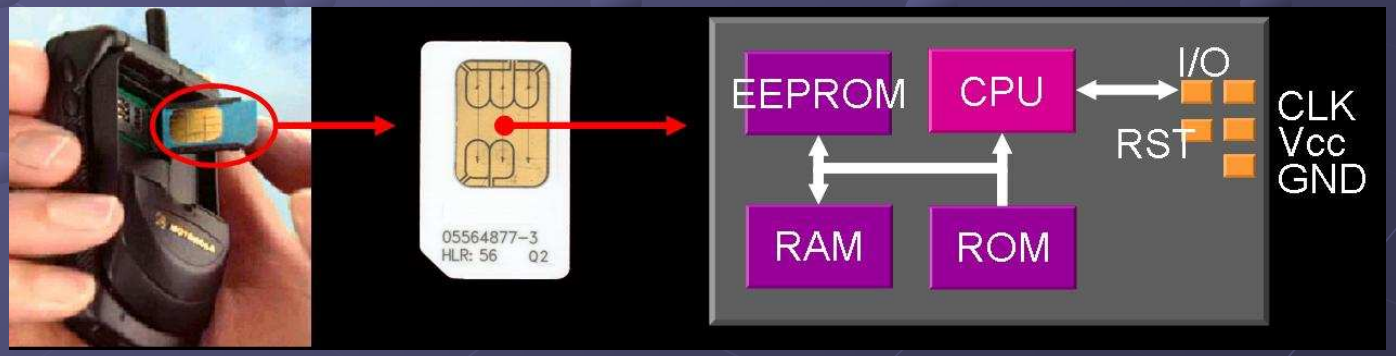
- Real A5 output is 228 bit for both directions

A5 Encryption

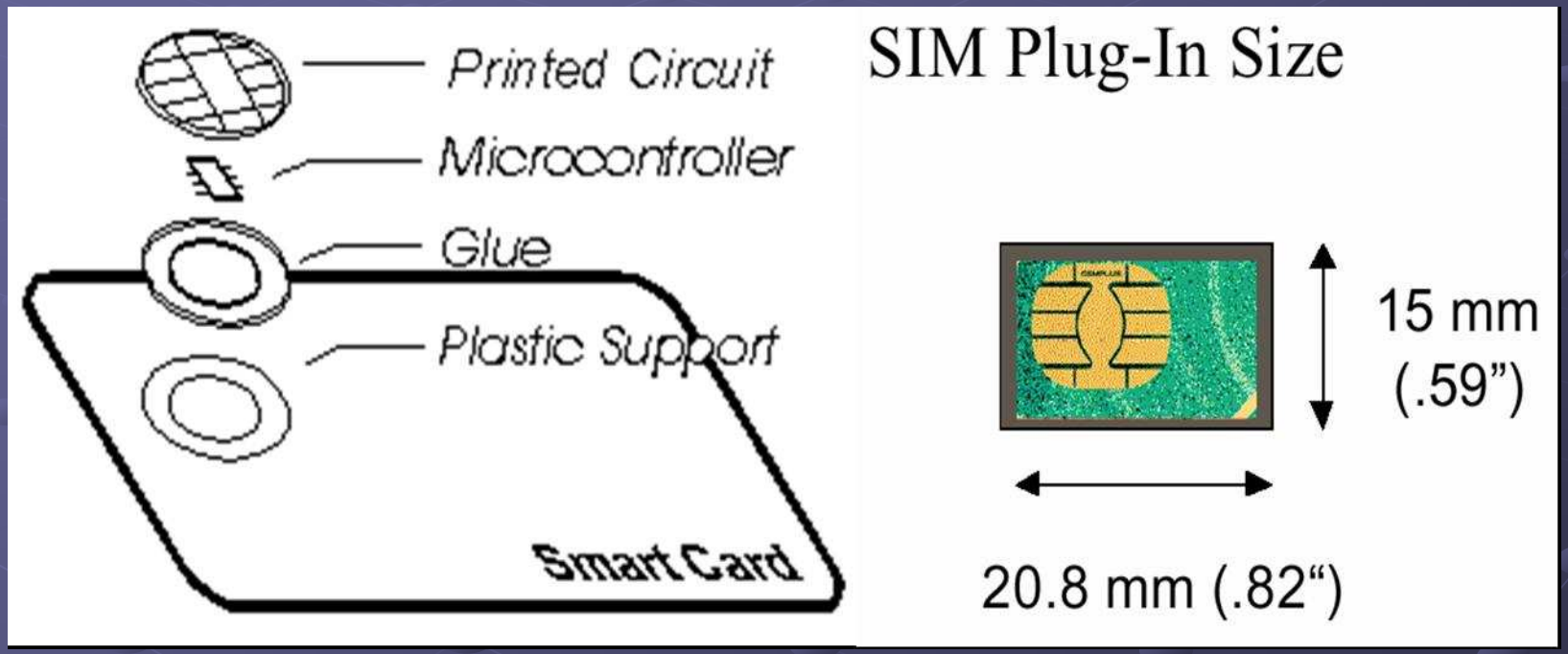


SIM Anatomy

- Subscriber Identification Module (SIM)
  - Smart Card – a single chip computer containing OS, File System, Applications
  - Protected by PIN
  - Owned by operator (i.e. trusted)
  - SIM applications can be written with SIM Toolkit



Smart Card Anatomy



Microprocessor Cards

- Typical specification
  - 8 bit CPU
  - 16 K ROM
  - 256 bytes RAM
  - 4K EEPROM
  - Cost: $5-50
- Smart Card Technology
  - Based on ISO 7816 defining
    - Card size, contact layout, electrical characteristics
    - I/O Protocols: byte/block based
    - File Structure

Algorithm Implementations and Attacks

Attack Categories

- SIM Attacks
- Radio-link interception attacks
- Operator network attacks
  - GSM does not protect an operator's network

Attack History

- 1991
  - First GSM implementation.
- April 1998
  - The Smartcard Developer Association (SDA) together with U.C. Berkeley researches cracked the COMP128 algorithm stored in SIM and succeeded to get K_i within several hours. They discovered that Kc uses only 54 bits.
- August 1999
  - The week A5/2 was cracked using a single PC within seconds.
- December 1999
  - Alex Biryukov, Adi Shamir and David Wagner have published the scheme breaking the strong A5/1 algorithm. Within two minutes of intercepted call the attack time was only 1 second.
- May 2002
  - The IBM Research group discovered a new way to quickly extract the COMP128 keys using side channels.

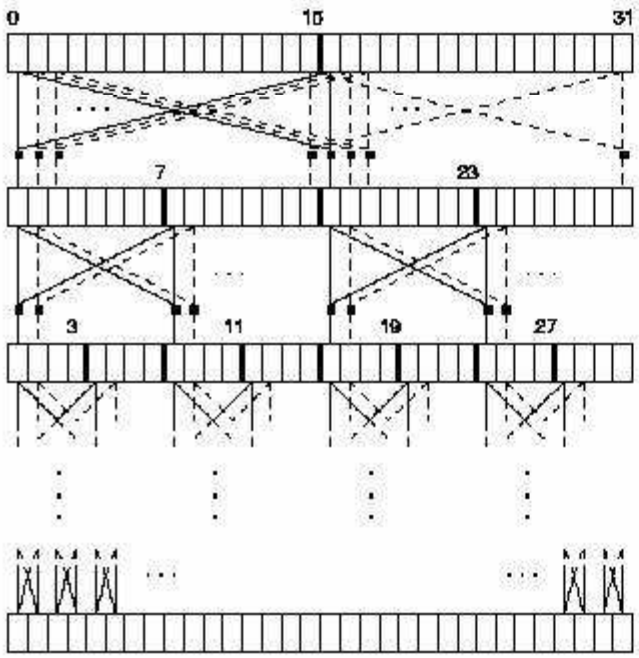
COMP128

Keyed hash function

COMP128

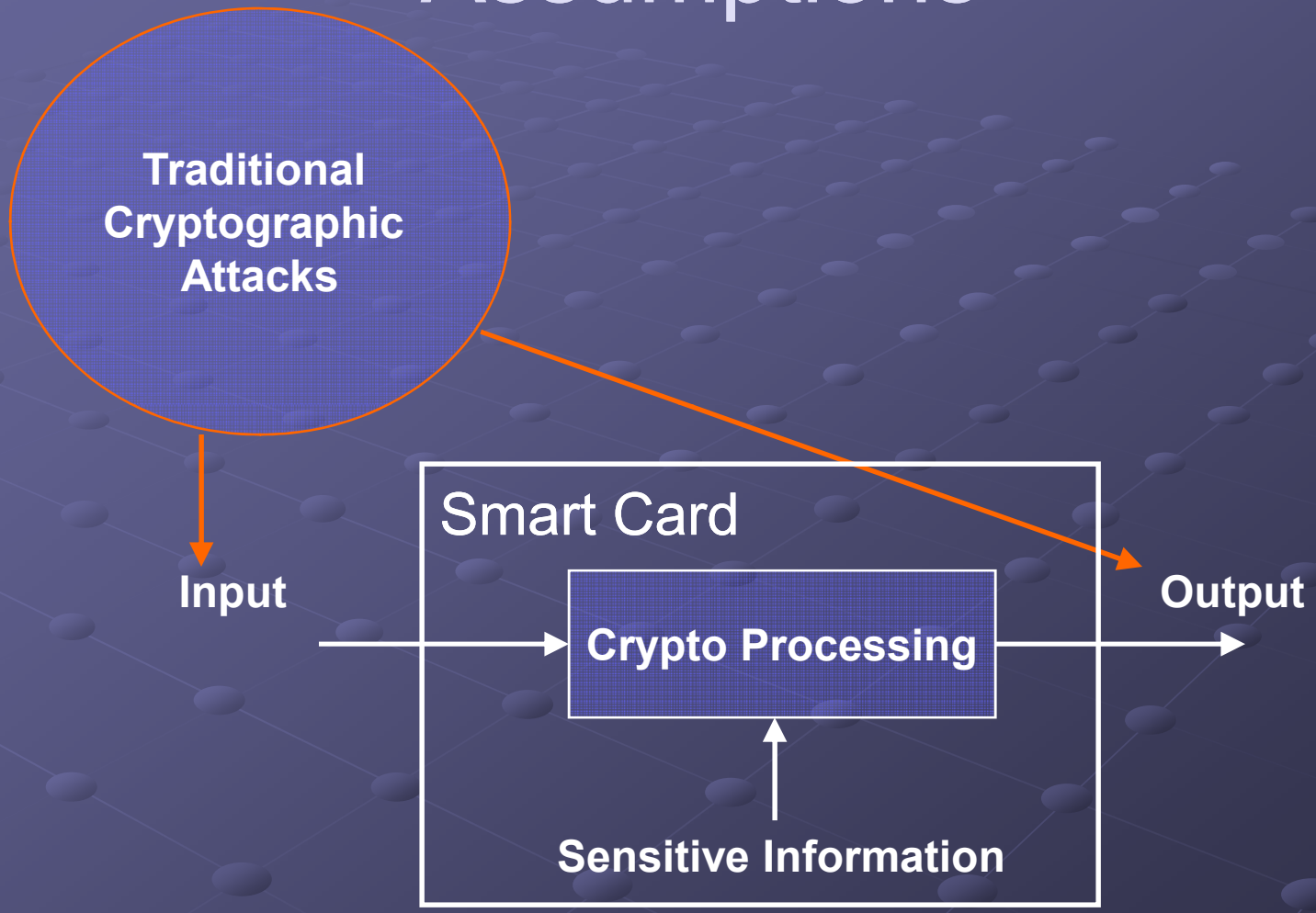
Pseudo-code of the compression in COMP128 algorithm

- ***X[0..15] = K_i; X[16..31] = RAND;***
- **Lookup tables: *T_0[512], T_1[256], T_2[128], T_3[64], T_4[32]***

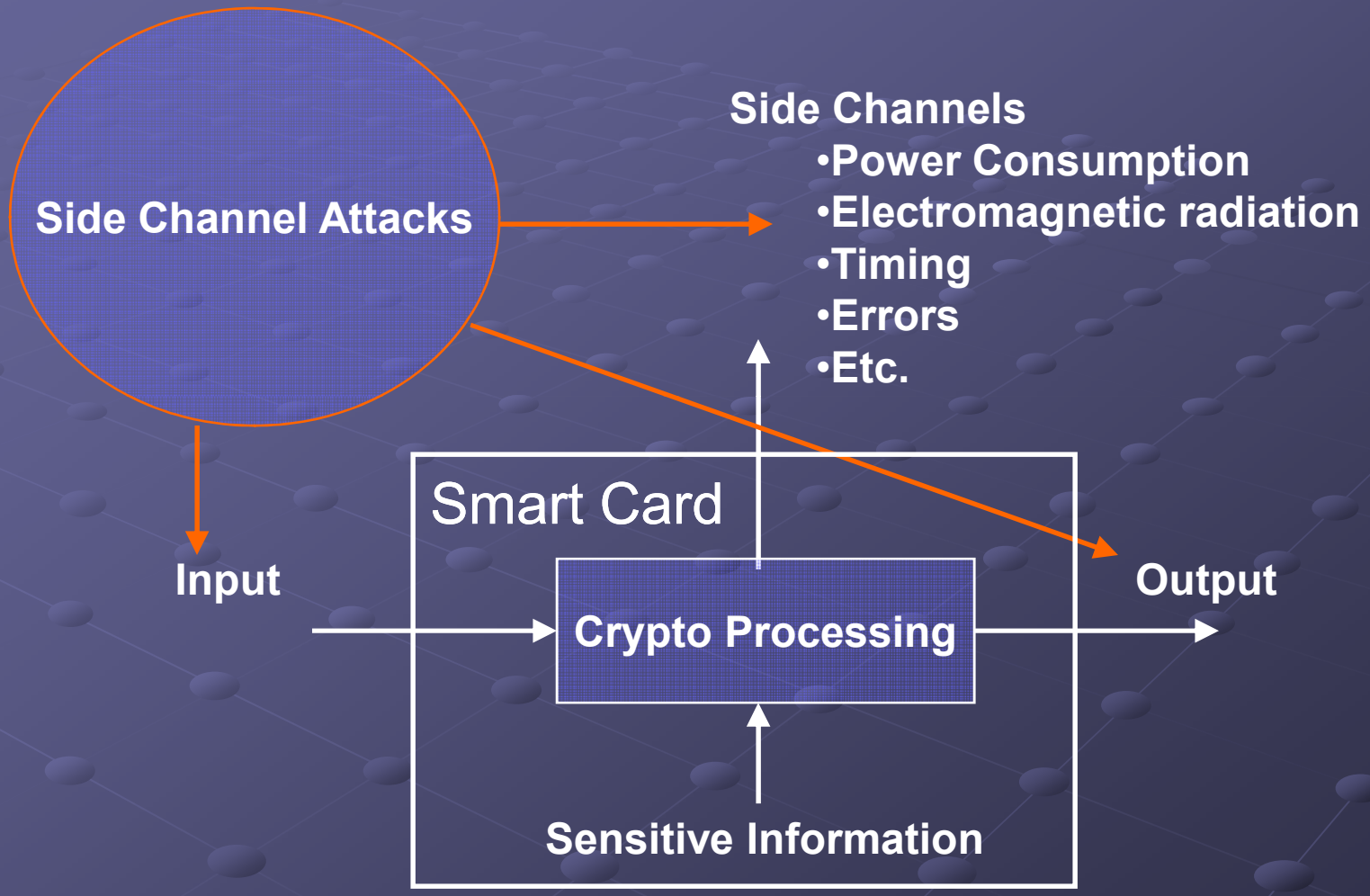


Level 0
$for\ j = 0\ to\ 4\ do\ \{$
$for\ k = 0\ to\ 2^{j}\text{-}1\ do\ \{$
$for\ l = 0\ to\ 2^{(4-j)}\text{-}1\ do\ \{$
$m = l + k*2^{(5-j)};$
Level 1
$n = m + 2^{(4-j)};$
$y = (X[m] + 2*X[n])\ mod\ 2^{(9-j)};$
$z = (2*X[m] + X[n])\ mod\ 2^{(9-j)};$
Level 2
$X[m] = Tj[y];$
$X[n] = Tj[z]$
$\}$
Level 4
$\}$
$\}$

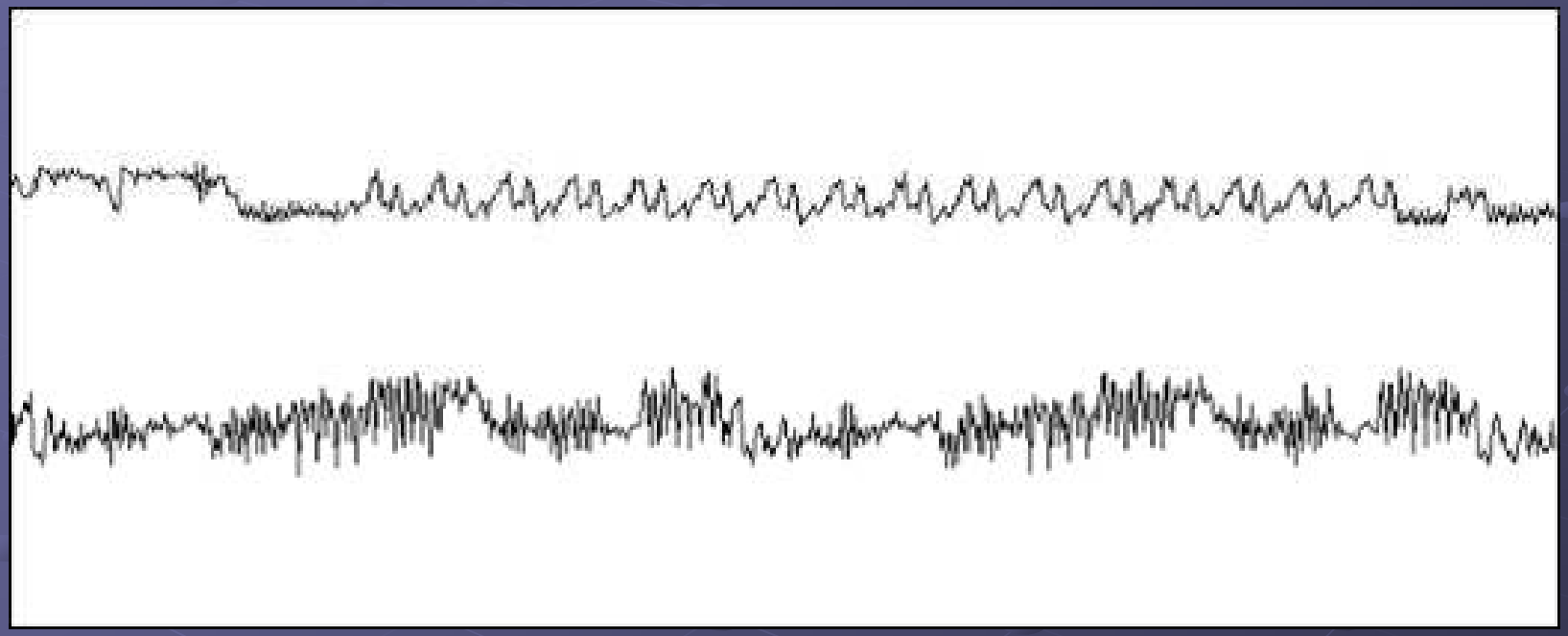
Traditional Cryptographic Assumptions



Actual Information Available



Simple Power DES Analysis



- SPA of DES operation performed by a typical Smart Card
  - Above: initial permutation, 16 DES rounds, final permutation
  - Below: detailed view of the second and third rounds

Partitioning Attack on COMP128

- Attack Goal
  - K_i stored on SIM card
  - Knowing K_i it's possible to clone SIM
- Cardinal Principle
  - *Relevant bits of all intermediate cycles and their values should be statistically independent of the inputs, outputs, and sensitive information.*
- Attack Idea
  - Find a violation of the *Cardinal Principle*, i.e. side channels with signals does depend on input, outputs and sensitive information
  - Try to exploit the *statistical dependency* in signals to extract a sensitive information

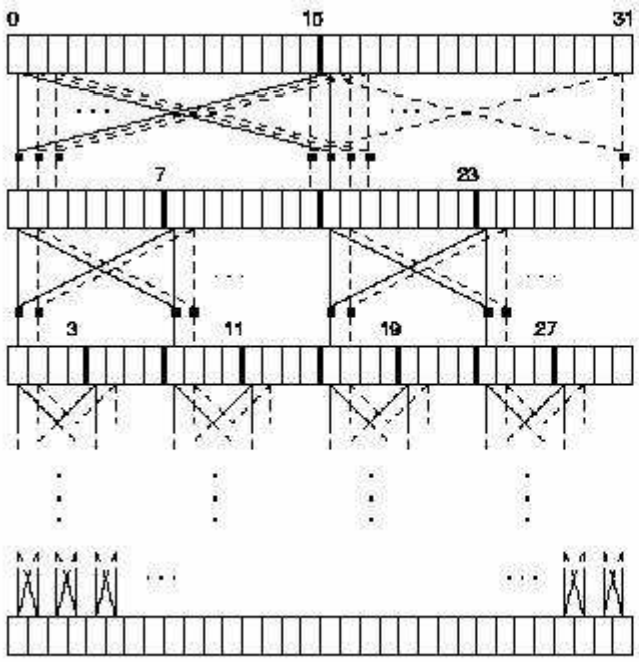
Partitioning Attack on COMP128

- How to implement 512 element T_0 table on 8 bit Smart Card (i.e. index is 0..255)?
  - Split 512 element table into two 256 element tables
- **It's possible to detect access of different tables via side channels!**
  - Power Consumption
  - Electromagnetic radiation

Partitioning Attack on COMP128

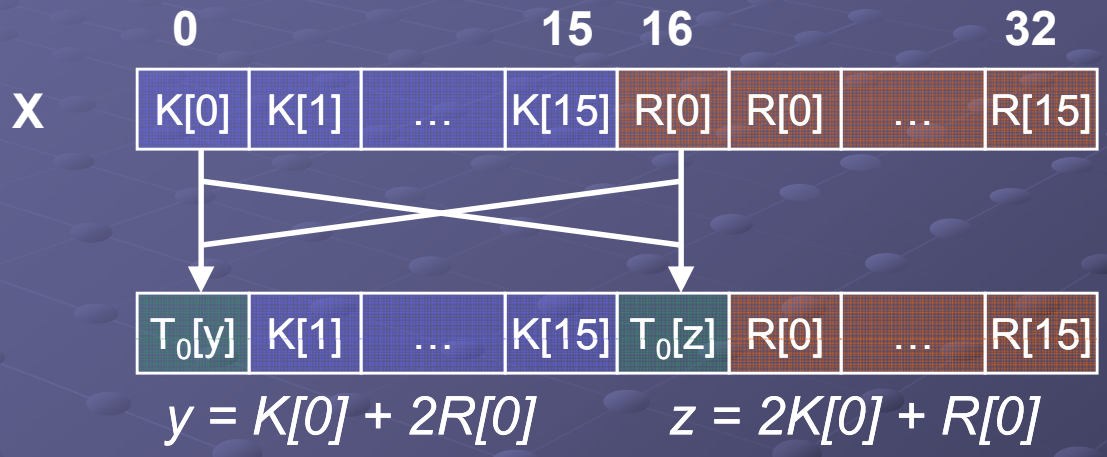
Pseudo-code of the compression in COMP128 algorithm

- ***X[0..15] = K_i; X[16..31] = RAND;***
- **Lookup tables: *T_0[512], T_1[256], T_2[128], T_3[64], T_4[32]***




```
Level 0   for j = 0 to 4 do {
              for k = 0 to 2^j - 1 do {
                  for l = 0 to 2^(4-j) - 1 do {
                      m = l + k*2^(5-j);
Level 1               n = m + 2^(4-j);
                      y = (X[m] + 2*X[n]) mod 2^(9-j);
                      z = (2*X[m] + X[n]) mod 2^(9-j);
Level 2               X[m] = Tj[y];
                      X[n] = Tj[z]
                  }
              }
Level 4   }
```

Partitioning Attack on COMP128



- Values of *y* and *z* depend on the first bytes of *K* and *R*
- It's possible to detect via side channels whether values of *y* and *z* are within [0..255] or [256..511].

Partitioning Attack on COMP128

- All we need is…
  - A) Find *R[0]* such that

    K[0] + 2R[0] (mod 512) < 256

    K[0] + 2(R[0]+1) (mod 512) >= 256

    (There are only two options)
  - B) Find R'[0] such that

    2K[0] + R'[0] (mod 512) < 256

    2K[0] + R'[0] + 1 (mod 512) >= 256
  - C) One of *K[0]* from A) will match B)
- The key byte is always uniquely determined from partitioning information.
- Computation of the others bytes of *K* is similar.

Summary

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- SIM Anatomy
- Algorithms and Attacks
  - COMP128
  - Partitioning Attack on COMP128