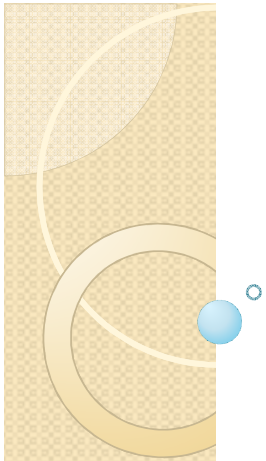


Wireless Security I
--Cellular Networks

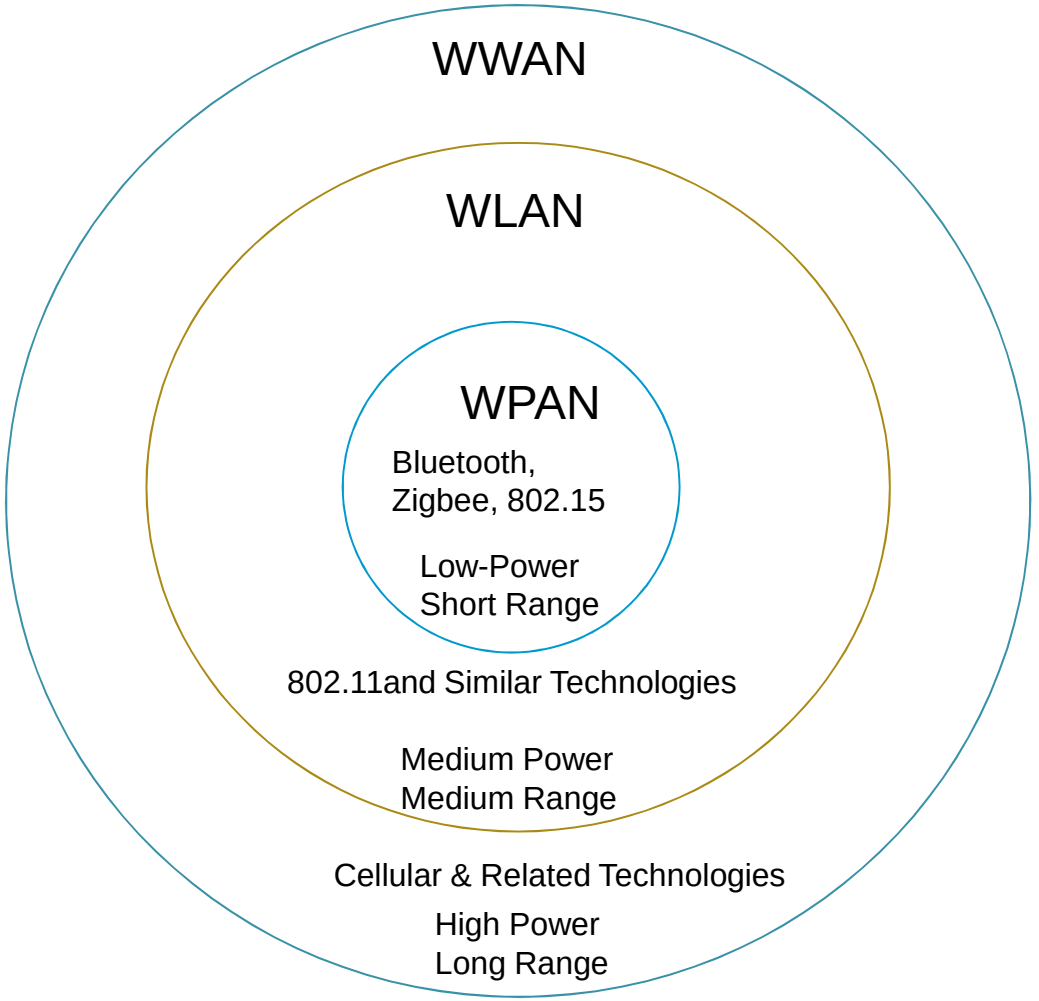
Outline

- Wireless networks
- Wireless security challenges
- GSM security
  - current status, attacks and remedies
- 3GPP security

Classification of Wireless Networks

- WLAN: 802.11
- Cellular networks: GSM, 3GPP
- WWAN: WiMAX, 802.16
- Ad hoc networks
- Sensor networks
- WPAN: Bluetooth, Zigbee, 802.15
- Wireless mesh networks

Modern Wireless Networks



Wireless Protocols

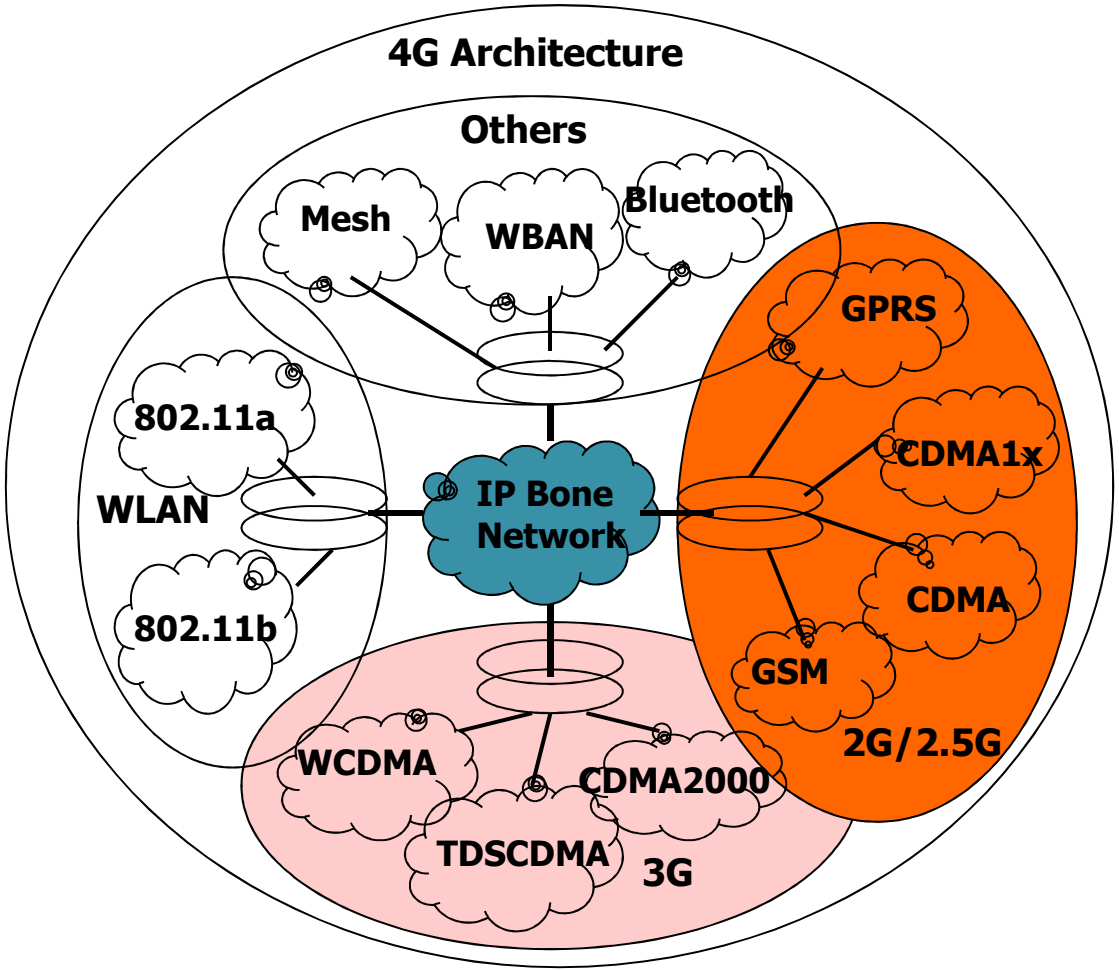
- Bluetooth
- 802.11a
- 802.11b
- 802.11g
- Others

Transportation (SSL/TLS)
Network (IPSec, VPN)
MAC (WEP, WPA, WPA2, 802.11i)

Wireless Security Challenges

- A number of unsolved threats in wired networks
- Shared wireless medium
- Vulnerable protocol design
- Difficulty in identifying anomalies
- Physical loss or theft of mobile devices
- Resource constraints of mobile devices
- Lack of a centralized authority or administration
- More…

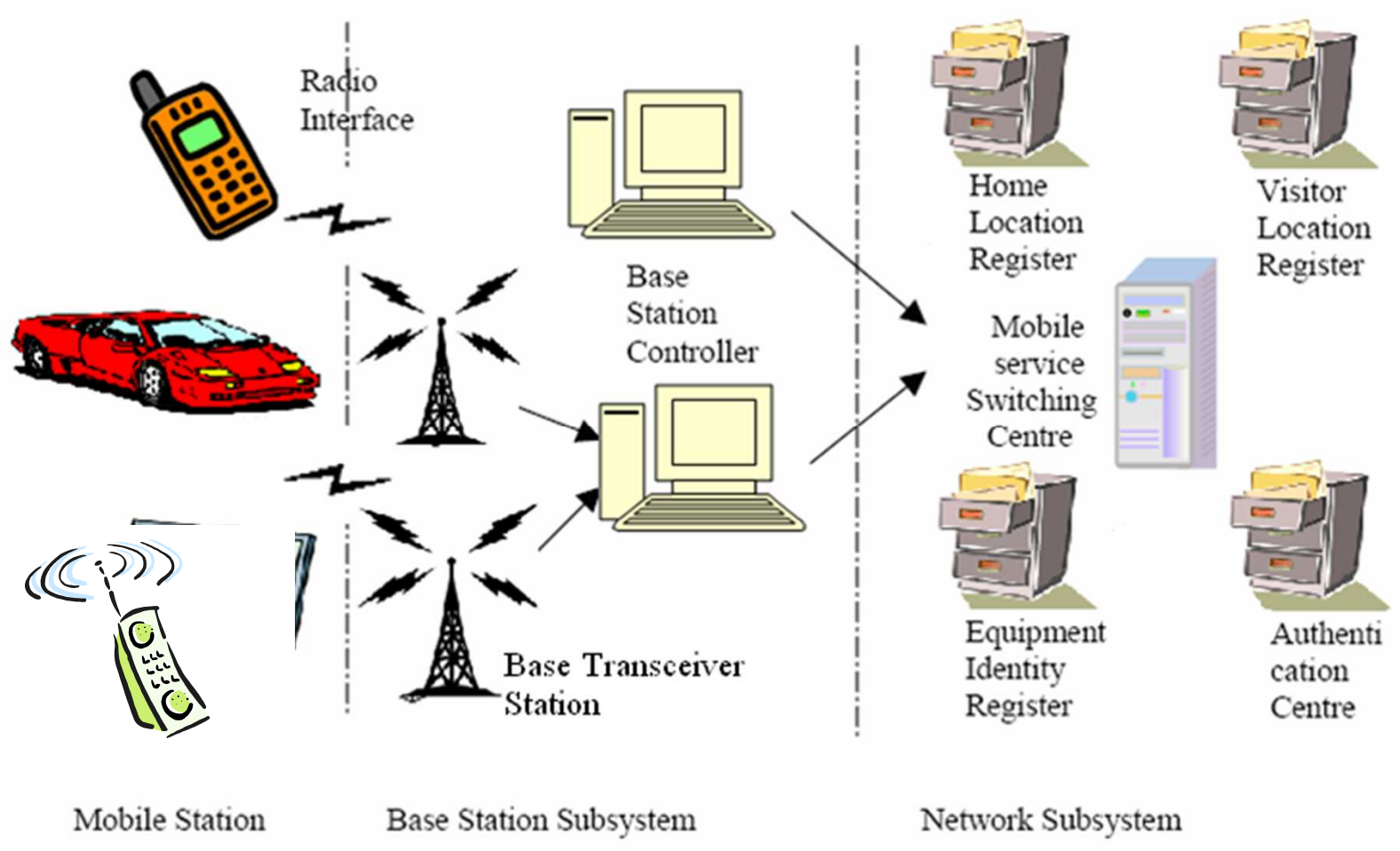
Cellular Networks



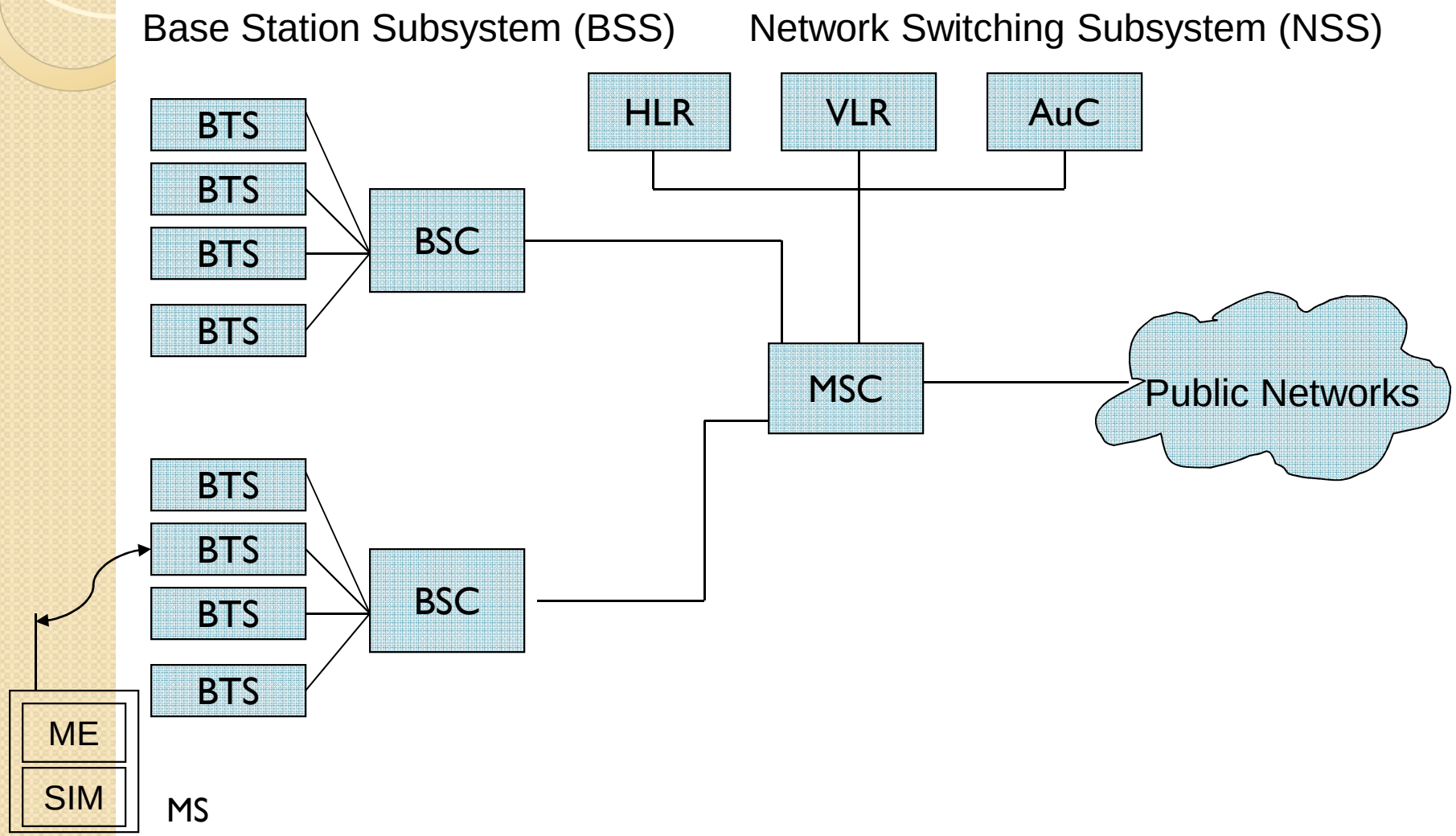
GSM

- Global System for Mobile Communications
  - GSM is most popular standard for mobile phones
  - The GSM Association estimates 82% of the global mobile market uses this standard
  - Two billion people across more than 200 countries use GSM
- Services
  - Voice Communication, Short Messaging Service, …etc.

GSM Architecture 1



GSM Architecture 2



Mobile Station

- Mobile Equipment
  - International Mobile Equipment Identity (IMEI)
- Subscriber Identity Module (SIM) card
  - Smart Card containing identifiers, keys and algorithms

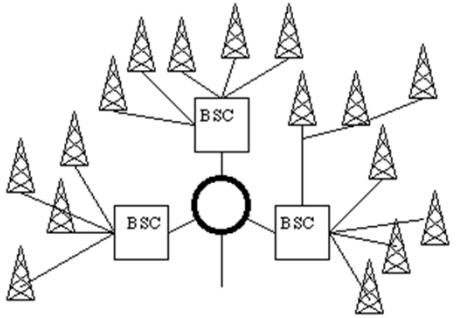
The SIM Card

- SIM (Subscriber Identity Module)
  - A small smartcard inserted into a GSM phone
  - Contains (at least)
    - IMSI – International Mobile Subscriber Identity
    - Ki – a 128-bit key obtained from AuC during registration, the long-term key used for authentication and cipher key generation
    - A3/A8 implementations
  - Protected by an optional PIN and a PUK (PIN Unlock)
  - Locked after a few invalid inputs of PIN (normally 3) and becoming permanently useless after a number of invalid inputs of PUK (normally 10)

Base Station Subsystem

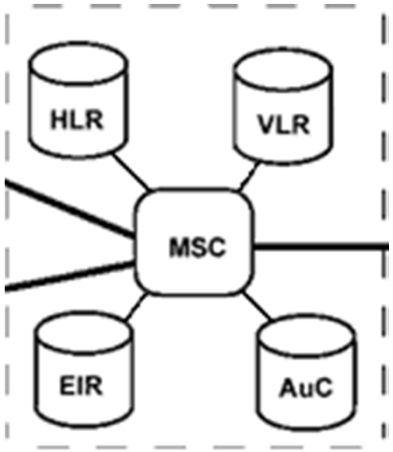
- Base Transceiver Station (BTS)
  - A cell is formed by the radio coverage of a BTS
  - Provide the radio channels and handle the radio-link protocol

- Base Station Controller (BSC)
  - Manage the radio resources for one or more BTS
  - Handle channel setup and handovers
  - Connect to the mobile service switching center



Network Subsystem

- Component in Network Subsystem
  - MSC: Mobile services Switching Center
  - HLR: Home Location Register
  - VLR: Visitor Location Register
  - AuC: Authentication Center
  - EIR: Equipment Identity Register
- Network Subsystem features
  - Telephone switching function
  - Subscriber profile
  - Mobility management



GSM Basic Security Goals

- Subscriber authentication to protect the operator against the billing fraud
- Confidentiality on the radio path
- User anonymity/location privacy

GSM Security Design Requirements

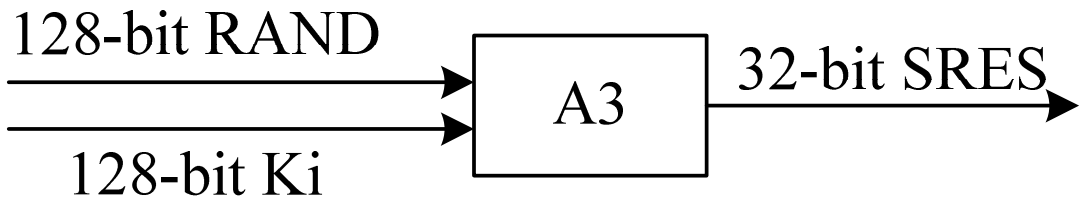
- The security mechanism
  - MUST NOT
    - Add significant overhead on call set up
    - Increase bandwidth of the channel
    - Increase error rate
    - Add expensive complexity to the system
  - MUST
    - Use cost effective scheme
- How to Design?

GSM Security Features

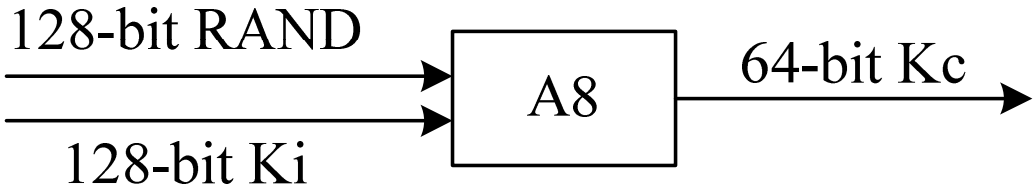
- Subscriber authentication
  - The operator knows for billing purposes who is using the system
- Signaling and user data confidentiality
- Subscriber identity protection/user privacy
  - The transmission of the IMSI in plaintext over the air should be avoided wherever possible
  - Somebody intercepting communications should not be able to learn if a particular mobile user in the area
- Key management is independent of equipment
- Detection of compromised equipment

Crypto Algorithms in GSM

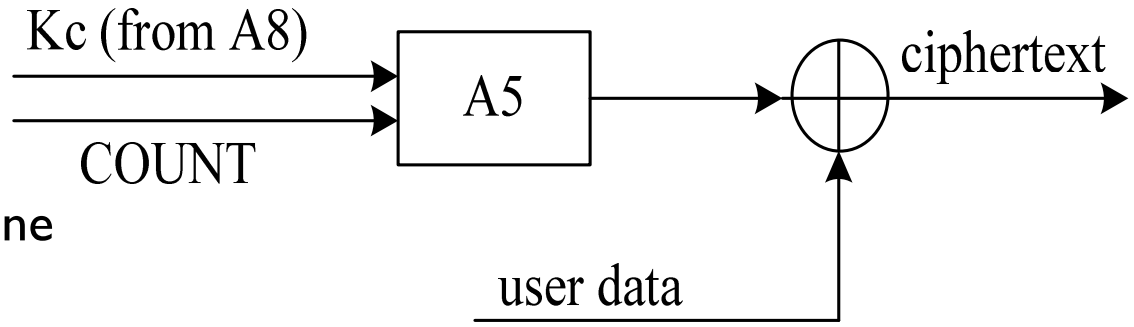
- Authentication
  - In the SIM



- Key generation
  - In the SIM



- Encryption
  - In the phone



Crypto Algorithms in GSM

- A3/A8 left at the discretion of the operator
- COMP128 – ill-advised by GSM standards
  - Outputs a 128-bit result
  - First 32 bits producing the A3 output
  - Last 54 bits concatenated by 10 zeros producing the A8 output
  - Cracked in 1998 and still in use

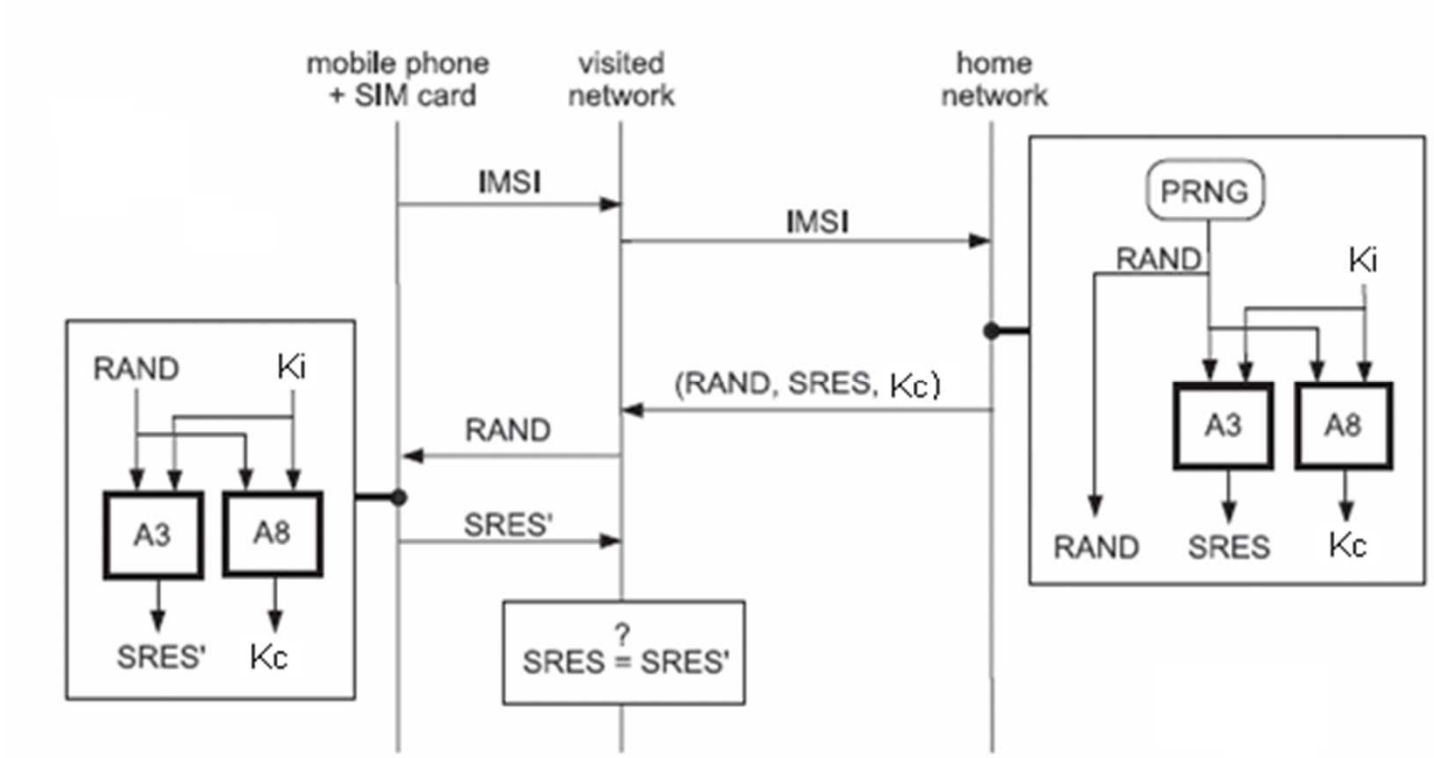
Authentication

- Authentication Goals
  - Subscriber (SIM holder) authentication, protection of the network against unauthorized use
  - Create a session key for the next communication
- Authentication Scheme
  - Subscriber identification: IMSI
  - Challenge-Response authentication of the subscriber
  - Long-term secret key shared between the subscriber and the home network
  - Supports roaming without revealing long-term key to the visited networks

Authentication Parameters

- Network Contains
  - AuC : Authentication Center
  - HLR : Home Location Register
- Algorithms
  - A3: Mobile Station Authentication Algorithm
  - A8: Session (cipher) key generation Algorithm
  - PRNG: Pseudo-Random Number Generator
- Random number, keys and signed response

GSM Authentication Protocol



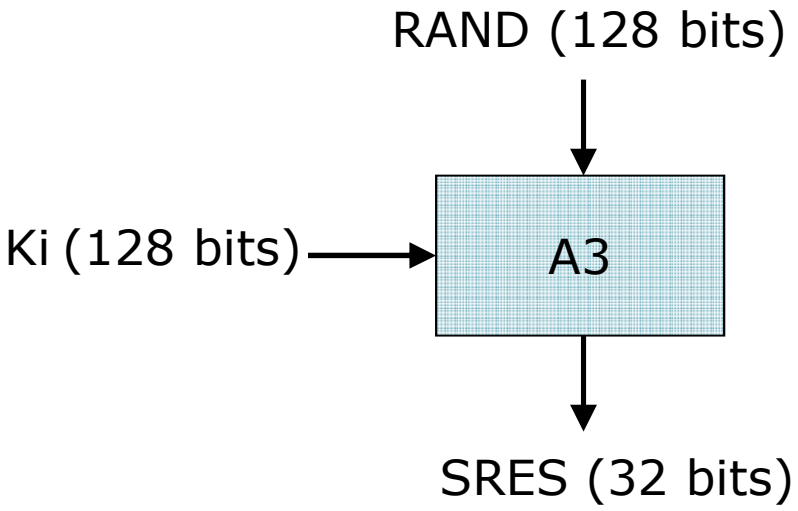
IMSI: International Mobile Subscriber Identity
RAND: Random Number
SRES: Signed Response
Ki: Stored in the HLR as well as in the SIM
Kc: Cipher Key

Authentication Procedure

- MS send IMSI to the network subsystem (AuC and HLR)
- The network subsystem received the IMSI and find the correspondent Ki of the IMSI
- The AuC generate a 128-bit RAND and send (RAND, SRES, Kc) to MS
- The AuC calculate the SRES with A3 algorithm
- MS calculates a SRES with A3 using Ki and the given RAND
- MS sends the SRES' to the network
- The visited network compare the SRES and SRES' for verification

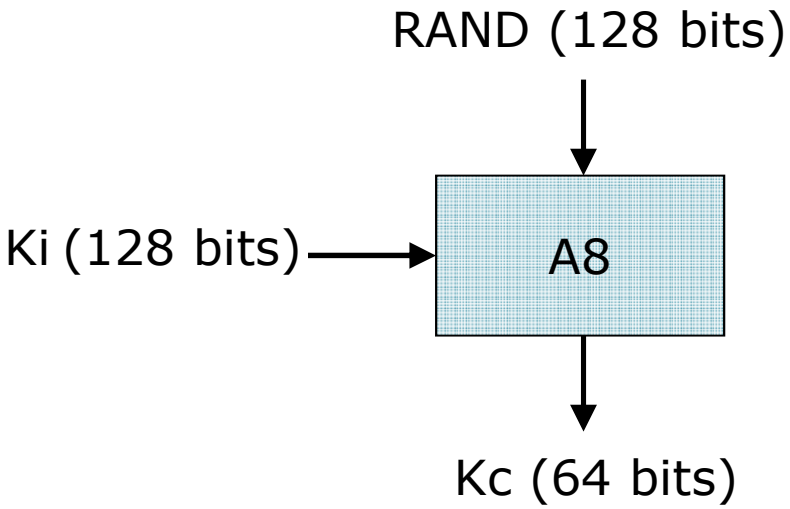
A3 – Authentication Algorithm

- Goal
  - Generation of SRES response to random number RAND



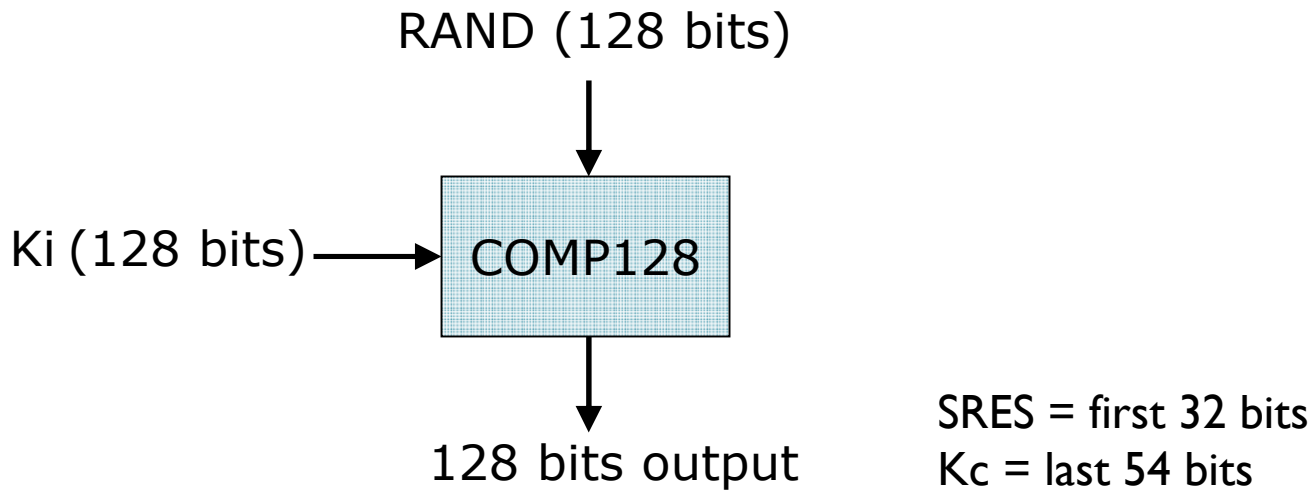
A8 – Cipher Key Generation Algorithm

- Goal - Voice Privacy
  - Generation of Cipher key - Kc



Implementation of A3 and A8

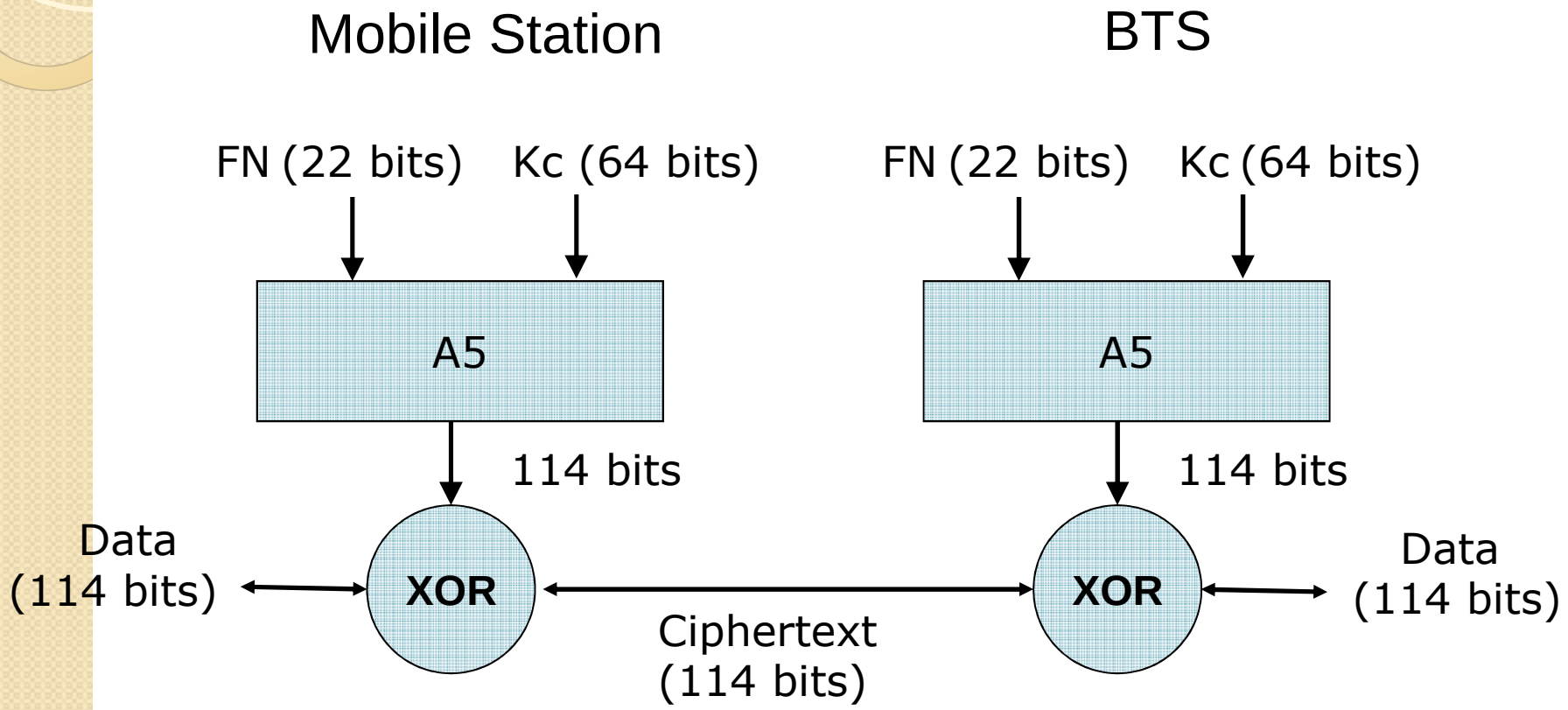
- Both A3 and A8 algorithms are implemented on the SIM. It is independent of hardware manufacturers and network operators.
- COMP128 is keyed hash function, used for both A3 and A8 in most GSM networks.



Confidentiality

- After the authentication protocol, cipher key Kc is shared between the subscriber and the visited network.
- A5 is used as an over-the-air voice privacy algorithm
  - A5 is a stream cipher
  - Implemented very efficiently on hardware
  - A5/1 – the strong version
  - A5/2 – the weak version

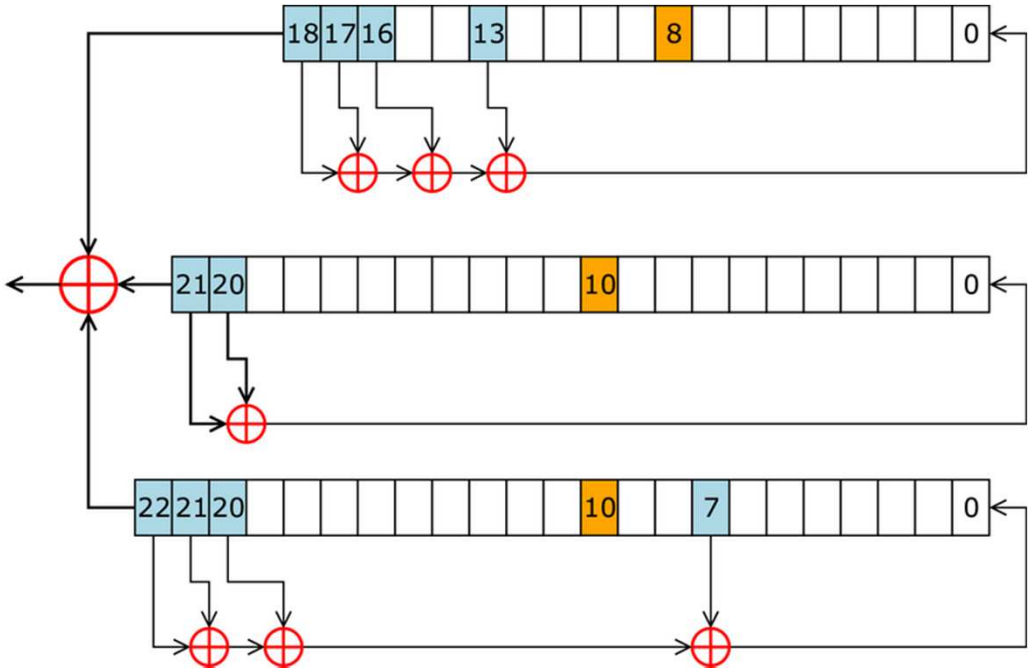
Encryption Scheme



FN : Frame Number

CK: Cipher Key

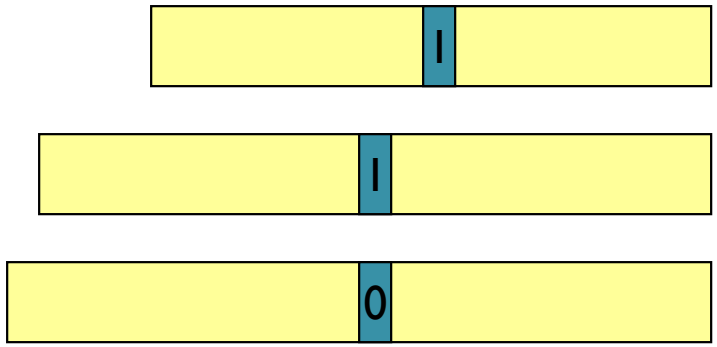
A5/1 Shift Registers



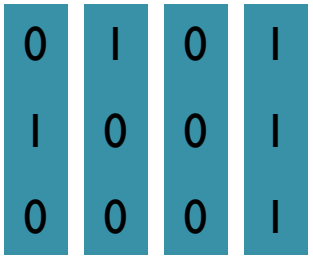
LFSR	Length in bits	Characteristic polynomial	Clocking bit	Tapped bits
1	19	$x^{18} + x^{17} + x^{16} + x^{13} + 1$	8	13, 16, 17, 18
2	22	$x^{21} + x^{20} + 1$	10	20, 21
3	23	$x^{22} + x^{21} + x^{20} + x^{7} + 1$	10	7, 20, 21, 22

Clock Controlling of A5/1

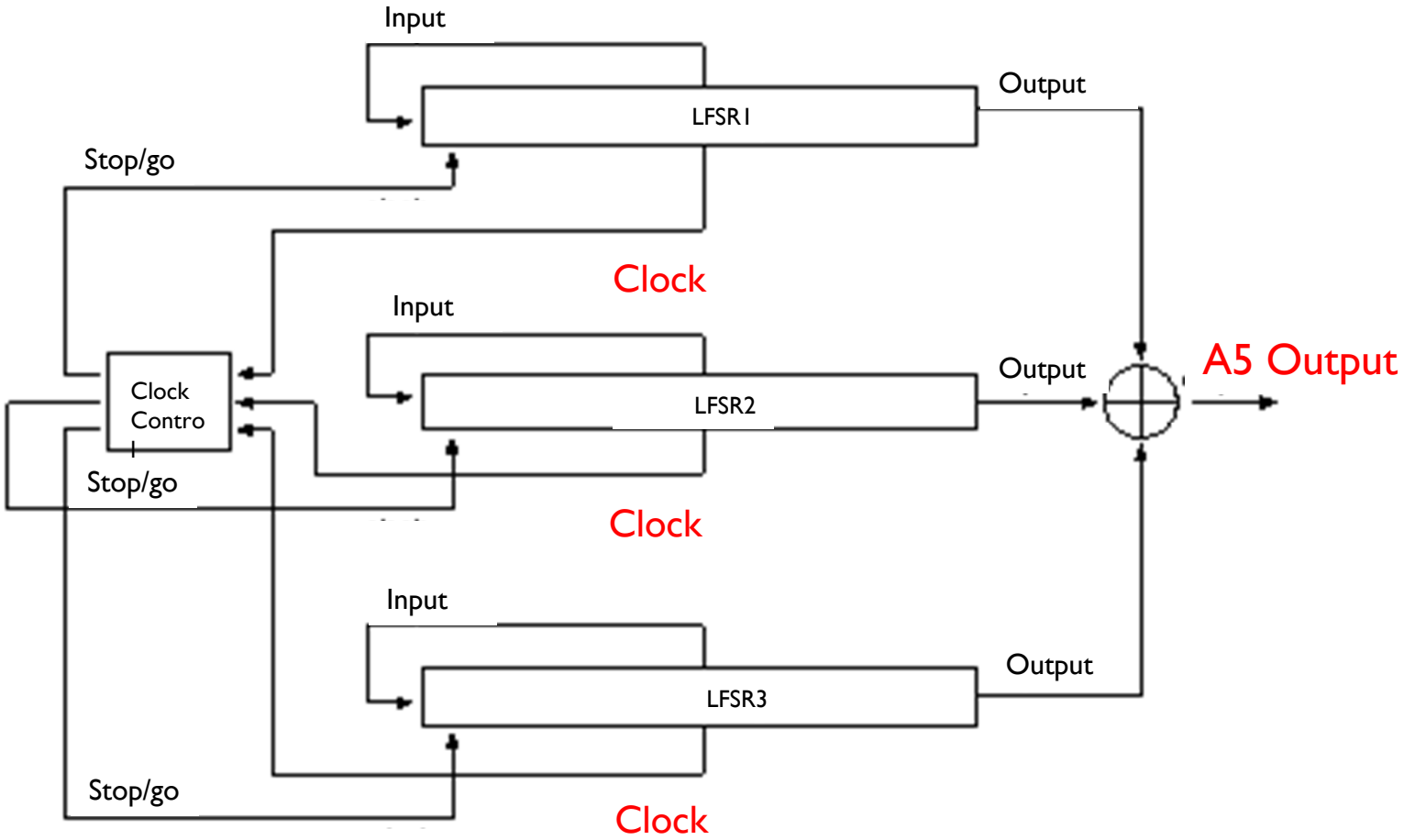
- Three clocking bits in the middle of register are extracted and their majority is calculated
- Two or three registers whose bit agrees with the majority are clocked



How about?



A5/1 Architecture



Description of A5/1

1. Set all LFSRs to 0 ($R_1 = R_2 = R_3 = 0$).
2. For $i := 0$ to 63 do
   (a) $R_1[0] = R_1[0] \oplus Key[i]$
   (b) $R_2[0] = R_2[0] \oplus Key[i]$
   (c) $R_3[0] = R_3[0] \oplus Key[i]$
   (d) Clock all three registers (i.e., for $j > 0$ $R_i[j] \leftarrow R_i[j-1]$, and $R_i[0]$ is set to the result of the primitive polynomial on the previous value of R_i).
3. For $i := 0$ to 21 do
   (a) $R_1[0] = R_1[0] \oplus Frame[i]$
   (b) $R_2[0] = R_2[0] \oplus Frame[i]$
   (c) $R_3[0] = R_3[0] \oplus Frame[i]$
   (d) Clock all three registers.
4. For $i := 0$ to 99, clock the cipher by its regular majority clocking mechanism, and discard the output.

Anonymity

- Protection of the subscriber's identity from eavesdroppers on the wireless interface
- Usage of short-term temporary identifiers

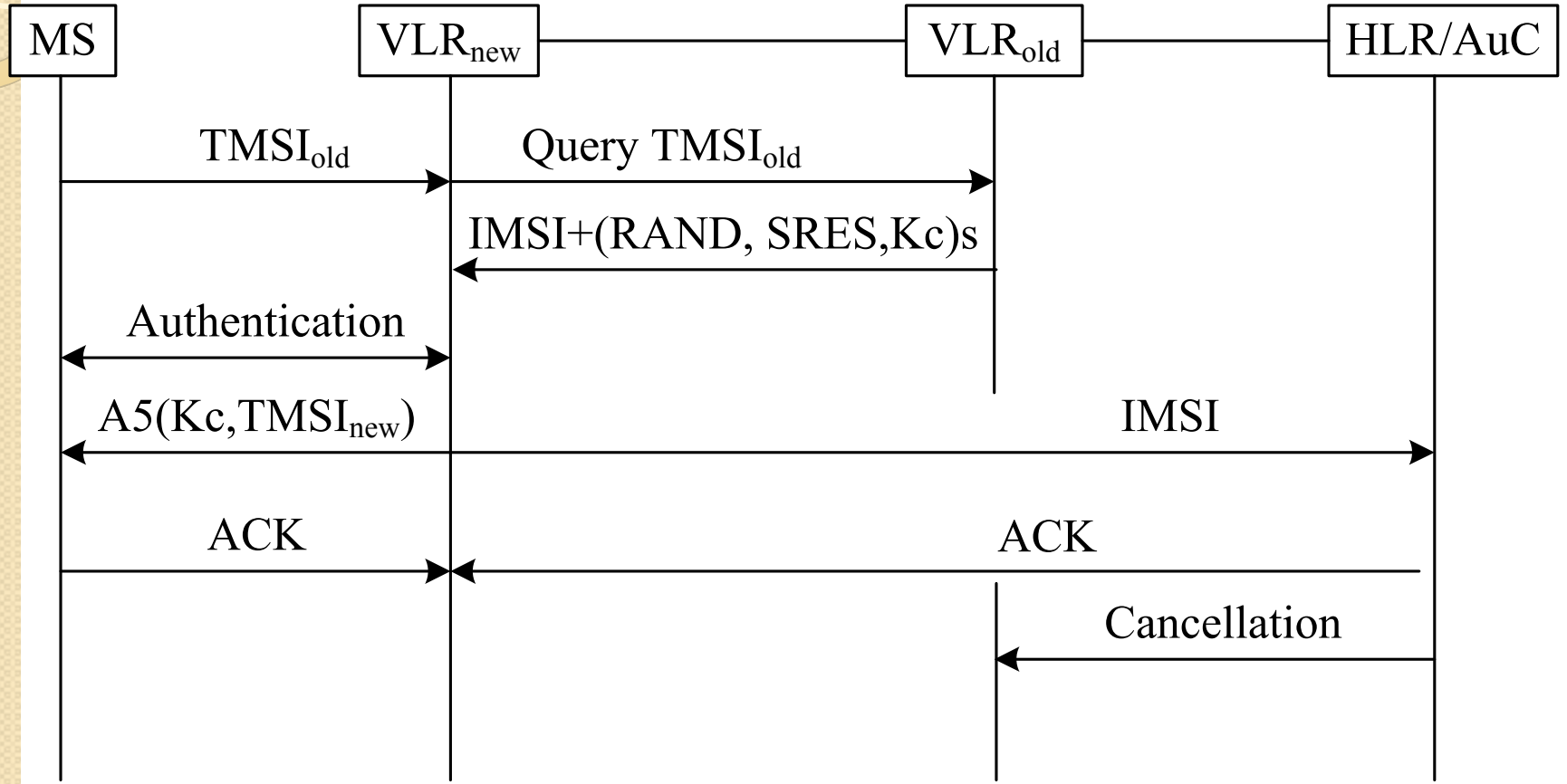
Subscriber Identity Protection

- TMSI – Temporary Mobile Subscriber Identity
  - TMSI is used instead of IMSI as an a temporary subscriber identifier.
  - TMSI prevents an eavesdropper from identifying of subscriber.
  - A 32-bit pseudo-random number only valid in a particular Location Area

Subscriber Identity Protection

- Usage
  - TMSI is assigned when IMSI is transmitted to AuC on the first phone switch on.
  - TMSI is used by the MS to report to the network, and network uses TMSI to communicate with MS.
  - The VLR is in charge of TMSI issuance and update
  - Updated at least every location update procedure; or changed by the VLR at any time
  - The new TMSI is sent in encrypted form whenever possible so that an attacker cannot map it to an old one and "follow" a user
  - On MS switch off TMSI is stored on SIM card to be reused next time.

Subscriber Identity Protection



Key Management Scheme

- Ki – 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
  - Subscribers can change handsets without compromising security

Detection of Compromised Equipment

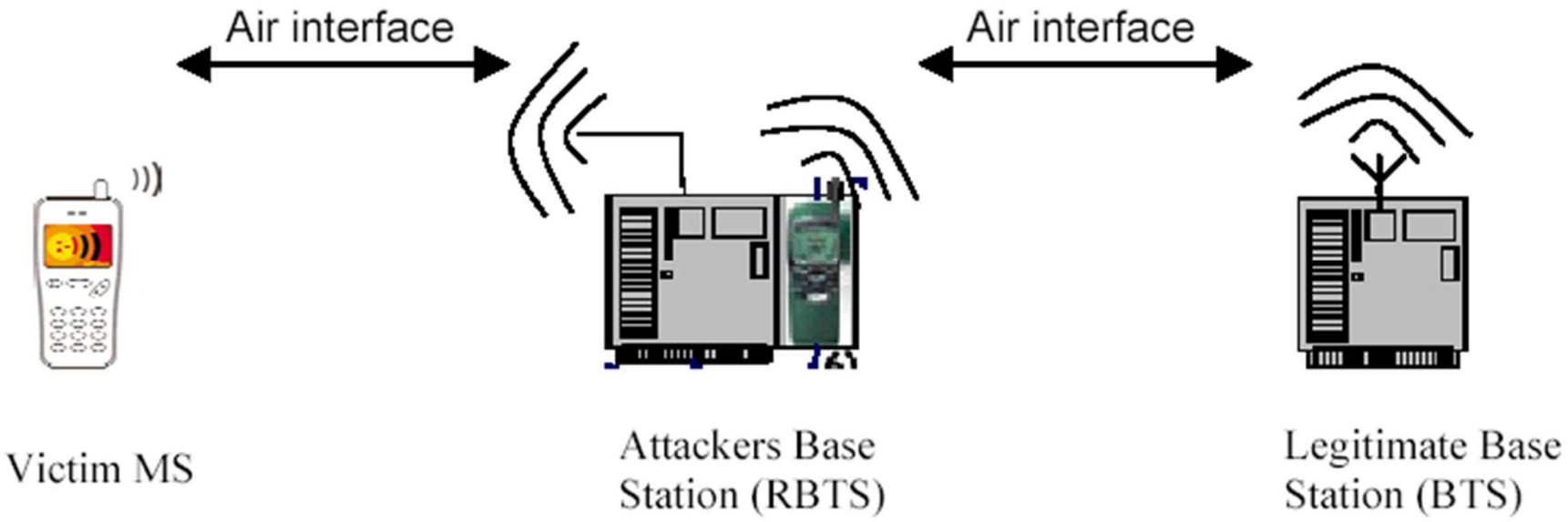
- International Mobile Equipment Identity (IMEI)
  - Identity allows to identify mobile phones
  - IMEI is independent of SIM
  - Used to identify stolen or compromised equipment
- Equipment Identity Register (EIR)
  - Black list – stolen or non-type mobiles
  - White list – valid mobiles
  - Gray list – local tracking mobiles

Overview of GSM Security Flaws

- Cryptanalysis attacks against A3/A5/A8/COMP-128 algorithm
- Over-the-air interception using fake BTS
- Only air interface transmission is encrypted
- Ciphering key (Kc) used for encryption is only 54 bits long
- Key recovery allowing SIM cloning

Security Flaws in GSM

- Network does not authenticate itself to a phone
  - The most serious fault with the GSM authentication system
  - Leading to the man-in-the-middle attack



Security Flaws in GSM

- Common implementation of A3/A8 is flawed
  - COMP128 is used for both A3 and A8
  - Goldberg and Wagner (UC Berkeley) took 8 hours to break COMP128 in 1998
    - Require physical access to the target SIM, an off-the-shelf card reader and a computer to direct the operation
    - Send 2^{19} challenges to the SIM and analyze the responses to obtain the Ki stored in the SIM
  - IBM researchers cracked COMP128 in less than one minute in 2002
  - Aftermath
    - The victim SIM can be cloned!!!

Security Flaws in GSM

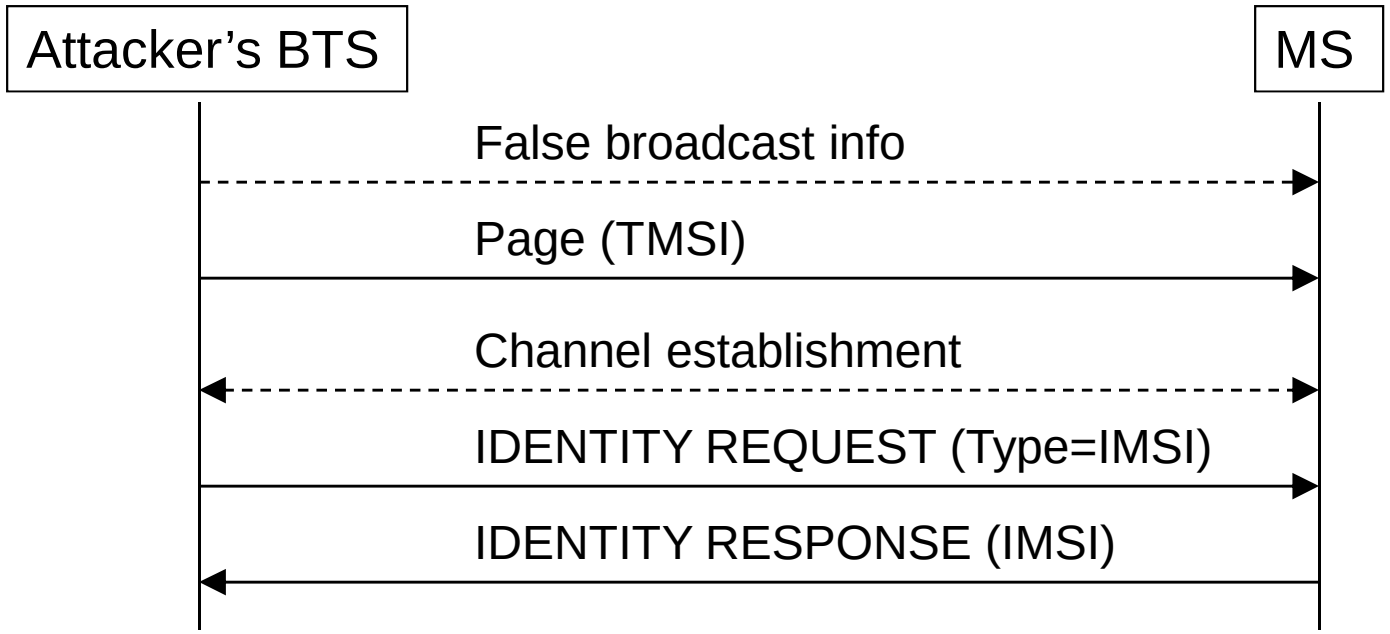
- Another deliberate flaw in COMP128
  - The lease significant 10 bits of the 64-bit Kc is always set to 0
  - Security is reduced by a factor of 1024
- Flaws in A5
  - A5/1 : originally used in Europe
  - A5/2 : a deliberately weakened version of A5/1 created for export and used in the United States
  - A5/3 : strong encryption algorithm created by 3GPP

Security Flaws in GSM

- Flaws in A5
  - Biryukov, Shamir and Wagner cracked A5/1 under one second on a typical PC in 2000
  - Goldberg , Wagner and Green broke A5/2 in 1999 in about 10 ms
  - Barkhan, Eli Biham and Keller showed an attack on A5/2 within a few dozen milliseconds in 2003, and also described attacks on A5/1 and A5/3
  - A5/3 has not been broken yet but may be soon

Security Flaws in GSM

- Vulnerabilities in the subscriber identity confidentiality mechanism
  - If the network somehow loses track of a particular TMSI, it must ask the subscriber its IMSI sent in plaintext over the radio link
  - An attacker can utilize this to map a TMSI to its IMSI



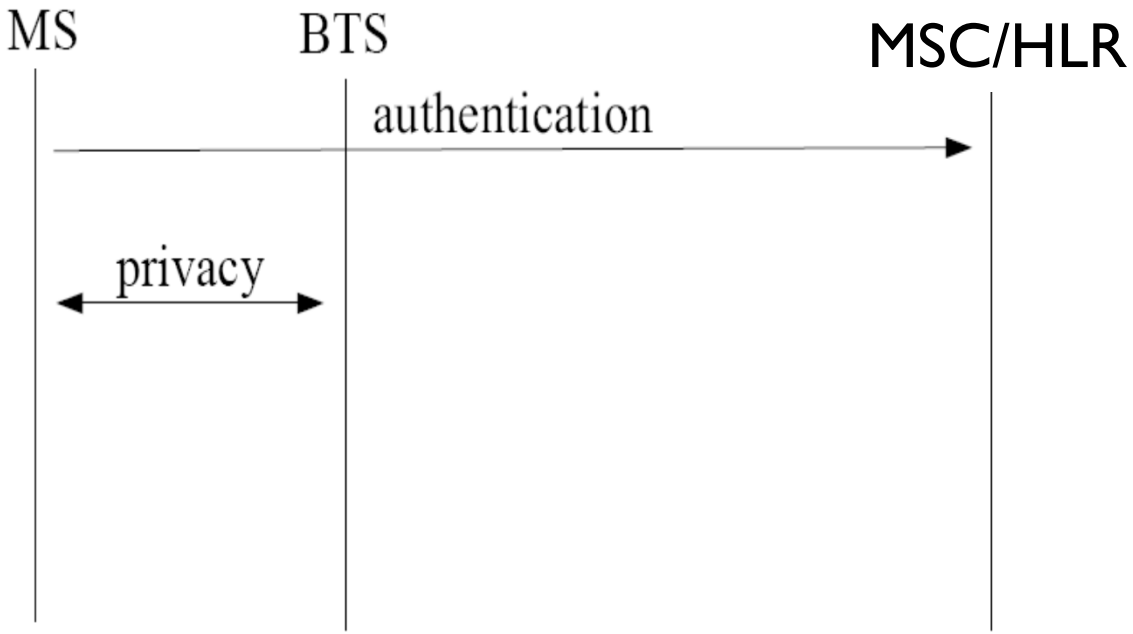
Security Flaws in GSM

- Ciphering occurs after FEC
  - FEC (forward error correction) is used over the radio link to assist in correcting errors from noise or fading
  - FEC works by adding redundancy to the data stream, thus increasing the amount of bits to transfer
  - In GSM ciphering occurs after FEC
  - The known redundancy patterns of FEC could be used to assist in a cryptanalytic attack
    - Attackers know part of the plaintext and the full ciphertext

Attacks on GSM Security

- Attacks on A3/A8, A5/1
  - Through air interface
  - With possession of mobile equipment
- False base station
  - GSM does unilateral authentication
- Attacks on SIM card (SIM Editor, SIM Scanner)
- DoS (Denial of Service)
  - Jamming the signal
  - Preventing the MS from communicating

Attacks on GSM Security

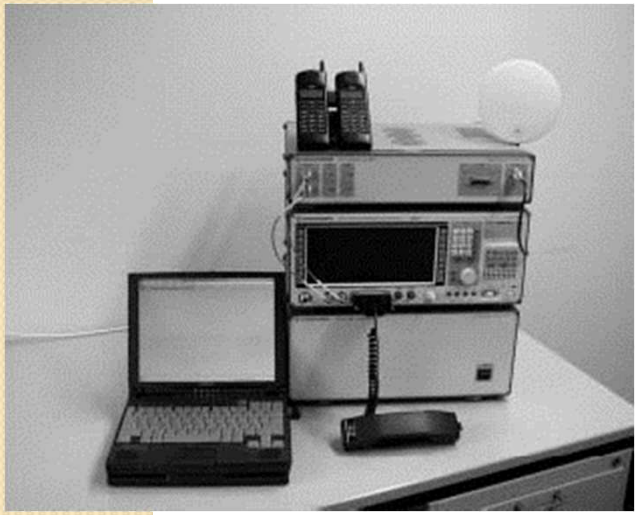


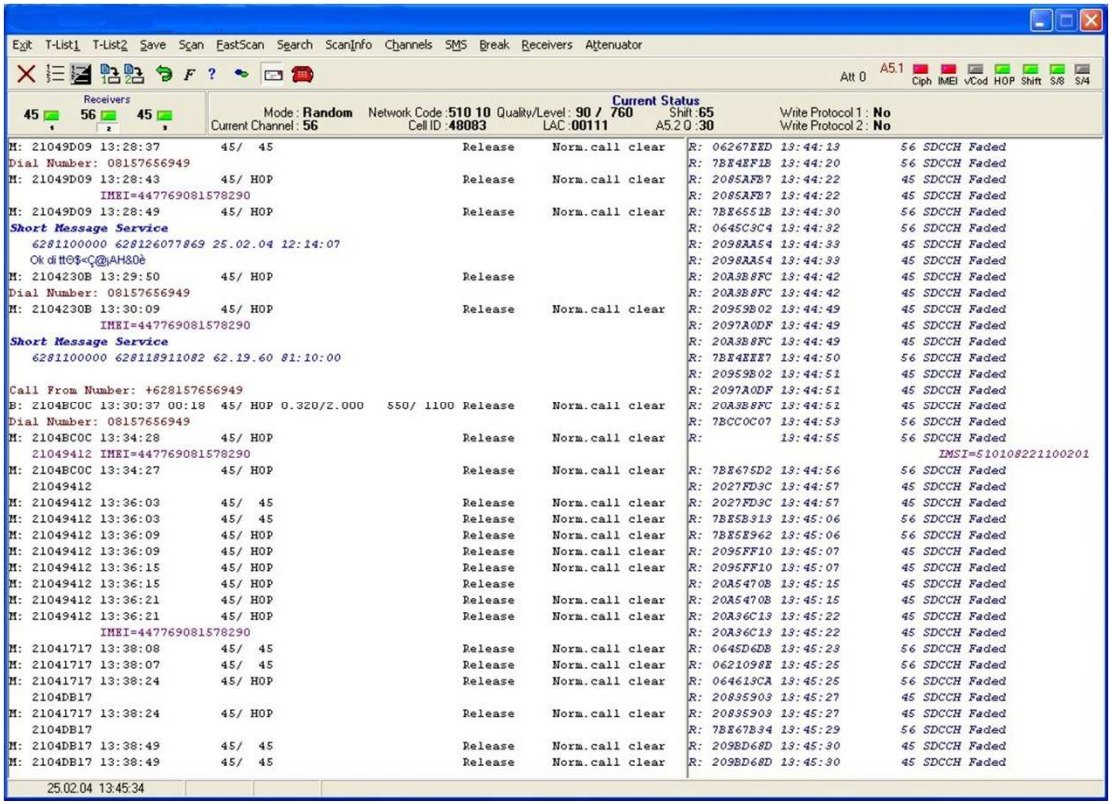
The network is not authenticated!

No privacy for network signals!

IMSI Catcher (Fake Base Station)

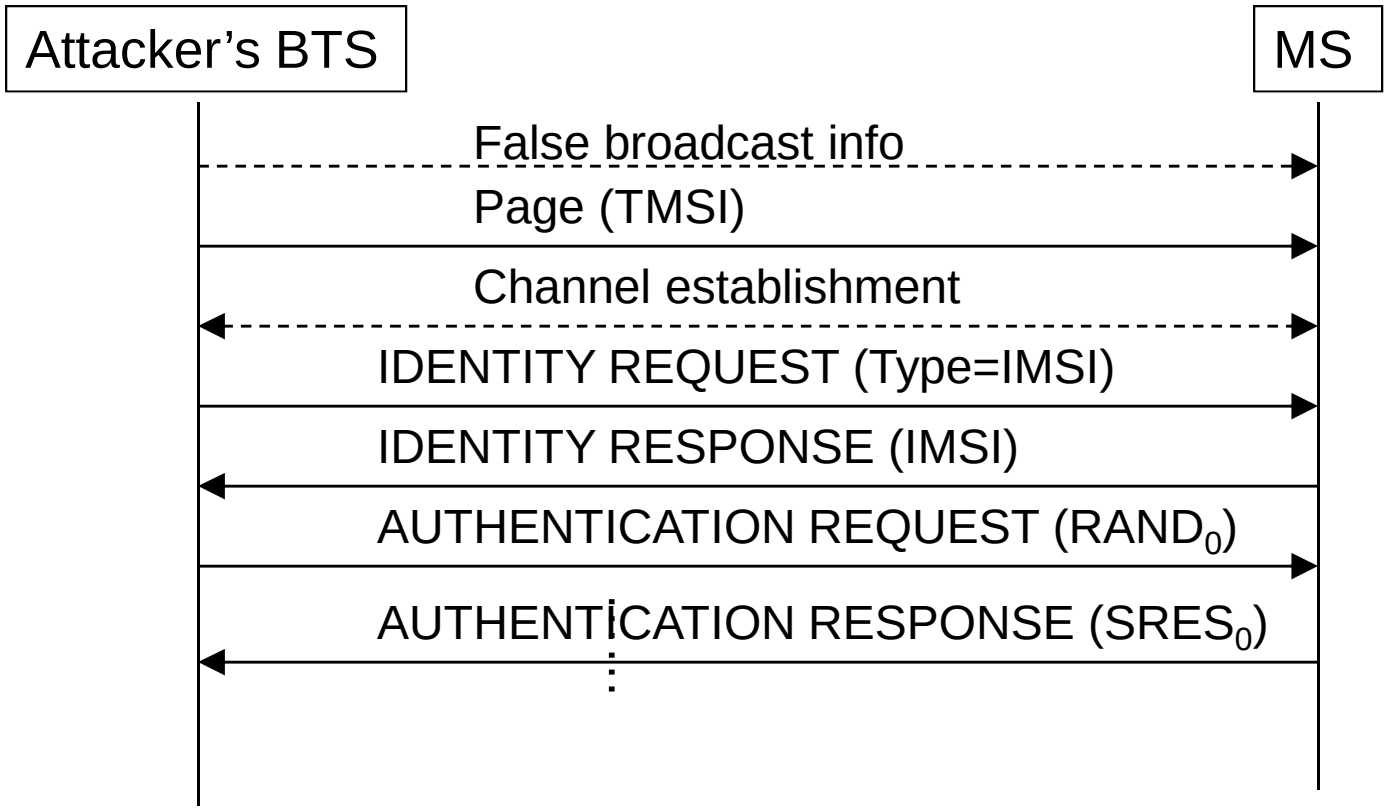
- IMSI-catchers are used by law enforcement and intelligence agencies.



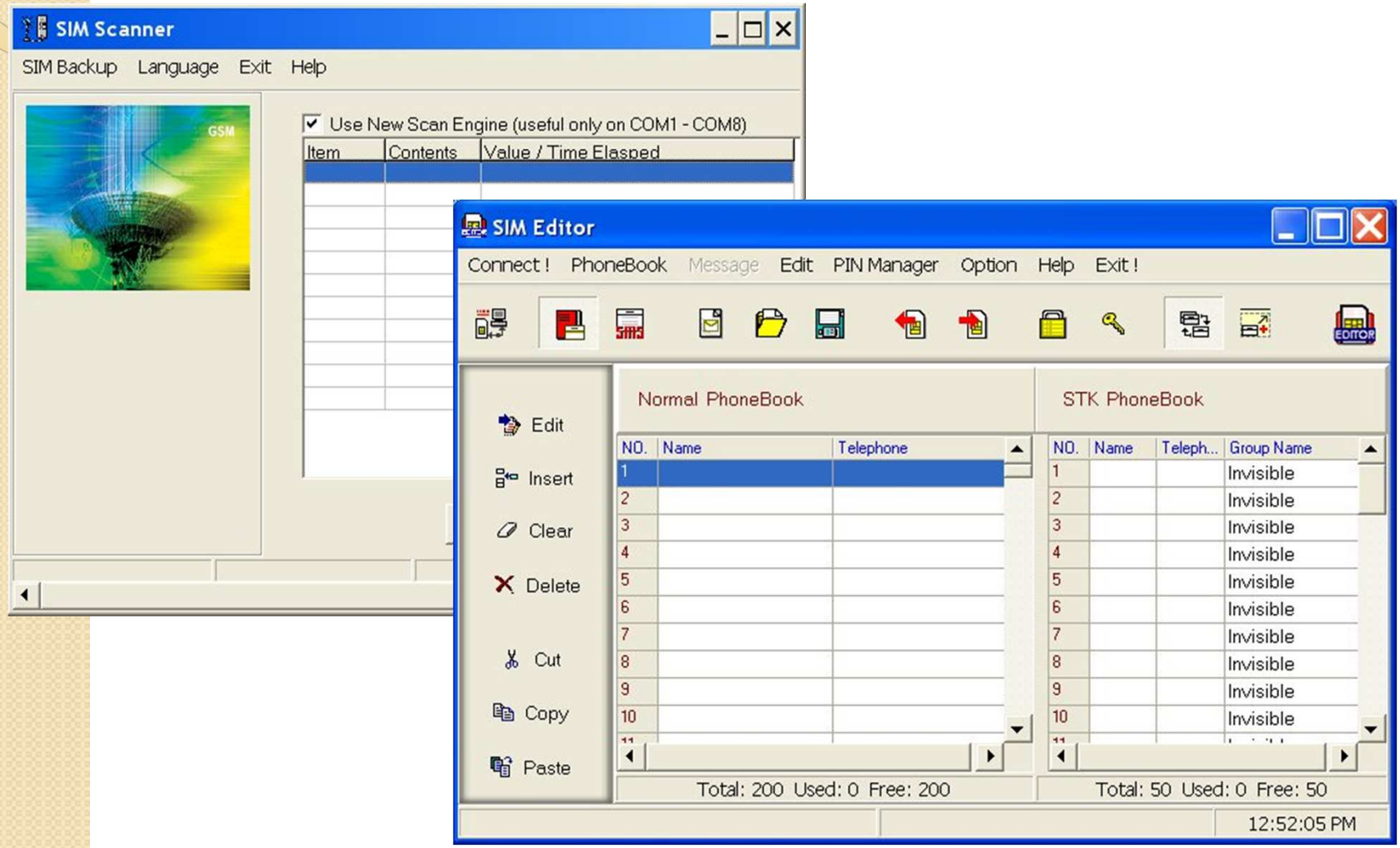


Cracking Long Term Key

- Over-the-air cracking of Ki and cloning of the SIM
  - By imitating a legitimate GSM network, the attacker can learn the IMSI and Ki of a user and clone its SIM card over the air



SIM Card Cloning



Conclusion

- GSM fails to deliver most of the security criteria described in GSM 02.09
- GSM's faults result from designing algorithms in secret and deliberately weakening the system
  - This lesson tells us that security algorithms should be exposed to public scrutiny before deployment
- None of the attacks are easily carried out, so
  - For most average users, the security concerns may not be that great
  - Those using GSM for highly sensitive information should think twice however

Countermeasures

- New A3/A8 implementation
  - COMP128-2 and COMP128-3
    - Still developed in secret (security through obscurity)
    - A rather slow migration from COMP128-1 to COMP128-2/3
  - 3GPP have defined brand-new authentication algorithms for use with the UMTS system
- A5/3
  - Added by GSM in 2002
  - Only few networks and handsets support A5/3 currently
- GPRS/UMTS
  - Ciphering before FEC

Countermeasures

- UMTS Security (3GPP)
  - Improved, stronger and open crypto algorithms
  - Support network authentication to phone
    - The network sends to the mobile the RAND and an Authentication Token to prove its knowledge of Ki
    - The AUTH includes a sequence number (SN) encrypted using Ki and a message authentication code (MAC) generated also with Ki
    - The mobile decrypts the SN and recalculates the MAC
    - If the result matches with what the network sent, it considers the network legitimate and then returns an XRES
    - The network authenticates the mobile if the XRES is correct

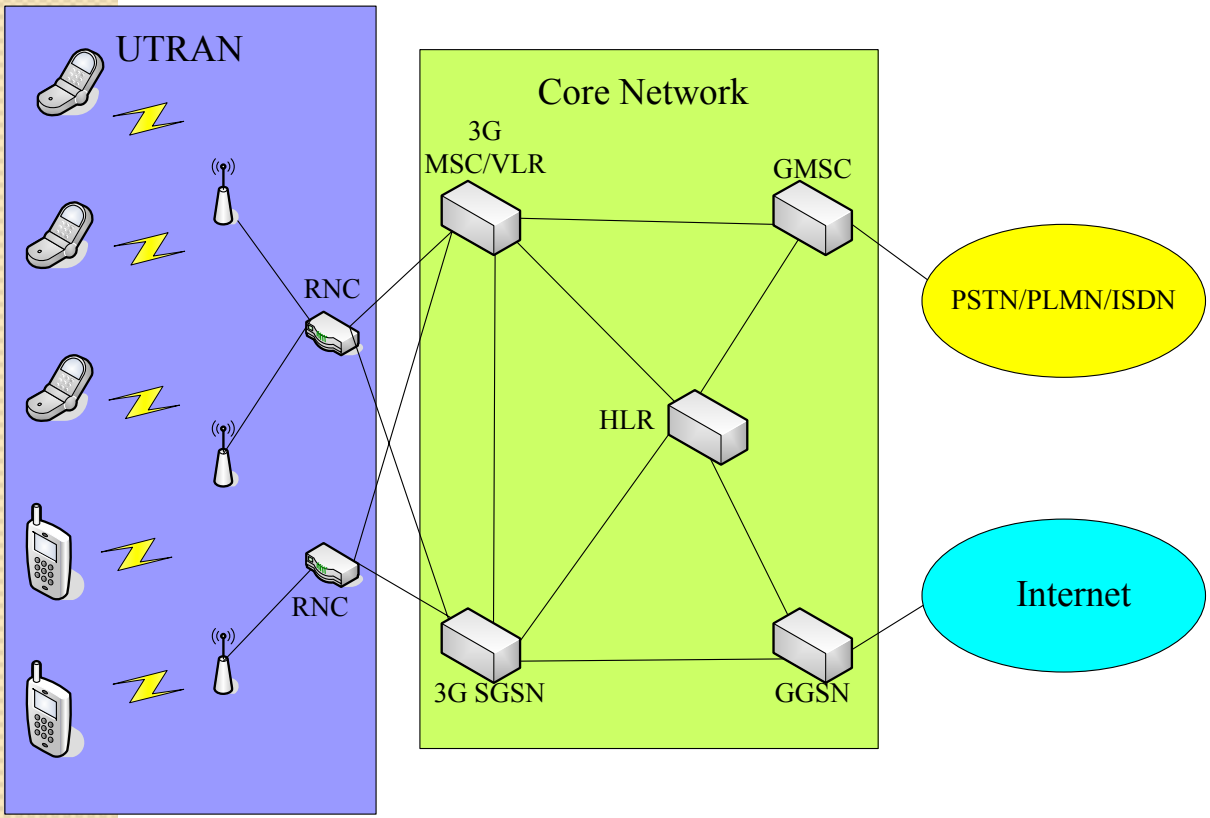
3GPP Security

- The 3rd Generation Partnership Project, built on GSM
- Mutual authentication
- Data Integrity
- Better algorithms
  - KASUMI (A5/3)

3GPP Introduction

- 3G features exceeding over 2G provide
  - Higher data rate, massive network capacity
  - Interactive multimedia service, QoS
  - Global roaming
- 3G communications standards
  - CDMA2000(USA), W-CDMA (Europe/Japan), TD-SCDMA (China)
- Applications
  - Multimedia Message Service (MMS), Email, Video phone
  - Video streaming, Services from the Internet

3GPP Architecture



UTRAN: UMTS Terrestrial Radio Access Network
RNC: Radio Network Controller

MSC: Mobile Service Switching Center
VLR: Visitor Location Register
GMSC: Gateway MSC

HLR: Home Location Register

SGSN: Serving GPRS Support Node
GGSN: Gateway GPRS Support Node

GPRS: General Packet Radio Service
UMTS: Universal Mobile Telecommunications System

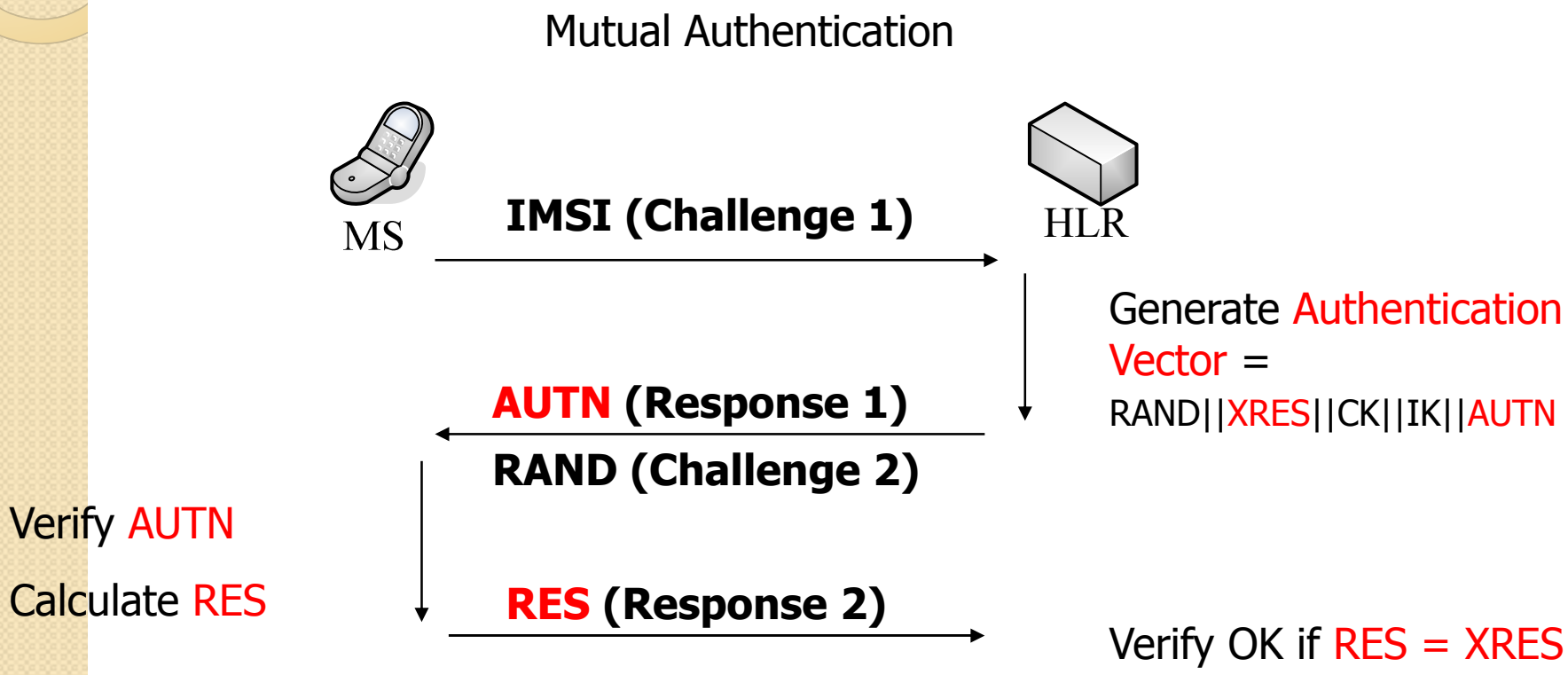
3GPP Security Principles

- Reuse of 2G (GSM) security principles:
  - Removable hardware security module, SIM based Authentication
    - In GSM: SIM card
    - In 3GPP: USIM (User Services Identity Module)
  - Radio interface encryption
  - Protection of the identity of the end user (especially on the radio interface)

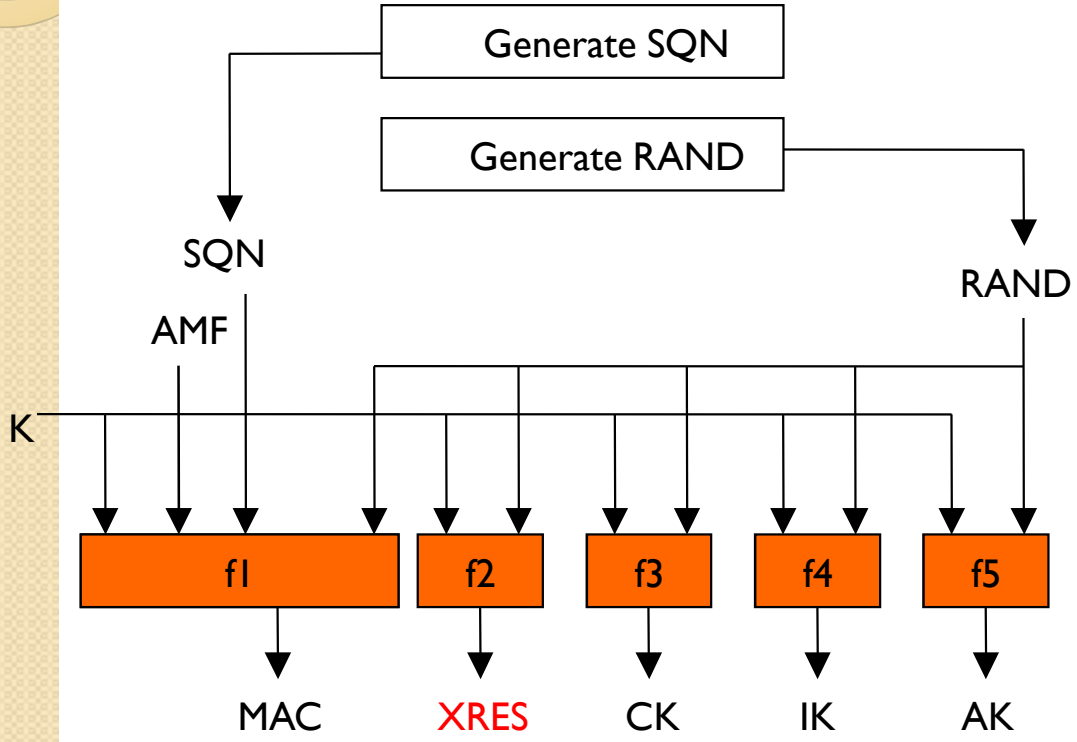
3GPP Security Principles

- Correction of the weaknesses of 2G:
  - Possible attacks from a faked base station → Mutual Authentication
  - Data integrity not provided →Integrity protection of signalling message
  - Use of stronger encryption
  - Assurance that authentication information and keys are not being re-used (key freshness)

3GPP Authentication and Key Agreement (AKA)



Generation of Authentication Vector



SQN: Sequence Number
RAND: Random Number
AMF: Authentication and Key Management Field
K: Shared Key

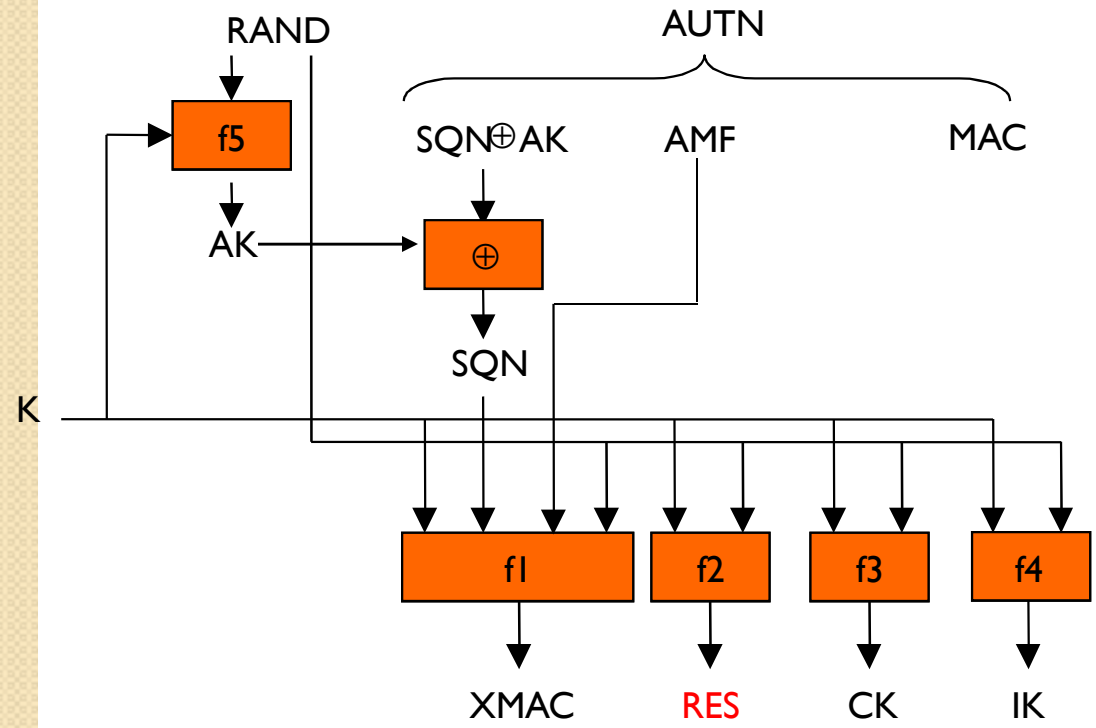
MAC: Message Authentication Code
XRES: Expected Response
CK: Cipher Key
IK: Integrity Key
AK: Anonymity Key

AV: Authentication Vector AUTN: Authentication Token

Generate: AV = RAND || XRES || CK || IK || AUTN

Send: AUTN = SQN⊕ AK || AMF || MAC

Verification on Mobile Station



Verify AUTH:

MAC = XMAC?

Verify that SQN is in the correct range

AUTN: Authentication Token
RAND: Random Number
K: Shared Key

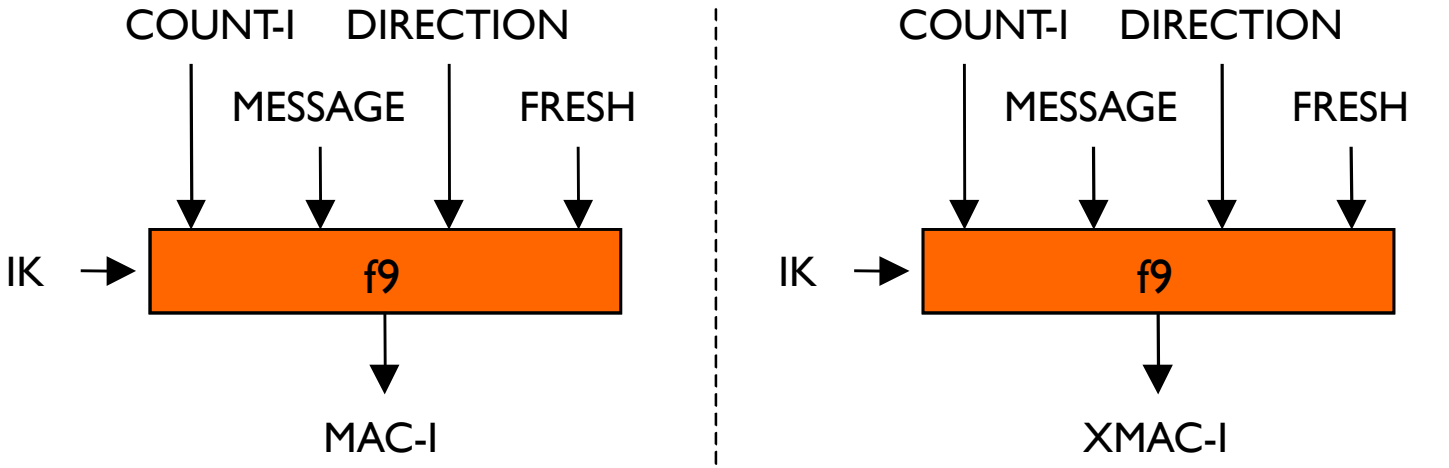
SQN: Sequence Number
AK: Anonymity Key
AMF: Authentication and Key Management Field
MAC: Message Authentication Code

XMAC: Expected MAC
RES: Response
CK: Cipher Key
IK: Integrity Key

Mutual Authentication in 3G

- Subscriber can authenticate the network by the secret K using f1 (K, SQN, AMF, RAND)
- SQN is introduced to prevent replay attacks
- AK is used to conceal SQN
- Cipher Key and Integrity Key are generated after the authentication (Key Agreement)

Data Integrity in 3GPP

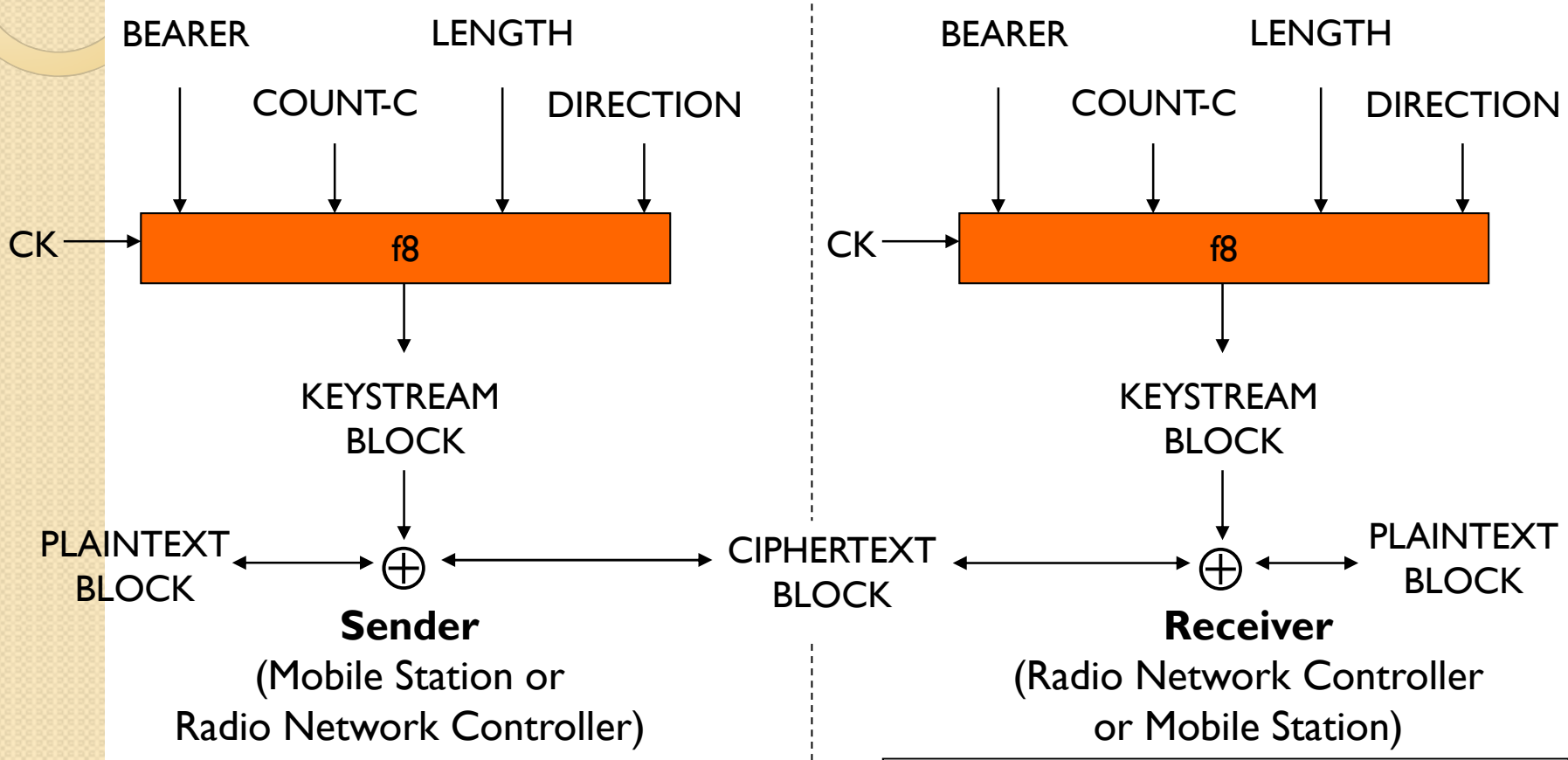


FRESH: Connection Nonce
COUNT-I: Integrity Sequence Number

Data Integrity in 3GPP

- Data Integrity
  - COUNT-I and FRESH are used to prevent replay attack
  - DIRECTION specifies the direction of the transmission (User to Network or Network to User)
- Secure network elements interconnection
- F9 uses Kasumi to form CBC-MAC

Ciphering Method in 3GPP



LENGTH: Length of Keystream Block
BEARER: Bearer Identity
COUNT-C: Ciphering Sequence Number

Problems of 3GPP Security

- IMSI is sent in cleartext when allocating TMSI to the user
- Signal jamming: physical layer attacks are hard to solve

Further Reading

- *Handbook of Applied Cryptography*, Chap 1, Menezes, Oorschot & Vanstone, CRC Press, 1997
- GSM Security Papers, http://www.gsm-security.net/gsm-security-papers.shtml

References to 3GPP Security

- Principles, objectives and requirements
  - TS 33.120 Security principles and objectives
  - TS 21.133 Security threats and requirement
- Architecture, mechanisms and algorithms
  - TS 33.102 Security architecture
  - TS 33.103 Integrity guidelines
  - TS 33.105 Cryptographic algorithm requirements
  - TS 22.022 Personalization of mobile equipment
- Lawful interception
  - TS 33.106 Lawful interception requirement
  - TS 33.107 Lawful interception architecture and functions

- Technical reports
  - TR 33.900 A guide to 3G security
  - TR 33.901 Criteria for cryptographic algorithm design process
  - TR 33.902 Formal analysis of the 3G authentication protocol
  - TR 33.908 General report on the design, specification and evaluation of 3GPP standard confidentiality and integrity algorithms
- Algorithm specifications
  - Specification of the 3GPP confidentiality and integrity algorithms
    - Document 1: f8 & f9
    - Document 2: KASUMI
    - Document 3: implementer's test data
    - Document 4: design conformance test data

References

- Eli Biham and Orr Dunkelman “Cryptanalysis of the A5/1 GSM Stream Cipher”, INDOCRYPT 2000
- Elad Barkan, Eli Biham, and Nathan Keller “Instant Ciphertext-Only Cryptanalysis of GSM Encrypted Communication”, CRYPTO 2003
- 3GPP (Third Generation Partnership Project), http://www.3gpp.org/
- UMTS forum, http://www.umts-forum.org/