Cellular Networks

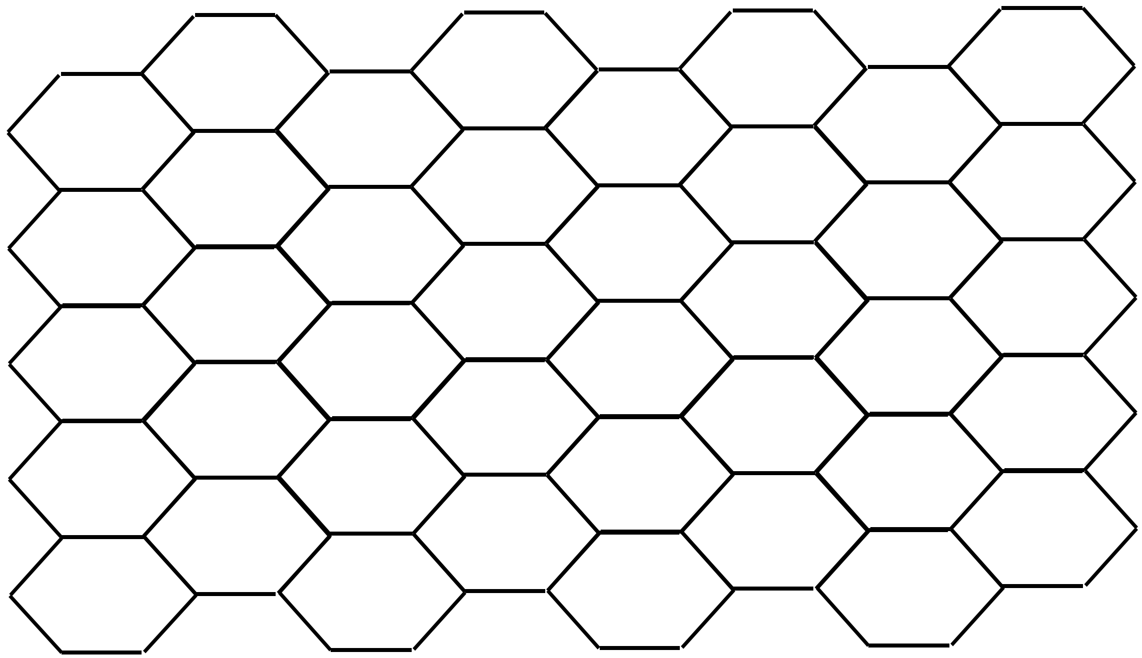
Cellular Network Organization

- Use multiple low-power transmitters (100 W or less)
- Areas divided into cells
  - Each served by its own antenna
  - Served by base station consisting of transmitter, receiver, and control unit
  - Band of frequencies allocated
  - Cells set up such that antennas of all neighbors are equidistant (hexagonal pattern)

Frequency Reuse

- Adjacent cells assigned different frequencies to avoid interference or crosstalk
- Objective is to reuse frequency in nearby cells
  - 10 to 50 frequencies assigned to each cell
  - Transmission power controlled to limit power at that frequency escaping to adjacent cells
  - The issue is to determine how many cells must intervene between two cells using the same frequency

Cellular Concept



- Several small cells instead of a single transmitter=> frequency reuse: better efficiency
- Fixed Channel Allocation:
- Cluster of size $N = i^2+ij+j^2$; and $D = \text{sqrt}(3N)R$
- R cell radius and
- D distance at which a frequency can be reused with acceptable interference

Frequency Assignment Problems

- Cellular systems provider allocates frequencies from a licensed spectrum
- Constraints:
  - For any cell, interference from nearby cells within an acceptable minimum
  - For any cell, the frequency bandwidth allocated sufficient to support the load in the cell
- Objectives:
  - Minimize the total bandwidth (or width of the spectrum) allocated across all cells
  - Minimize call blocking probability
  - Minimize average interference

Solving FAPs

- Since the programs are all integer programs, hard to solve in general
  - NP-hard
- Can apply standard mathematical programming heuristics
  - Branch and bound
  - Cutting plane techniques
  - Local search
  - Simulated annealing
  - Tabu search…
- Some problems can be expressed as graph coloring problems in specialized graphs

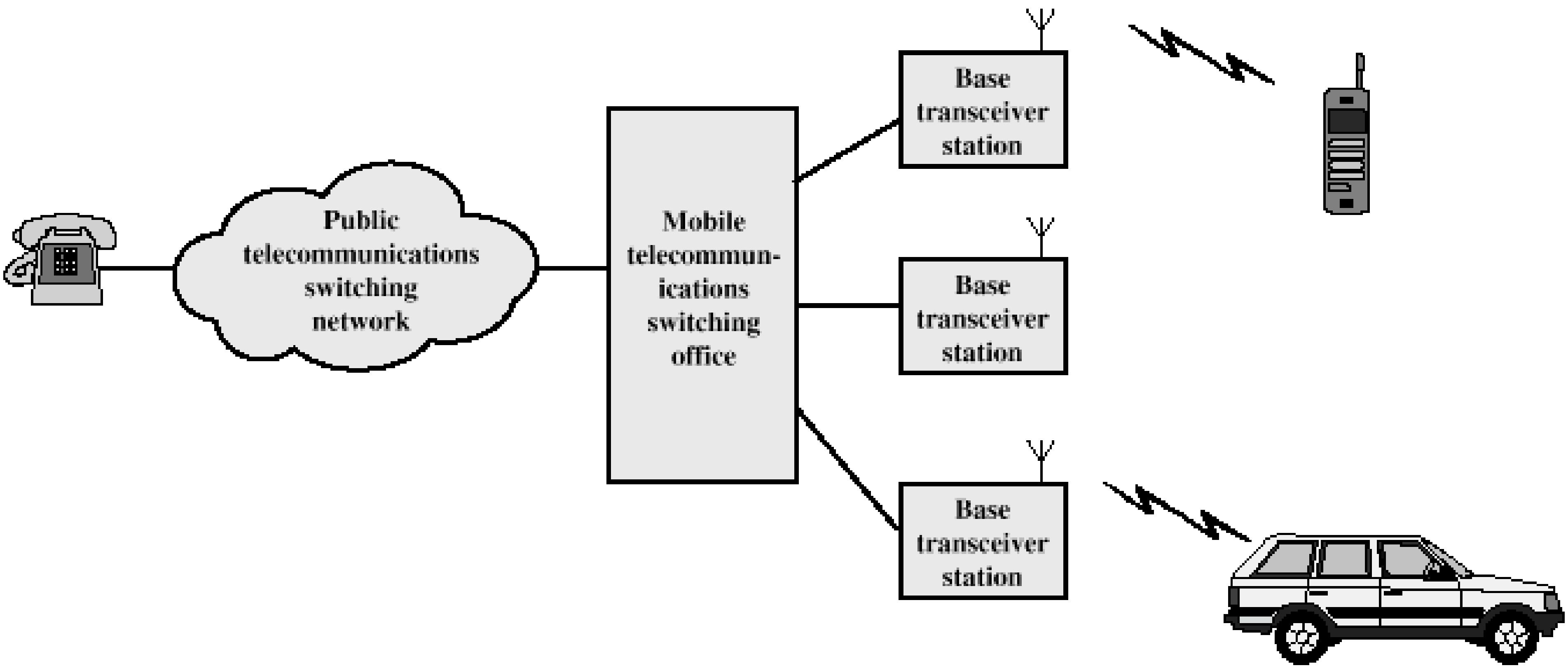
Formulating FAPs

- Can be expressed as mathematical programs
    - Mostly linear
    - Some non-linear (e.g., minimizing interference)
- Approach:
    - Represent the cellular structure as a graph
    - Each node represents a cell (center)
    - Interference relationships represented by the graph edges
    - Assigning a frequency same as assigning a fixed-width band centered around the frequency
    - Binary variables that indicate whether a (center) frequency is assigned

Approaches to Cope with Increasing Capacity

- Adding new channels
- Frequency borrowing – frequencies are taken from adjacent cells by congested cells
- Cell splitting – cells in areas of high usage can be split into smaller cells
- Cell sectoring – cells are divided into a number of wedge-shaped sectors, each with their own set of channels
- Microcells – antennas move to buildings, hills, and lamp posts

Cellular System Overview



Cellular Systems Terms

- Base Station (BS) – includes an antenna, a controller, and a number of receivers
- Mobile telecommunications switching office (MTSO) – connects calls between mobile units
- Two types of channels available between mobile unit and BS
  - Control channels – used to exchange information having to do with setting up and maintaining calls
  - Traffic channels – carry voice or data connection between users

Steps in an MTSO Controlled Call between Mobile Users

- Mobile unit initialization
- Mobile-originated call
- Paging
- Call accepted
- Ongoing call
- Handoff

Additional Functions in an MTSO Controlled Call

- Call blocking
- Call termination
- Call drop
- Calls to/from fixed and remote mobile subscriber

Mobile Radio Propagation Effects

- Signal strength
  - Must be strong enough between base station and mobile unit to maintain signal quality at the receiver
  - Must not be so strong as to create too much cochannel interference with channels in another cell using the same frequency band
- Fading
  - Signal propagation effects may disrupt the signal and cause errors

Handoff Performance Metrics

- Cell blocking probability – probability of a new call being blocked
- Call dropping probability – probability that a call is terminated due to a handoff
- Call completion probability – probability that an admitted call is not dropped before it terminates
- Probability of unsuccessful handoff – probability that a handoff is executed while the reception conditions are inadequate

Handoff Performance Metrics

- Handoff blocking probability – probability that a handoff cannot be successfully completed
- Handoff probability – probability that a handoff occurs before call termination
- Rate of handoff – number of handoffs per unit time
- Interruption duration – duration of time during a handoff in which a mobile is not connected to either base station
- Handoff delay – distance the mobile moves from the point at which the handoff should occur to the point at which it does occur

Handoff Strategies Used to Determine Instant of Handoff

- Relative signal strength
- Relative signal strength with threshold
- Relative signal strength with hysteresis
- Relative signal strength with hysteresis and threshold
- Prediction techniques

Power Control

- Design issues making it desirable to include dynamic power control in a cellular system
  - o Received power must be sufficiently above the background noise for effective communication
  - o Desirable to minimize power in the transmitted signal from the mobile
    - Reduce cochannel interference, alleviate health concerns, save battery power
  - o In SS systems using CDMA, it's desirable to equalize the received power level from all mobile units at the BS

Types of Power Control

- Open-loop power control
  - o Depends solely on mobile unit
  - o No feedback from BS
  - o Not as accurate as closed-loop, but can react quicker to fluctuations in signal strength
- Closed-loop power control
  - o Adjusts signal strength in reverse channel based on metric of performance
  - o BS makes power adjustment decision and communicates to mobile on control channel

Traffic Engineering

- Ideally, available channels would equal number of subscribers active at one time
- In practice, not feasible to have capacity handle all possible load
- For N simultaneous user capacity and L subscribers
  - $L < N$ – nonblocking system
  - $L > N$ – blocking system

Blocking System Performance Questions

- Probability that call request is blocked?
- What capacity is needed to achieve a certain upper bound on probability of blocking?
- What is the average delay?
- What capacity is needed to achieve a certain average delay?

Traffic Intensity

- Load presented to a system:

$$A = \lambda h$$

  - λ = mean rate of calls attempted per unit time
  - h = mean holding time per successful call
  - A = average number of calls arriving during average holding period

Capacity in Cellular Systems

- Blocking Probability (Grade Of Service): *Erlang B* formula

$$GOS = \frac{A^C / C!}{\sum_{n=0}^{C} A^n / n!}$$

- Based on the above formula, we can determine the minimum N needed to support a desired grade of service.

Factors that Determine the Nature of the Traffic Model

- Manner in which blocked calls are handled
  - Lost calls delayed (LCD) – blocked calls put in a queue awaiting a free channel
  - Blocked calls rejected and dropped
    - Lost calls cleared (LCC) – user waits before another attempt
    - Lost calls held (LCH) – user repeatedly attempts calling
- Number of traffic sources
  - Whether number of users is assumed to be finite or infinite

First-Generation Analog

- Advanced Mobile Phone Service (AMPS)
  - In North America, two 25-MHz bands allocated to AMPS
    - One for transmission from base to mobile unit
    - One for transmission from mobile unit to base
  - Each band split in two to encourage competition (12.5MHz per operator)
  - Channels of 30 KHz: 21 control channels (FSK), 395 traffic channels (FM voice) per operator
  - Frequency reuse exploited (N = 7)

AMPS Operation

- Subscriber initiates call by keying in phone number and presses send key
- MTSO verifies number and authorizes user
- MTSO issues message to user’s cell phone indicating send and receive traffic channels
- MTSO sends ringing signal to called party
- Party answers; MTSO establishes circuit and initiates billing information
- Either party hangs up; MTSO releases circuit, frees channels, completes billing

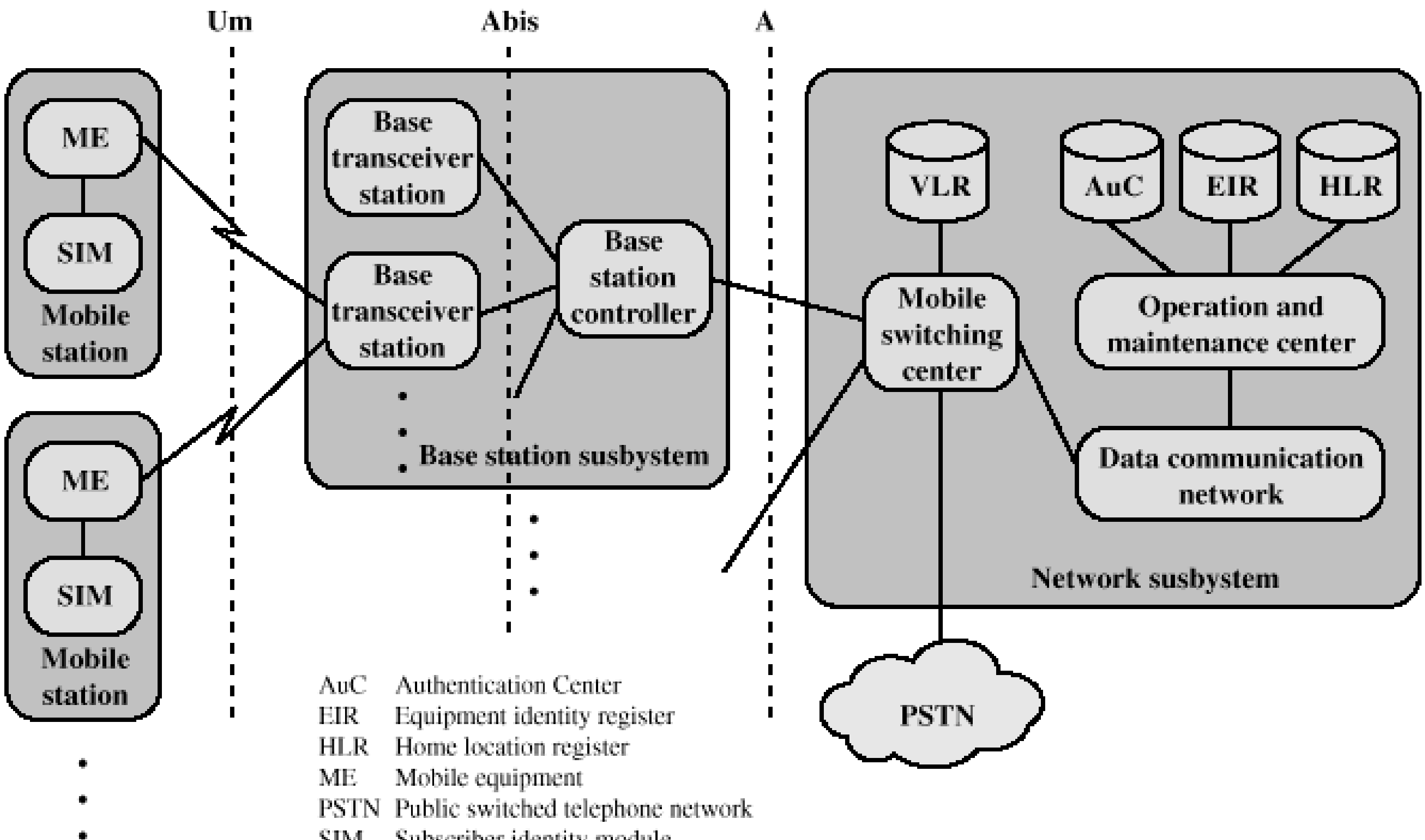
Differences Between First and Second Generation Systems

- Digital traffic channels – first-generation systems are almost purely analog; second-generation systems are digital
- Encryption – all second generation systems provide encryption to prevent eavesdropping
- Error detection and correction – second-generation digital traffic allows for detection and correction, giving clear voice reception
- Channel access – second-generation systems allow channels to be dynamically shared by a number of users

TDMA Design Considerations

- Number of logical channels per physical channel (number of time slots in TDMA frame): 8
- Maximum cell radius (R): 35 km
- Frequency: region around 900 MHz
- Maximum vehicle speed (V_m):250 km/hr
- Maximum coding delay: approx. 20 ms
- Maximum delay spread (Δ_m): 10 μs
- Bandwidth: Not to exceed 200 kHz (25 kHz per channel)

GSM Network Architecture



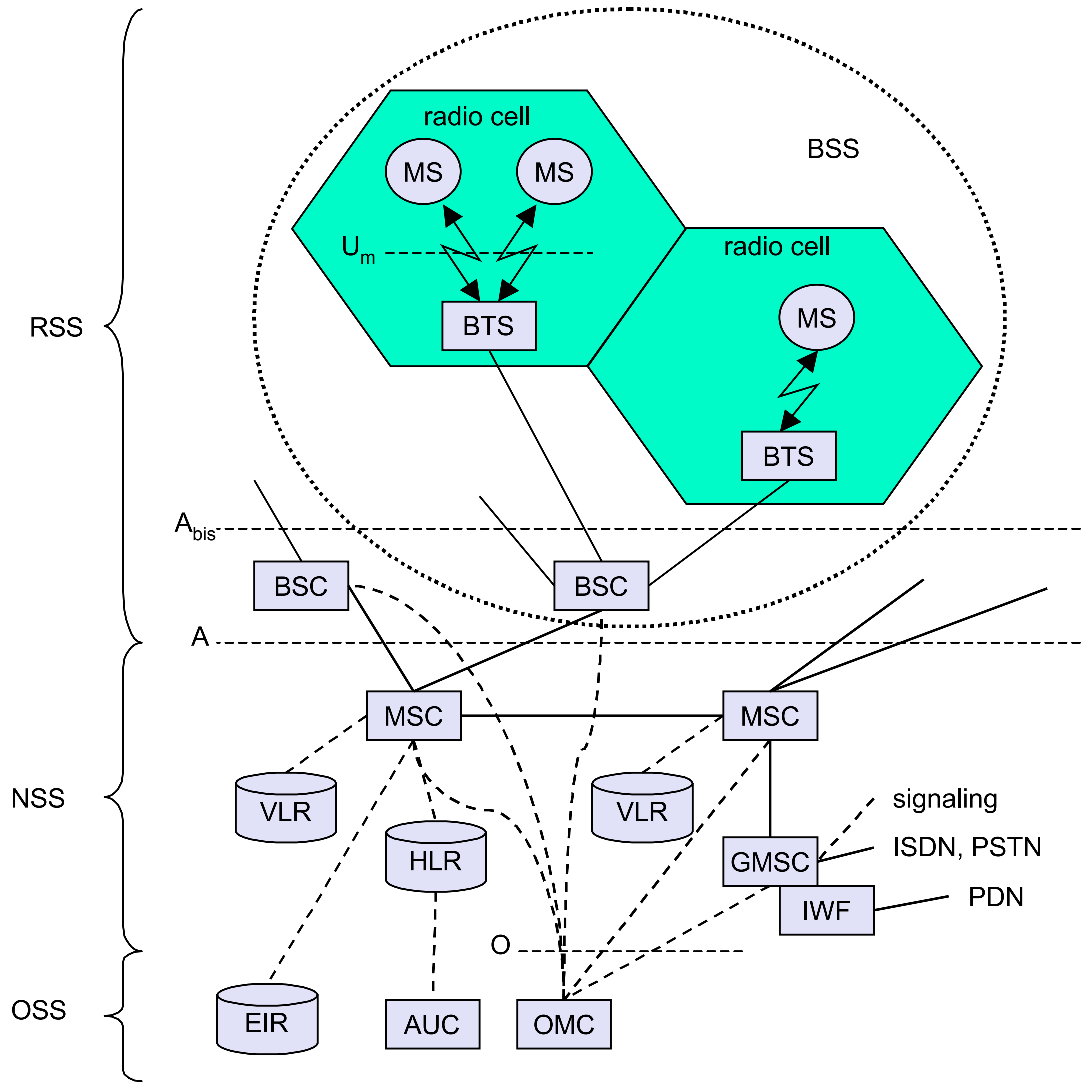
AuC Authentication Center
EIR Equipment identity register
HLR Home location register
ME Mobile equipment
PSTN Public switched telephone network
SIM Subscriber identity module
VLR Visitor location register

Figure 10.14 Overall GSM Architecture

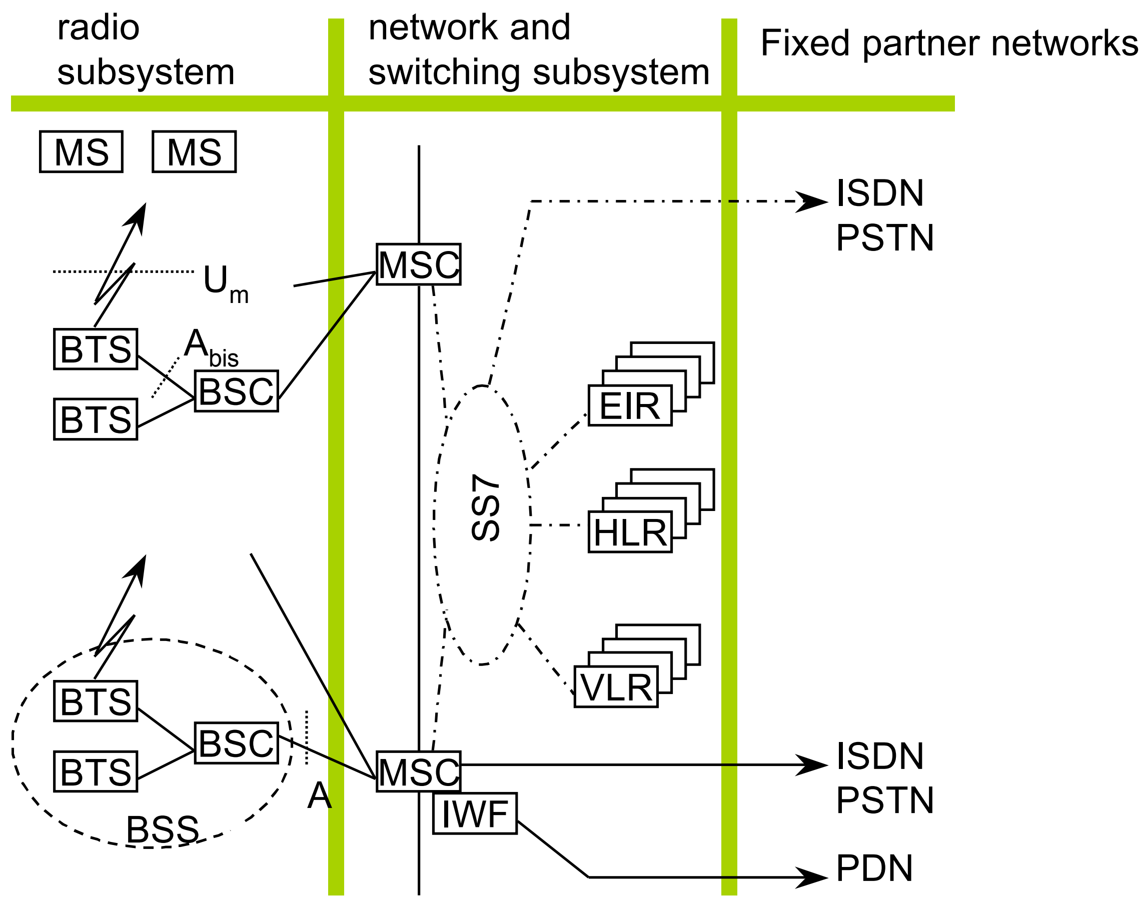
Architecture of the GSM system

- Several providers setup mobile networks following the GSM standard within each country
- Components
  - MS (mobile station)
  - BS (base station)
  - MSC (mobile switching center)
  - LR (location register)
- Subsystems
  - RSS (radio subsystem): covers all radio aspects
    - Base station subsystem
  - NSS (network and switching subsystem): call forwarding, handover, switching
  - OSS (operation subsystem): management of the network

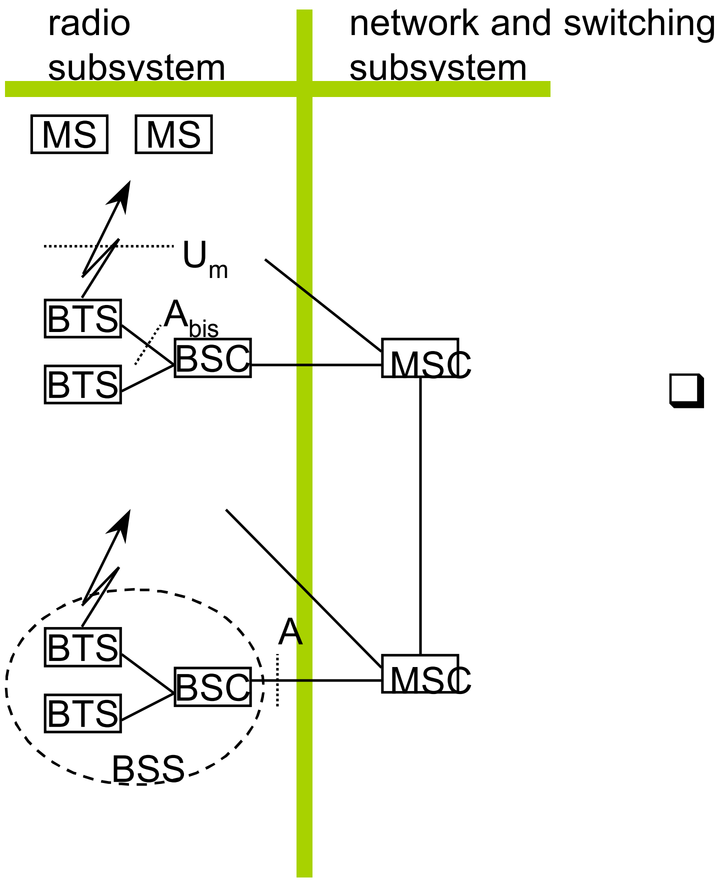
GSM: elements and interfaces



GSM: system architecture



Radio subsystem



- Components
  - *MS* (Mobile Station)
  - *BSS* (Base Station Subsystem): consisting of
    - *BTS* (Base Transceiver Station): sender and receiver
    - *BSC* (Base Station Controller): controlling several transceivers
- Interfaces
  - U_m : radio interface
  - A_{bis} : standardized, open interface with 16 kbit/s user channels
  - *A*: standardized, open interface with 64 kbit/s user channels

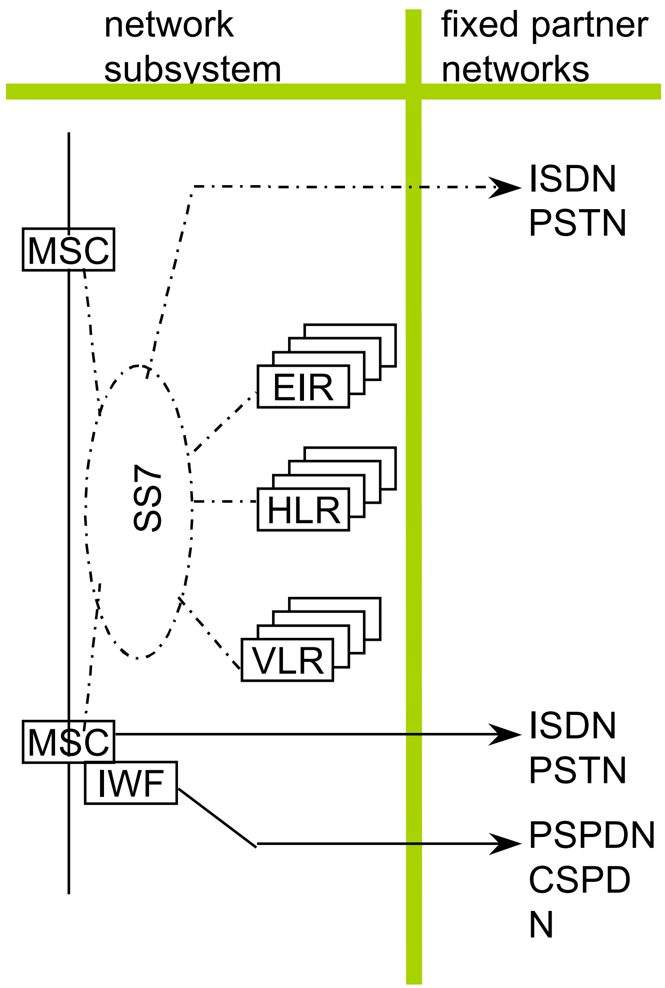
Mobile Station

- Mobile station communicates across Um interface (air interface) with base station transceiver in same cell as mobile unit
- Mobile equipment (ME) – physical terminal, such as a telephone or PDA
  - ME includes radio transceiver, digital signal processors and subscriber identity module (SIM)
- GSM subscriber units are generic until SIM is inserted
  - SIMs roam, not necessarily the subscriber devices

Base Station Subsystem (BSS)

- BSS consists of base station controller and one or more base transceiver stations (BTS)
- Each BTS defines a single cell
  - Includes radio antenna, radio transceiver and a link to a base station controller (BSC)
- BSC reserves radio frequencies, manages handoff of mobile unit from one cell to another within BSS, and controls paging

Network and switching subsystem



Components

- *MSC* (Mobile Services Switching Center):
- *IWF* (Interworking Functions)

- *ISDN* (Integrated Services Digital Network)
- *PSTN* (Public Switched Telephone Network)
- *PSPDN* (Packet Switched Public Data Net.)
- *CSPDN* (Circuit Switched Public Data Net.)

Databases

- *HLR* (Home Location *R*egister)
- *VLR* (Visitor Location *R*egister)
- *EIR* (Equipment Identity Register)

Network Subsystem (NS)

- Provides link between cellular network and PSTNs
- Controls handoffs between cells in different BSSs
- Authenticates users and validates accounts
- Enables worldwide roaming of mobile users
- Central element of NS is the mobile switching center (MSC)

Mobile Switching Center (MSC) Databases

- Home location register (HLR) database – stores information about each subscriber that belongs to it
- Visitor location register (VLR) database – maintains information about subscribers currently physically in the region
- Authentication center database (AuC) – used for authentication activities, holds encryption keys
- Equipment identity register database (EIR) – keeps track of the type of equipment that exists at the mobile station

TDMA Format – Time Slot Fields

- Trail bits – allow synchronization of transmissions from mobile units located at different distances
- Encrypted bits – encrypted data
- Stealing bit - indicates whether block contains data or is "stolen"
- Training sequence – used to adapt parameters of receiver to the current path propagation characteristics
  - Strongest signal selected in case of multipath propagation
- Guard bits – used to avoid overlapping with other bursts

GSM Speech Processing

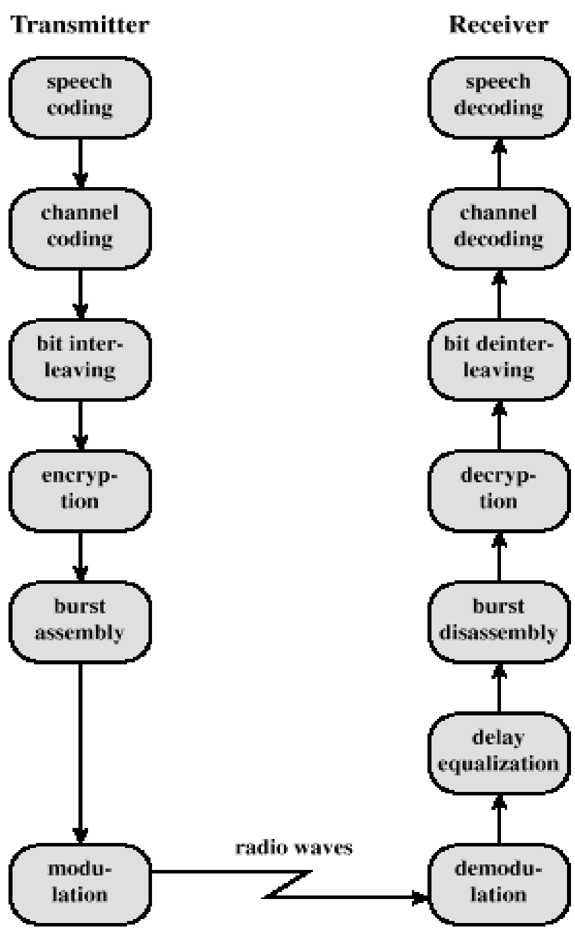
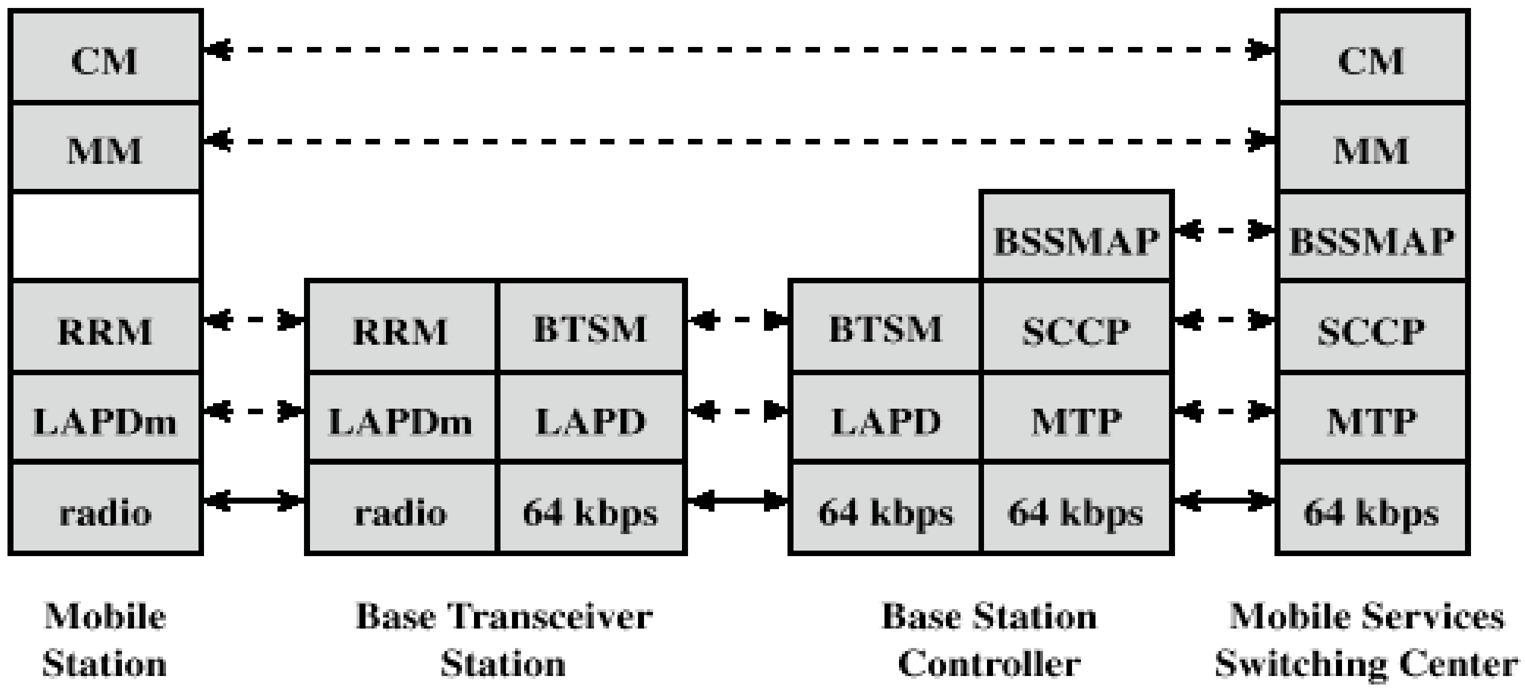


Figure 10.16 GSM Speech Signal Processing

GSM Speech Processing Steps

- Speech compressed using a predictive coding scheme
- Divided into blocks, each of which is protected partly by CRC and partly by a convolutional code
- Interleaving to protect against burst errors
- Encryption for providing privacy
- Assembled into time slots
- Modulated for analog transmission using FSK

GSM Signaling Protocol



BSSMAP = BSS mobile application part
BTSM = BTS management
CM = connection management
LAPD = link access protocol, D channel
MM = mobility management
MTP = message transfer part
RRM = radio resources management
SCCP = signal connection control part

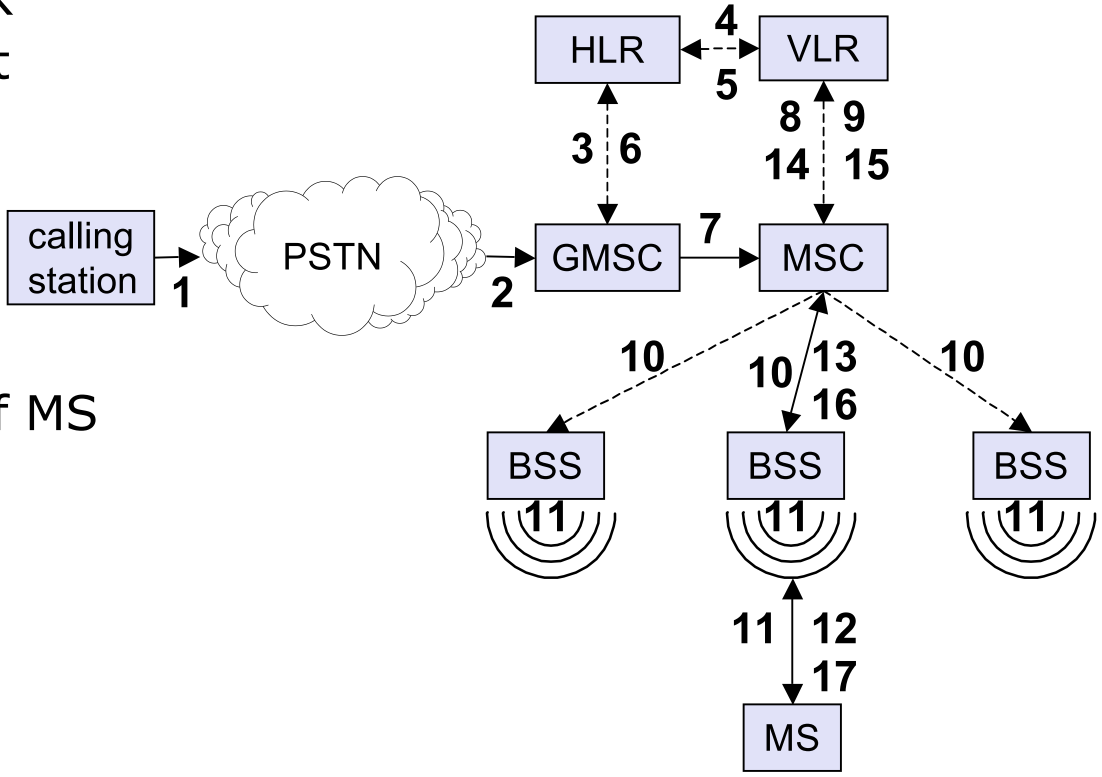
Figure 10.17 GSM Signaling Protocol Architecture

Functions Provided by Protocols

- Protocols above the link layer of the GSM signaling protocol architecture provide specific functions:
  - Radio resource management
  - Mobility management
  - Connection management
  - Mobile application part (MAP)
  - BTS management

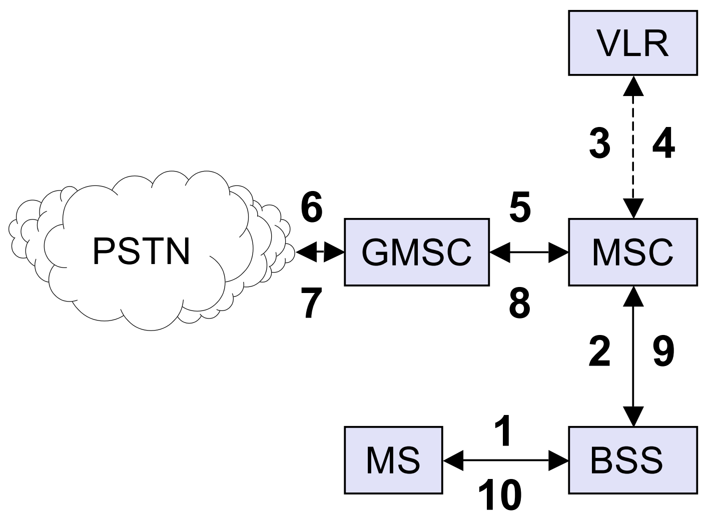
Mobile Terminated Call

- 1: calling a GSM subscriber
- 2: forwarding call to GMSC
- 3: signal call setup to HLR
- 4, 5: connect with current VLR
- 6: forward responsible MSC to GMSC
- 7: forward call to current MSC
- 8, 9: get current status of MS
- 10, 11: paging of MS
- 12, 13: MS answers
- 14, 15: security checks
- 16, 17: set up connection

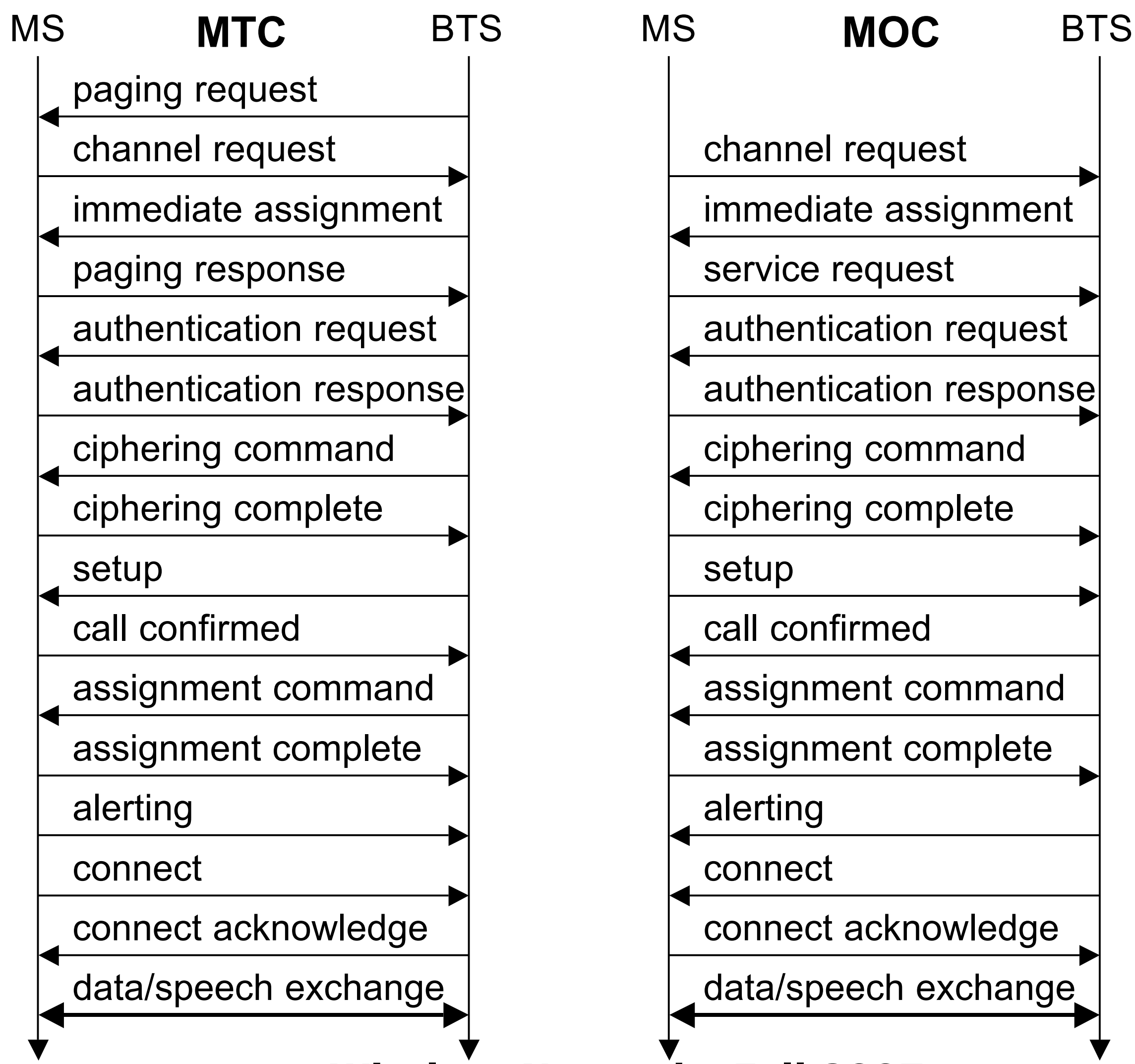


Mobile Originated Call

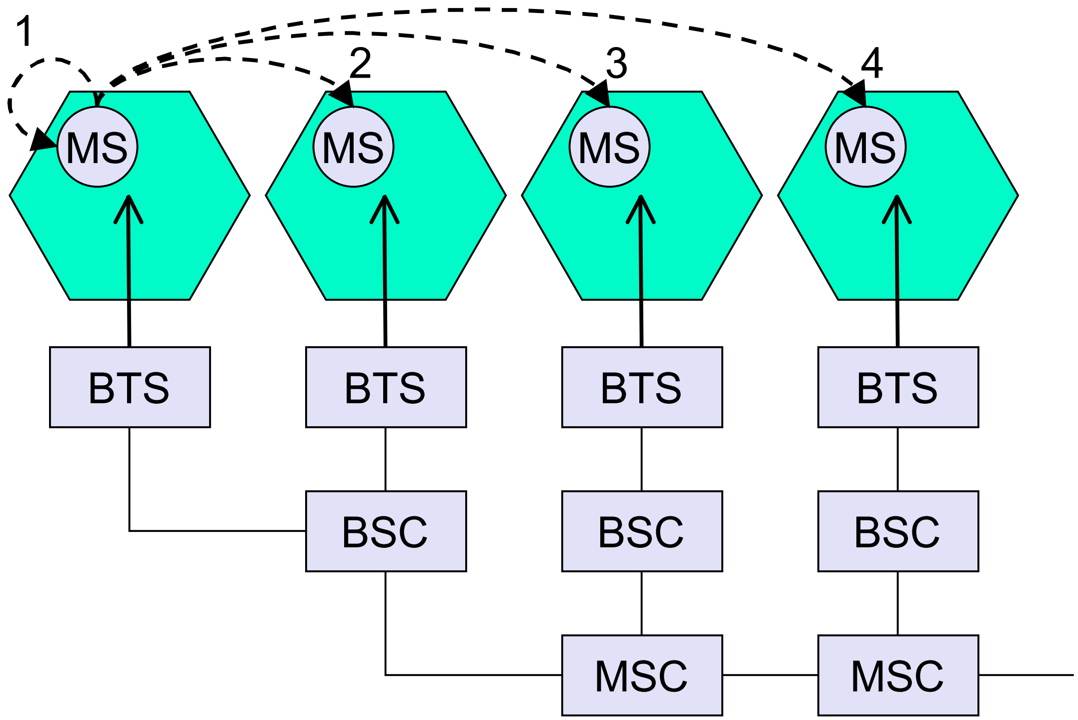
- 1, 2: connection request
- 3, 4: security check
- 5-8: check resources (free circuit)
- 9-10: set up call



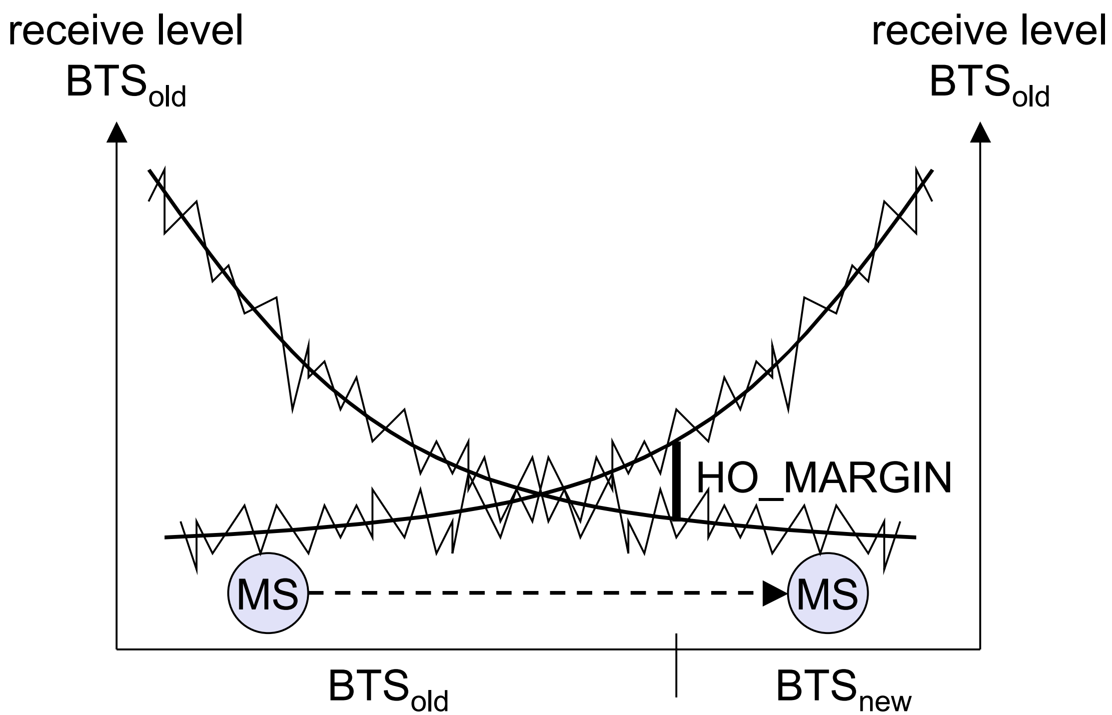
MTC/MOC


MS
MTC
BTS
paging request
channel request
immediate assignment
paging response
authentication request
authentication response
ciphering command
ciphering complete
setup
call confirmed
assignment command
assignment complete
alerting
connect
connect acknowledge
data/speech exchange
MS
MOC
BTS
channel request
immediate assignment
service request
authentication request
authentication response
ciphering command
ciphering complete
setup
call confirmed
assignment command
assignment complete
alerting
connect
connect acknowledge
data/speech exchange

4 types of handover



Handover decision

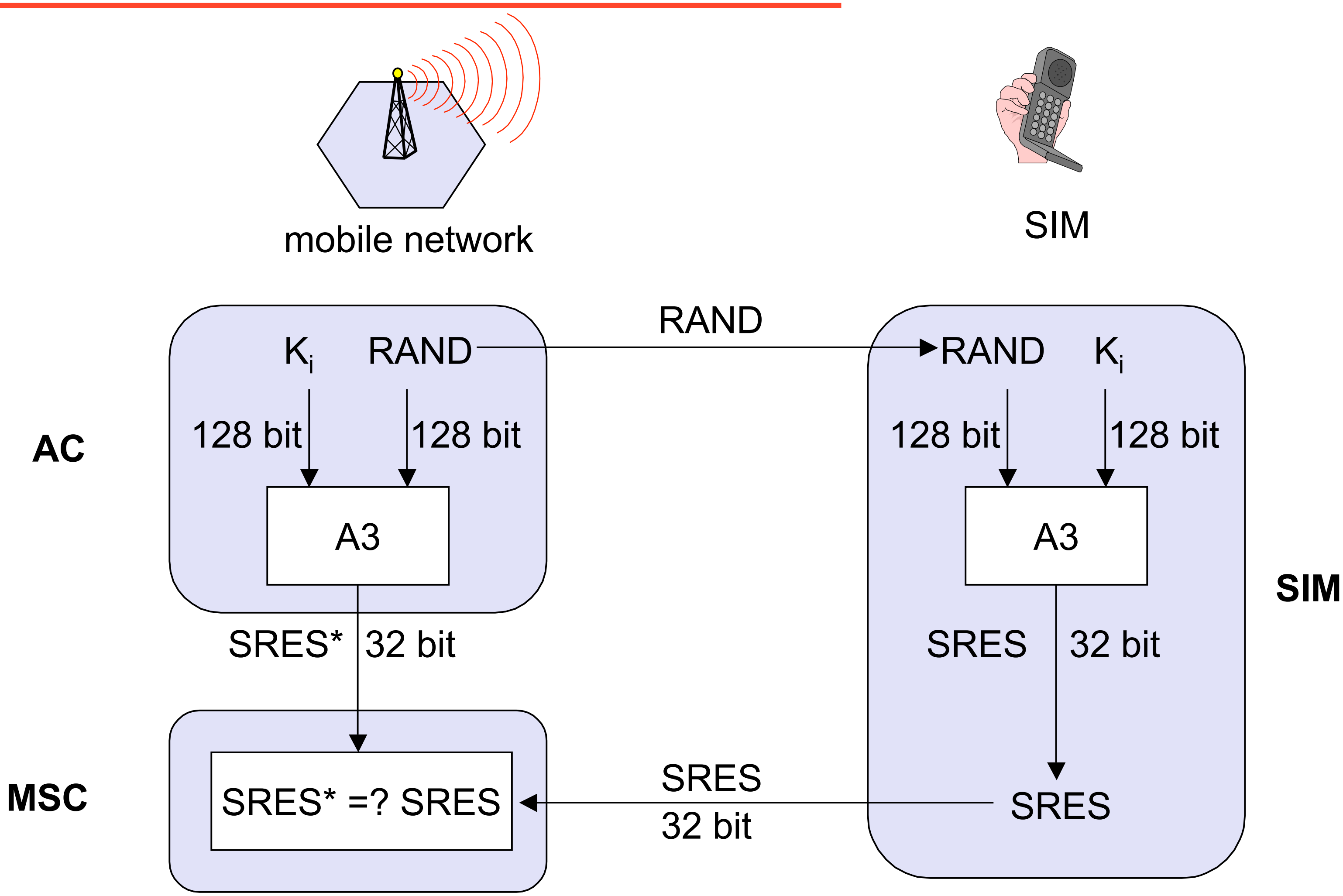


Security in GSM

- Security services
  - access control/authentication
    - user → SIM (Subscriber Identity Module): secret PIN (personal identification number)
    - SIM → network: challenge response method
  - confidentiality
    - voice and signaling encrypted on the wireless link (after successful authentication)
  - anonymity
    - temporary identity TMSI (Temporary Mobile Subscriber Identity)
    - newly assigned at each new location update (LUP)
    - encrypted transmission
- 3 algorithms specified in GSM
  - A3 for authentication ("secret", open interface)
  - A5 for encryption (standardized)
  - A8 for key generation ("secret", open interface)

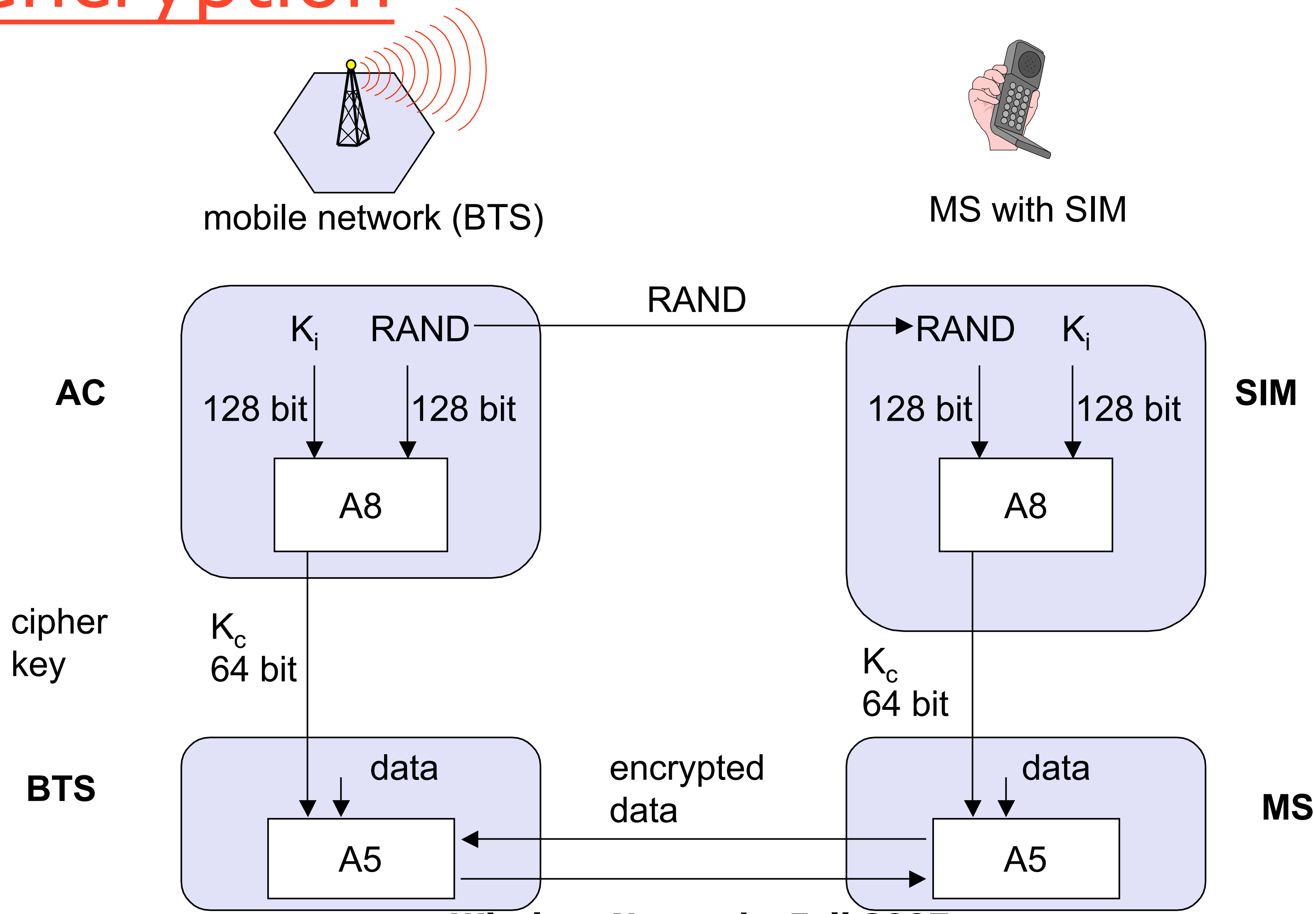
"secret":
• A3 and A8 available via the Internet
• network providers can use stronger mechanisms

GSM - authentication



K_i: individual subscriber authentication key   SRES: signed response

GSM - key generation and encryption



IS-95 (CdmaOne)

- IS-95: standard for the radio interface
- IS-41: standard for the network part
- Operates in 800MHz and 1900MHz bands
- Uses DS-CDMA technology (1.2288 Mchips/s)
- Forward link (downlink): (2,1,9)-convolutional code, interleaved, 64 chips spreading sequence (Walsh-Hadamard functions)
- Pilot channel, synchronization channel, 7 paging channels, up to 63 traffic channels
- Reverse link (uplink): (3,1,9)-convolutional code, interleaved, 6 bits are mapped into a Walsh-Hadamard sequence, spreading using a user-specific code
- Tight power control (open-loop, fast closed loop)

Advantages of CDMA Cellular

- Frequency diversity – frequency-dependent transmission impairments have less effect on signal
- Multipath resistance – chipping codes used for CDMA exhibit low cross correlation and low autocorrelation
- Privacy – privacy is inherent since spread spectrum is obtained by use of noise-like signals
- Graceful degradation – system only gradually degrades as more users access the system

Drawbacks of CDMA Cellular

- Self-jamming – arriving transmissions from multiple users not aligned on chip boundaries unless users are perfectly synchronized
- Near-far problem – signals closer to the receiver are received with less attenuation than signals farther away
- Soft handoff – requires that the mobile acquires the new cell before it relinquishes the old; this is more complex than hard handoff used in FDMA and TDMA schemes

CDMA Design Considerations

- RAKE receiver – when multiple versions of a signal arrive more than one chip interval apart, RAKE receiver attempts to recover signals from multiple paths and combine them
  - This method achieves better performance than simply recovering dominant signal and treating remaining signals as noise
- Soft Handoff – mobile station temporarily connected to more than one base station simultaneously

Principle of RAKE Receiver

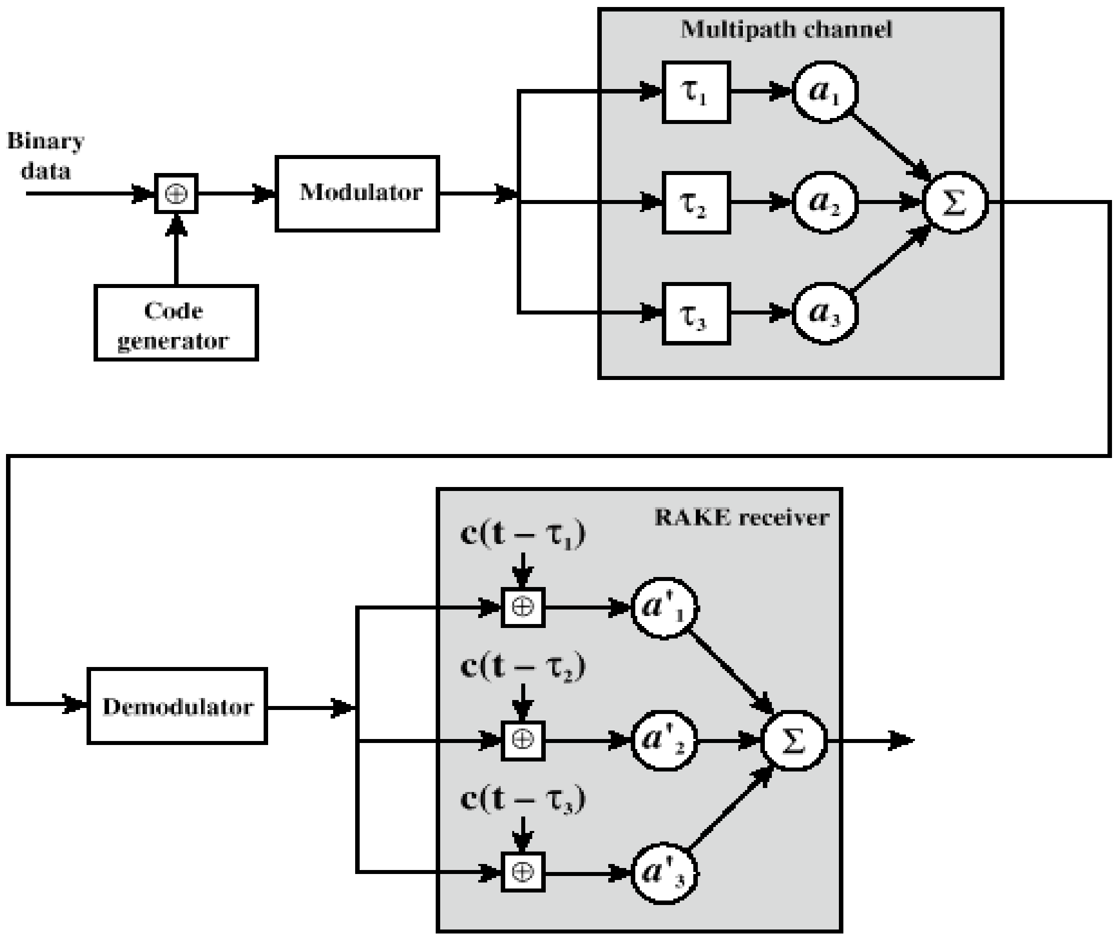


Figure 10.18 Principle of RAKE Receiver [PRAS98]

Forward Link Channels

- Pilot: allows the mobile unit to acquire timing information, provides phase reference and provides means for signal strength comparison
- Synchronization: used by mobile station to obtain identification information about cellular system
- Paging: contain messages for one or more mobile stations
- Traffic: the forward channel supports 55 traffic channels

Forward Traffic Processing Steps

- Speech is encoded at a rate of 8550 bps
- Additional bits added for error detection
- Data transmitted in 2-ms blocks with forward error correction provided by a convolutional encoder
- Data interleaved in blocks to reduce effects of errors
- Data bits are scrambled, serving as a privacy mask
  - Using a long code based on user’s electronic serial number

Forward Traffic Processing Steps

- Power control information inserted into traffic channel
- DS-SS function spreads the 19.2 kbps to a rate of 1.2288 Mbps using one row of 64 x 64 Walsh matrix
- Digital bit stream modulated onto the carrier using QPSK modulation scheme

Reverse Traffic Processing Steps

- Convolutional encoder at rate 1/3
- Spread the data using a Walsh matrix
  - Use a 6-bit piece of data as an index to the Walsh matrix
  - To improve reception at base station
- Data burst randomizer
- Spreading using the user-specific long code mask

Third-Generation Capabilities

- Voice quality comparable to the public switched telephone network
- 144 kbps data rate available to users in high-speed motor vehicles over large areas
- 384 kbps available to pedestrians standing or moving slowly over small areas
- Support for 2.048 Mbps for office use
- Symmetrical/asymmetrical data transmission rates
- Support for both packet switched and circuit switched data services