

Cellular Networks

Wireless Networks Fall 2007

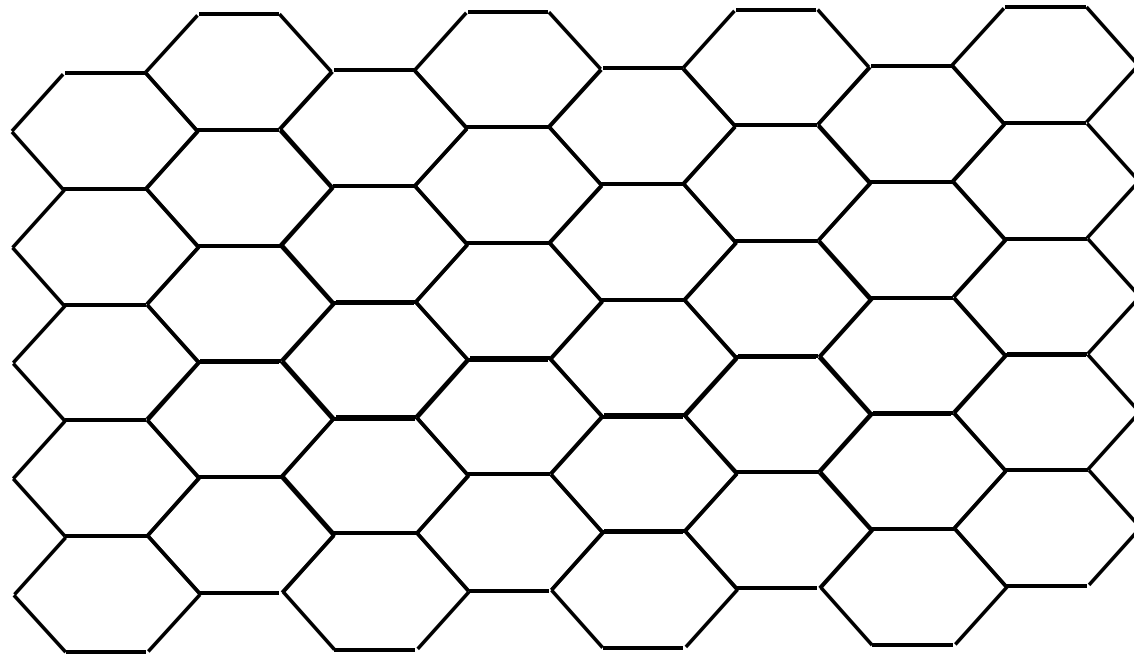
Cellular Network Organization

- ❑ Use multiple low-power transmitters (100 W or less)
- ❑ Areas divided into cells
 - o Each served by its own antenna
 - o Served by base station consisting of transmitter, receiver, and control unit
 - o Band of frequencies allocated
 - o 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
 - o 10 to 50 frequencies assigned to each cell
 - o Transmission power controlled to limit power at that frequency escaping to adjacent cells
 - o 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:
 - o For any cell, interference from nearby cells within an acceptable minimum
 - o For any cell, the frequency bandwidth allocated sufficient to support the load in the cell
- ❑ Objectives:
 - o Minimize the total bandwidth (or width of the spectrum) allocated across all cells
 - o Minimize call blocking probability
 - o Minimize average interference

Solving FAPs

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

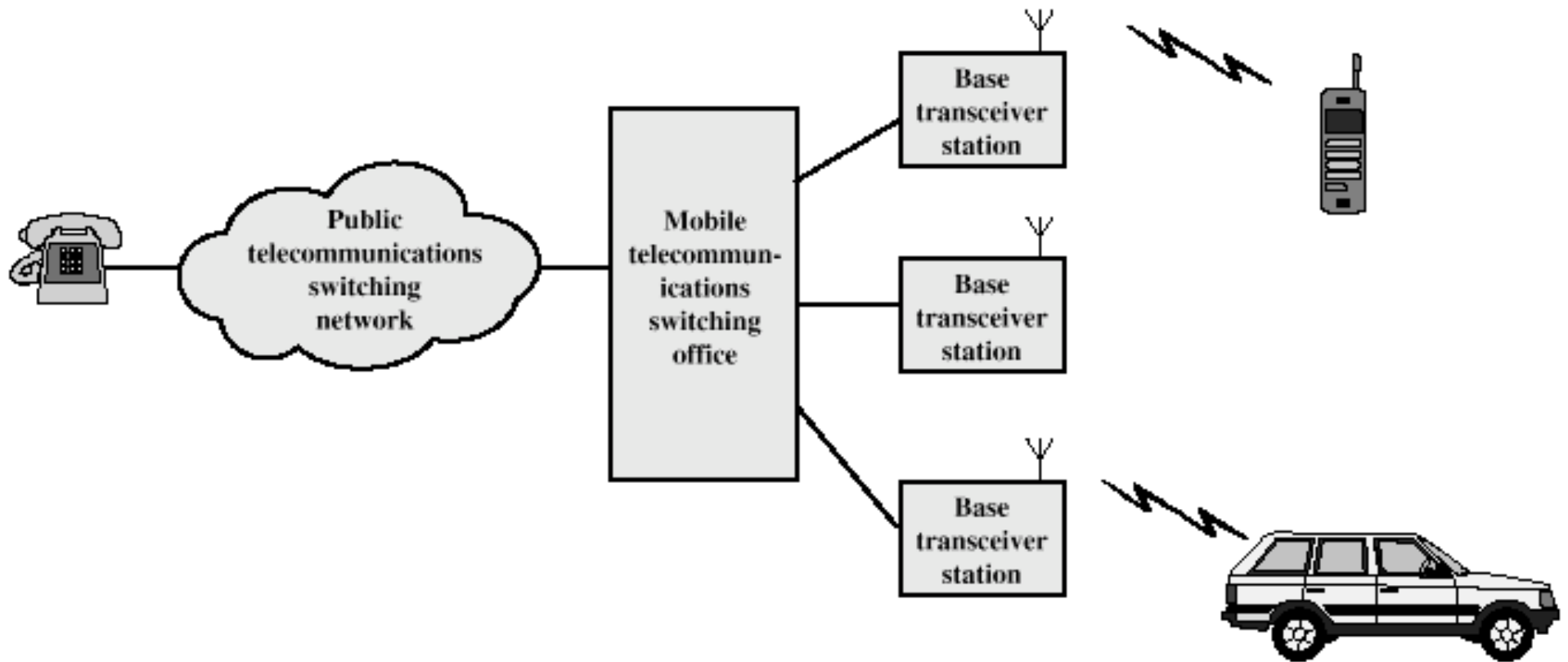
Formulating FAPs

- ❑ 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
 - o Control channels – used to exchange information having to do with setting up and maintaining calls
 - o 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

- o Must be strong enough between base station and mobile unit to maintain signal quality at the receiver
- o Must not be so strong as to create too much cochannel interference with channels in another cell using the same frequency band

□ Fading

- o 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
 - o $L < N$ – nonblocking system
 - o $L > N$ – 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
 - o Lost calls delayed (LCD) – blocked calls put in a queue awaiting a free channel
 - o 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
 - o Whether number of users is assumed to be finite or infinite

First-Generation Analog

□ Advanced Mobile Phone Service (AMPS)

- o 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
- o Each band split in two to encourage competition (12.5MHz per operator)
- o Channels of 30 KHz: 21 control channels (FSK), 395 traffic channels (FM voice) per operator
- o 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 μ s
- ❑ Bandwidth: Not to exceed 200 kHz (25 kHz per channel)

GSM Network Architecture

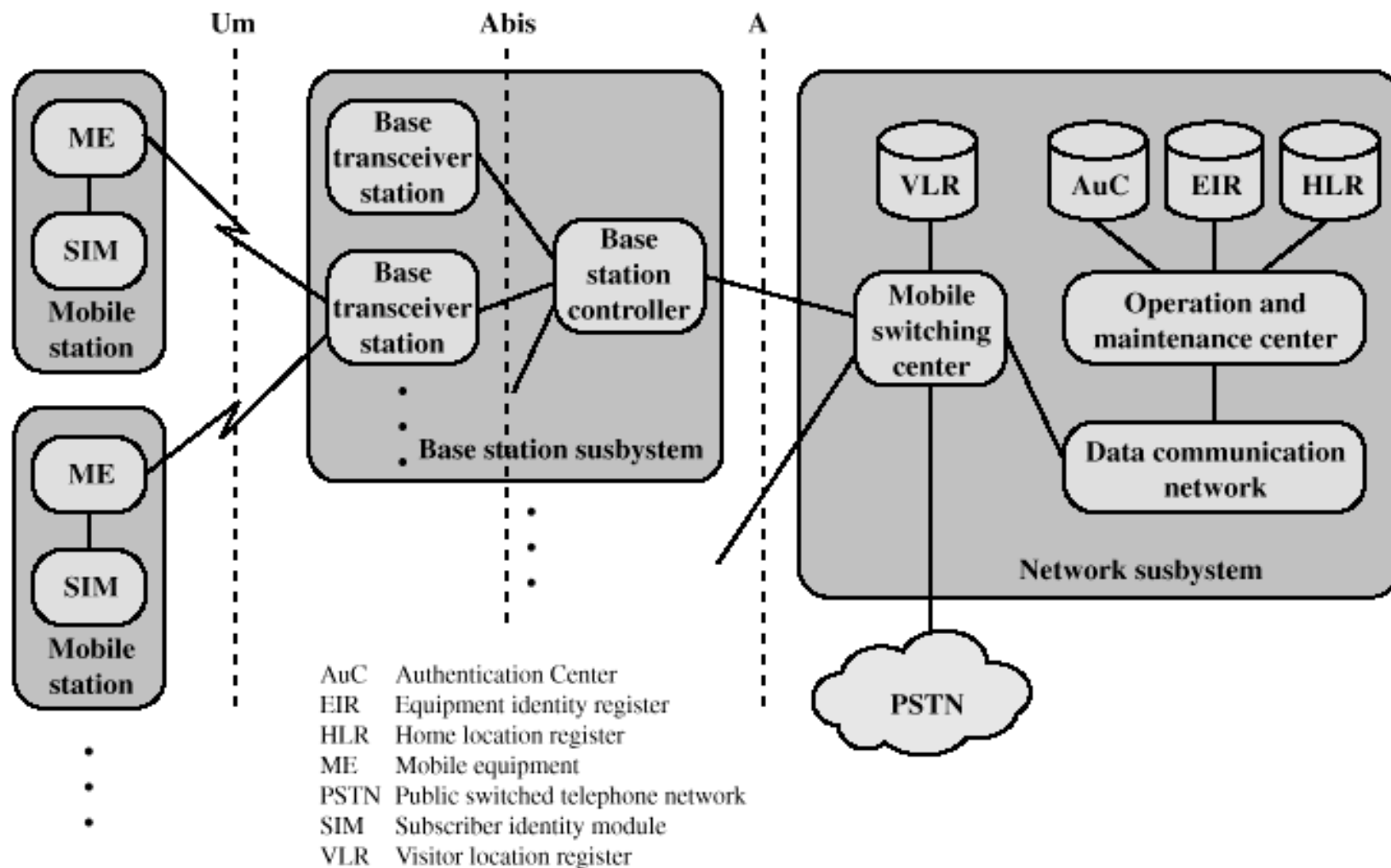
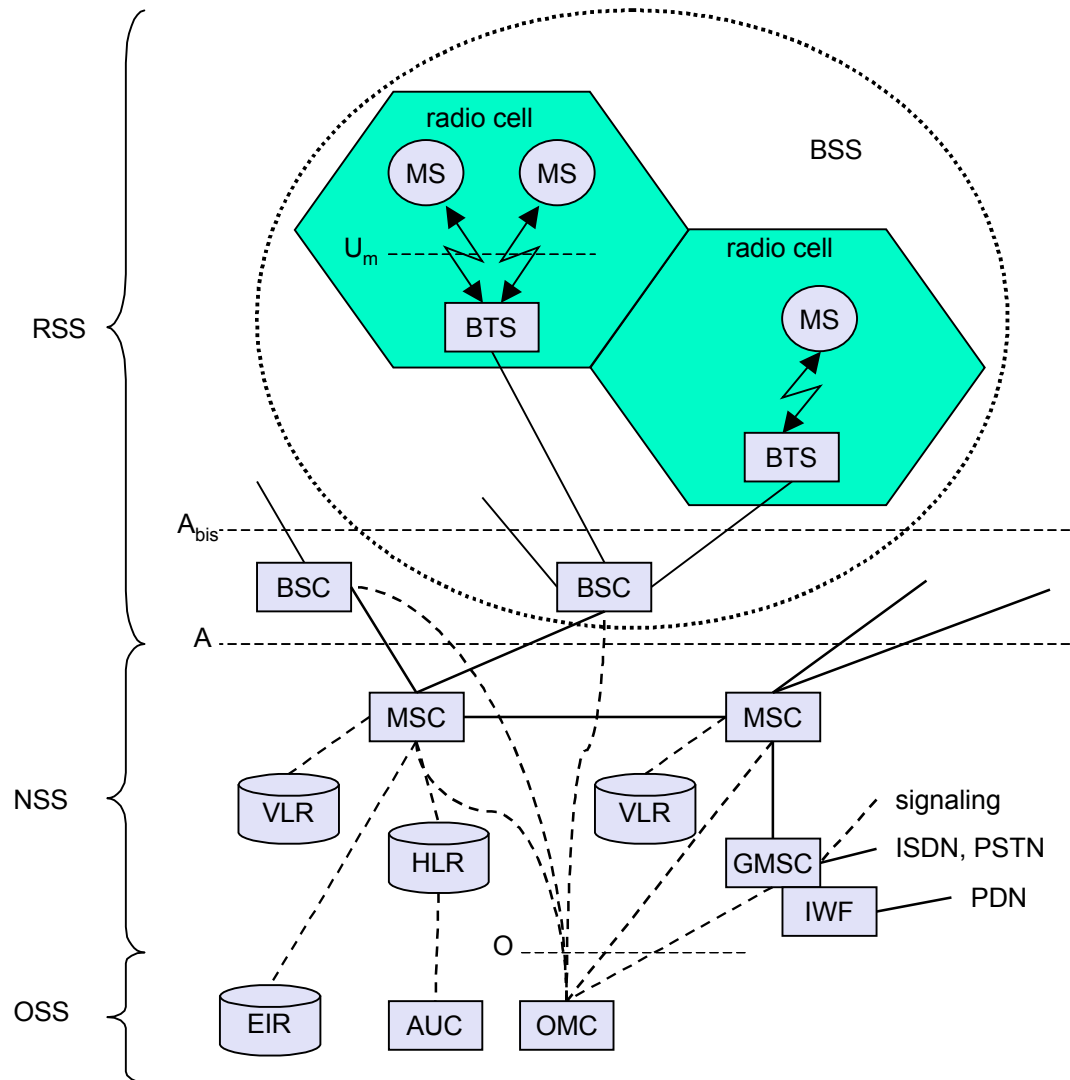


Figure 10.14 Overall GSM Architecture

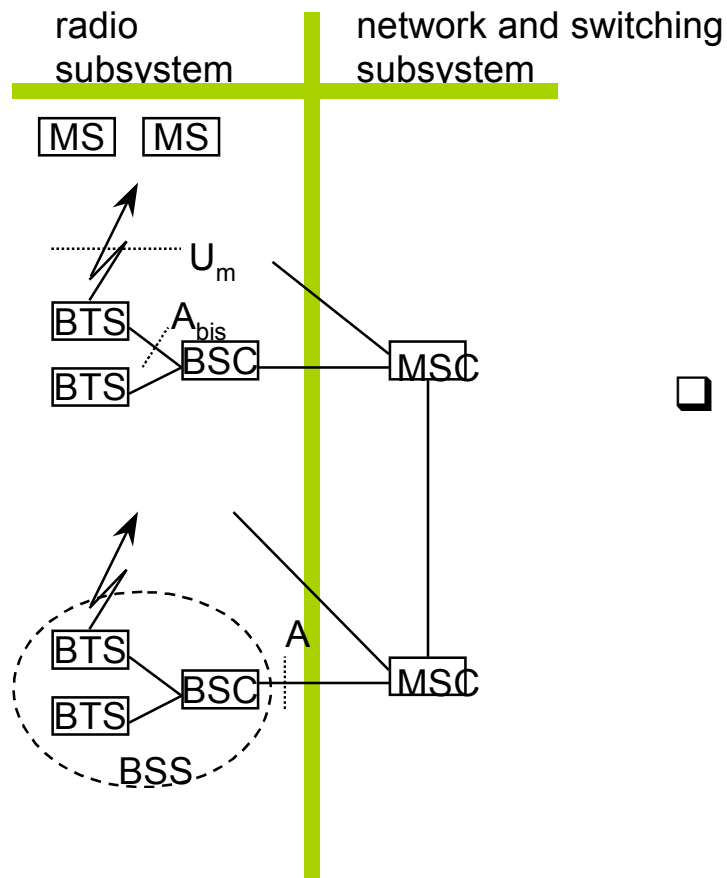
Architecture of the GSM system

- ❑ 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



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

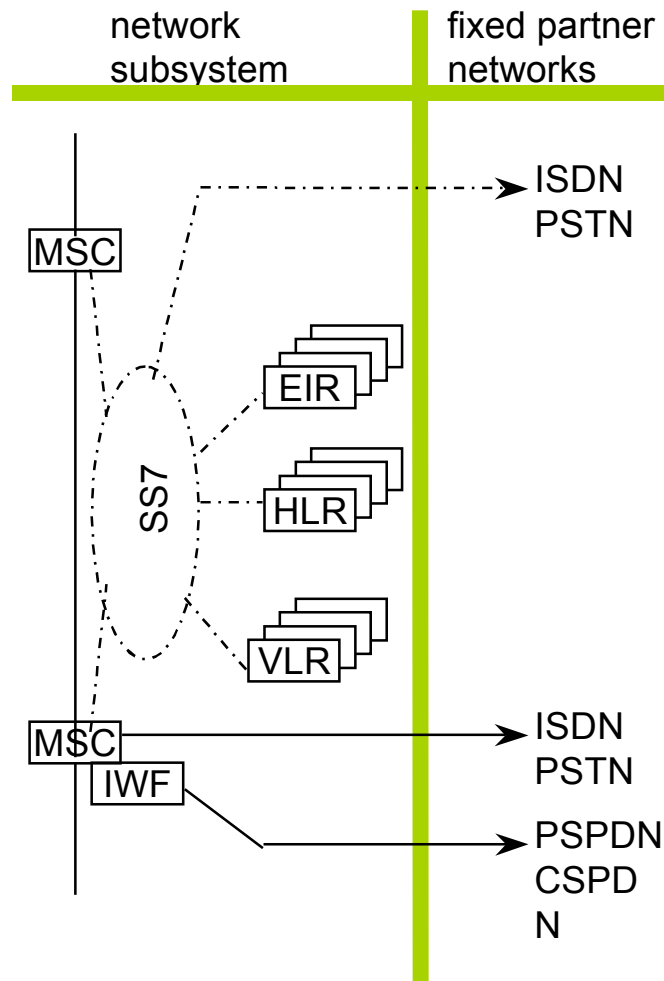
Mobile Station

- ❑ 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
 - o ME includes radio transceiver, digital signal processors and subscriber identity module (SIM)
- ❑ GSM subscriber units are generic until SIM is inserted
 - o 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
 - o 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 Register)
- ❑ *VLR* (Visitor Location Register)
- ❑ *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
 - o Strongest signal selected in case of multipath propagation
- ❑ Guard bits – used to avoid overlapping with other bursts

GSM Speech Processing

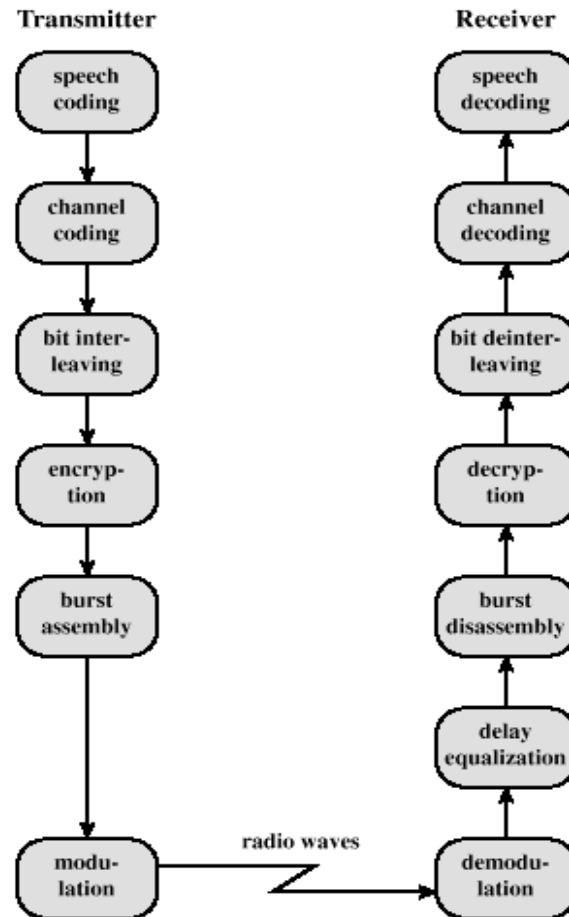
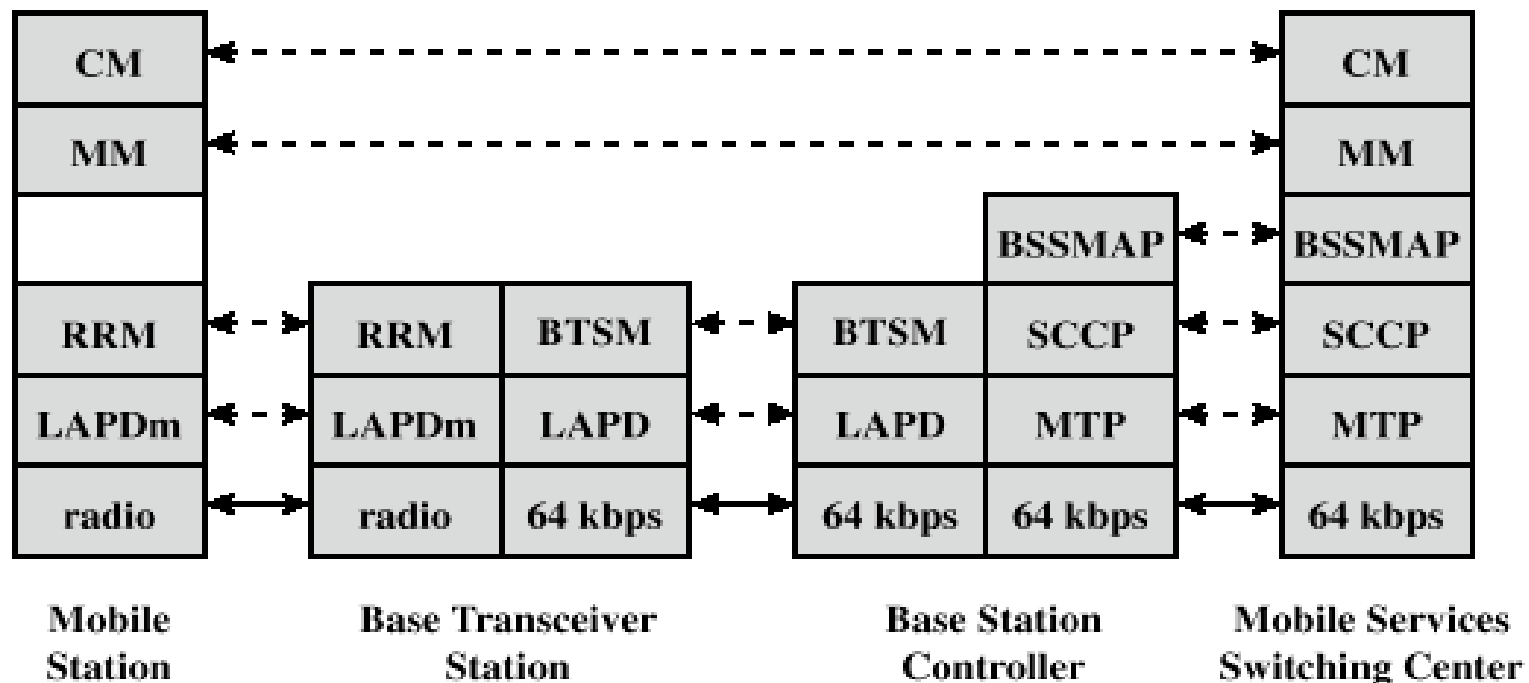


Figure 10.16 GSM Speech Signal Processing

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

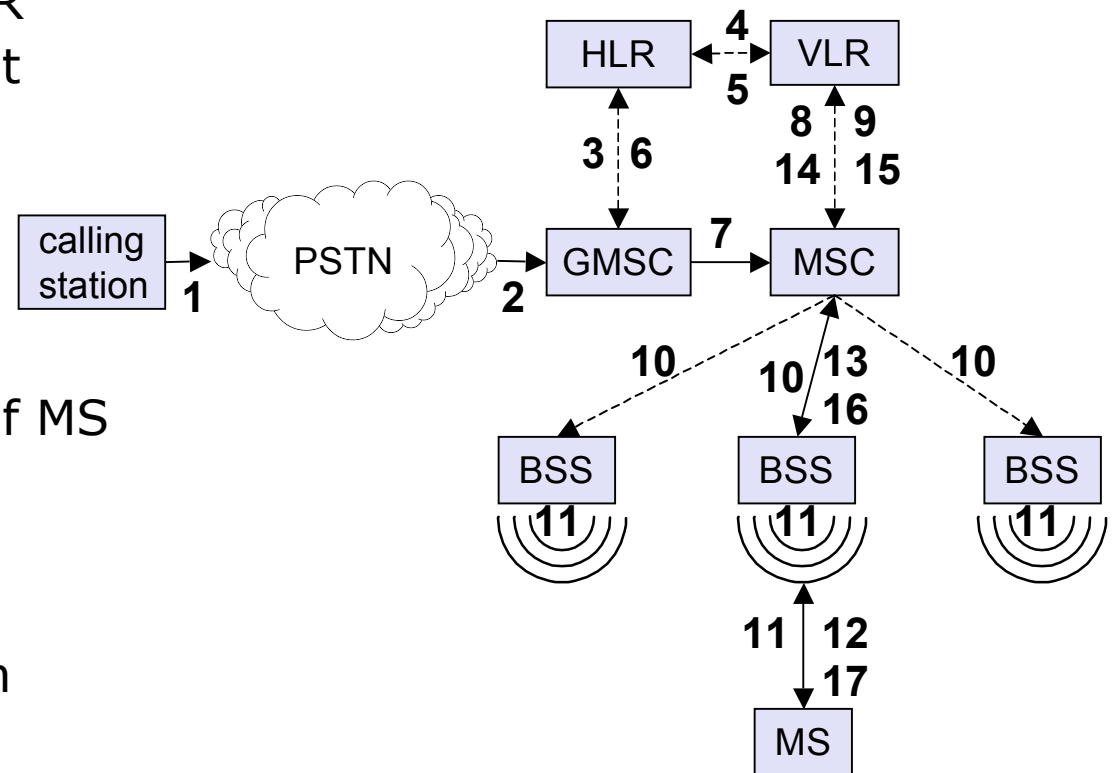
Figure 10.17 GSM Signaling Protocol Architecture

Functions Provided by Protocols

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

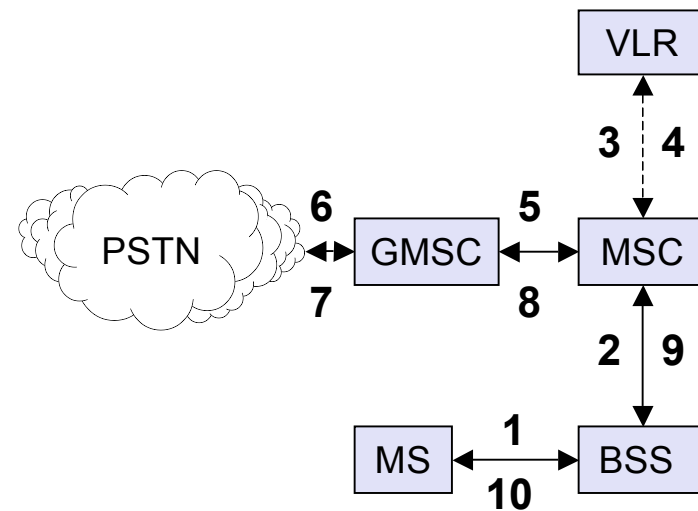
Mobile Terminated Call

- ❑ 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

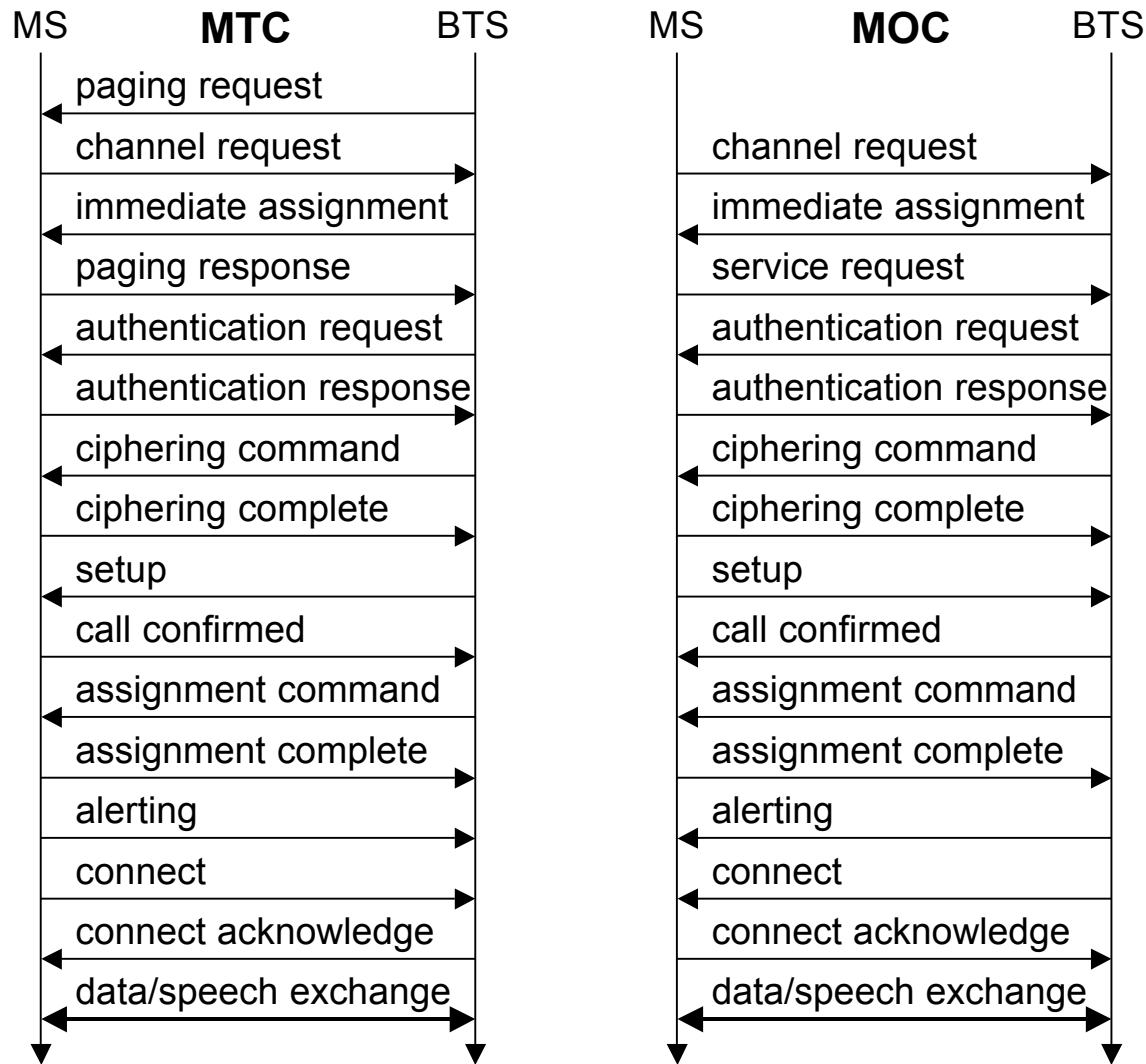


Mobile Originated Call

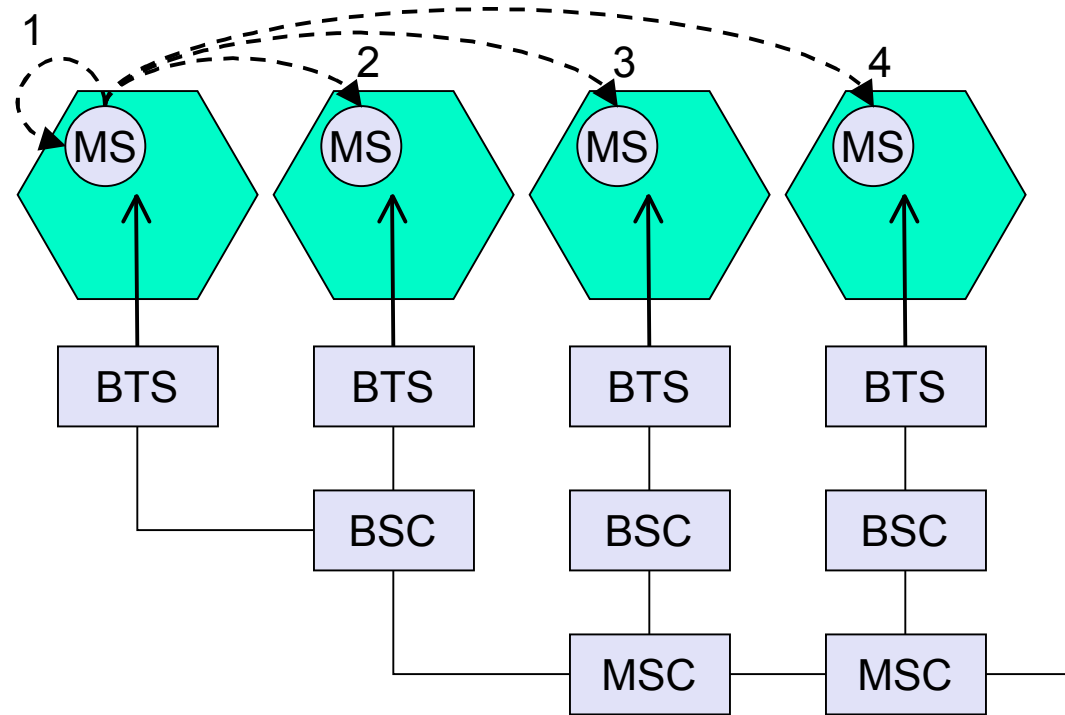
- ❑ 1, 2: connection request
- ❑ 3, 4: security check
- ❑ 5-8: check resources (free circuit)
- ❑ 9-10: set up call



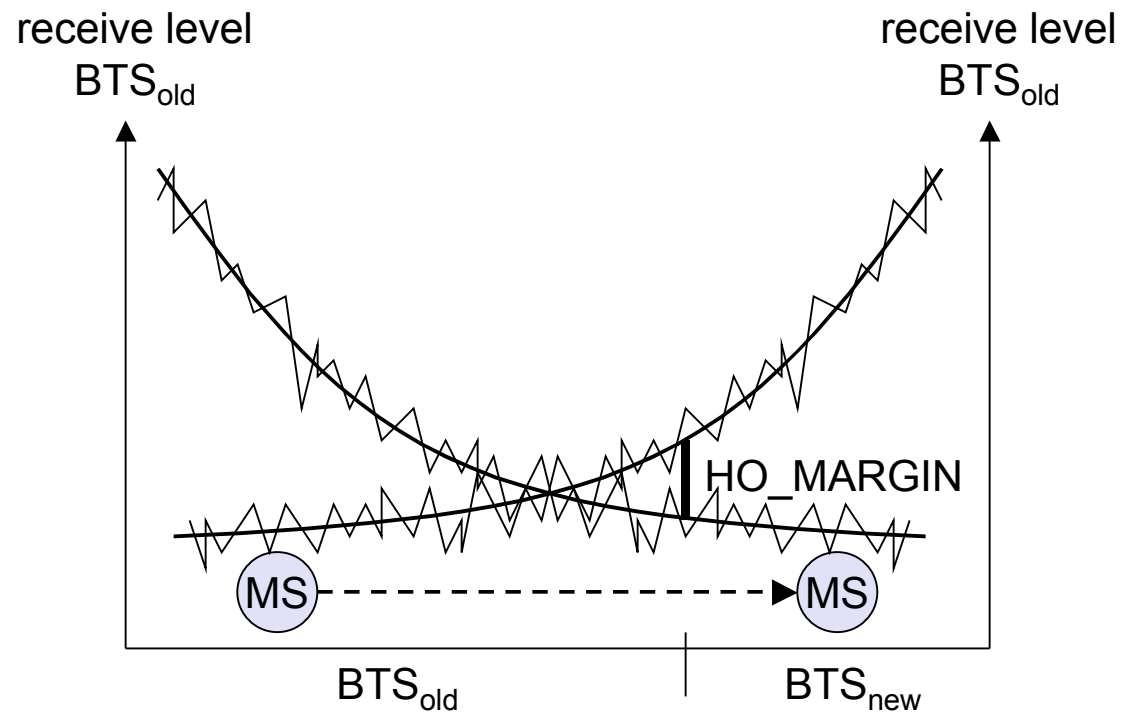
MTC/MOC



4 types of handover



Handover decision



Security in GSM

❑ Security services

o access control/authentication

- user → SIM (Subscriber Identity Module): secret PIN (personal identification number)
- SIM → network: challenge response method

o confidentiality

- voice and signaling encrypted on the wireless link (after successful authentication)

o anonymity

- temporary identity TMSI (Temporary Mobile Subscriber Identity)
- newly assigned at each new location update (LUP)
- encrypted transmission

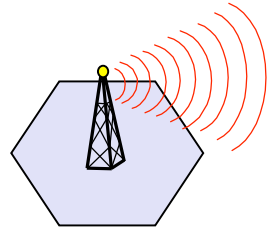
❑ 3 algorithms specified in GSM

- o A3 for authentication (“secret”, open interface)
- o A5 for encryption (standardized)
- o A8 for key generation (“secret”, open interface)

“secret”:

- A3 and A8 available via the Internet
- network providers can use stronger mechanisms

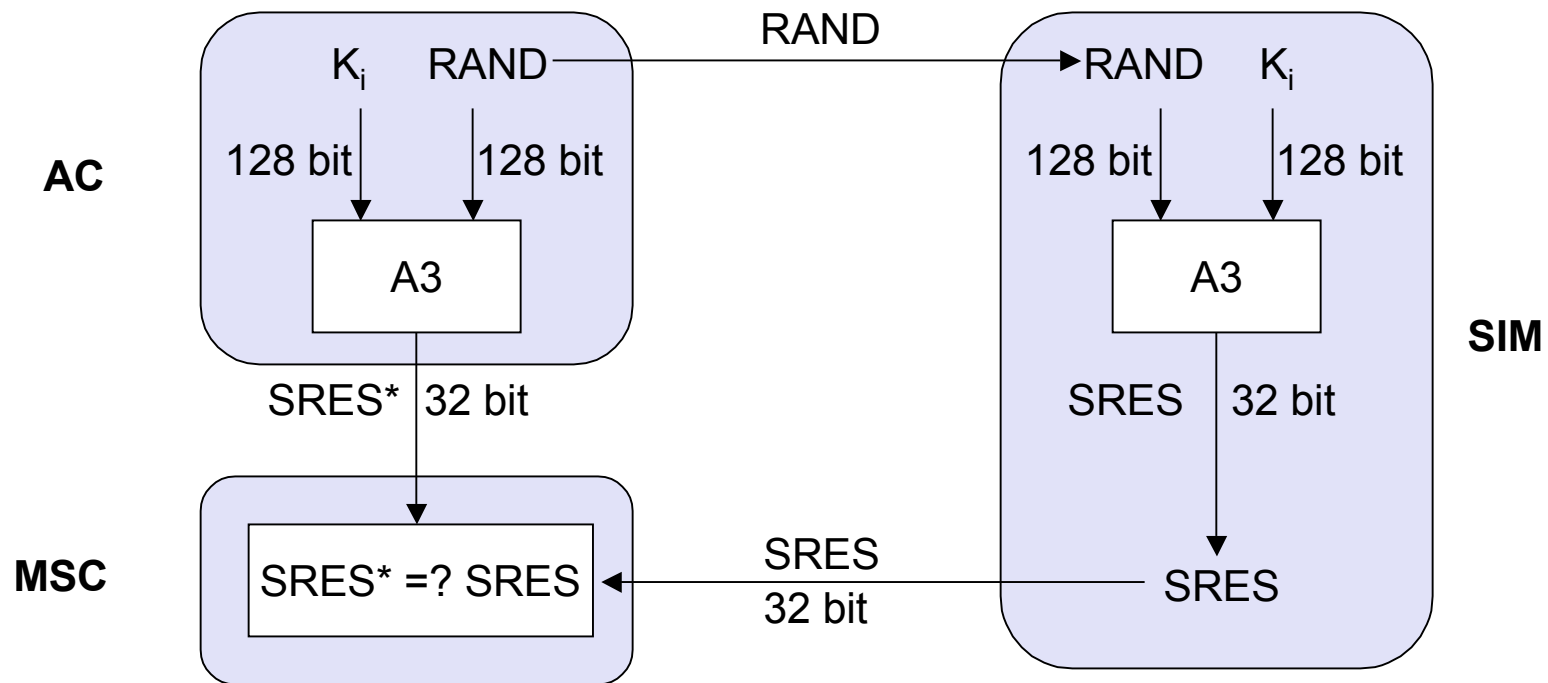
GSM - authentication



mobile network

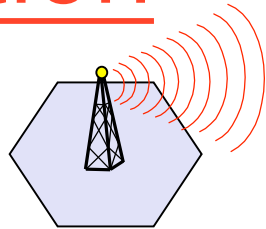


SIM



K_i : individual subscriber authentication key SRES: signed response

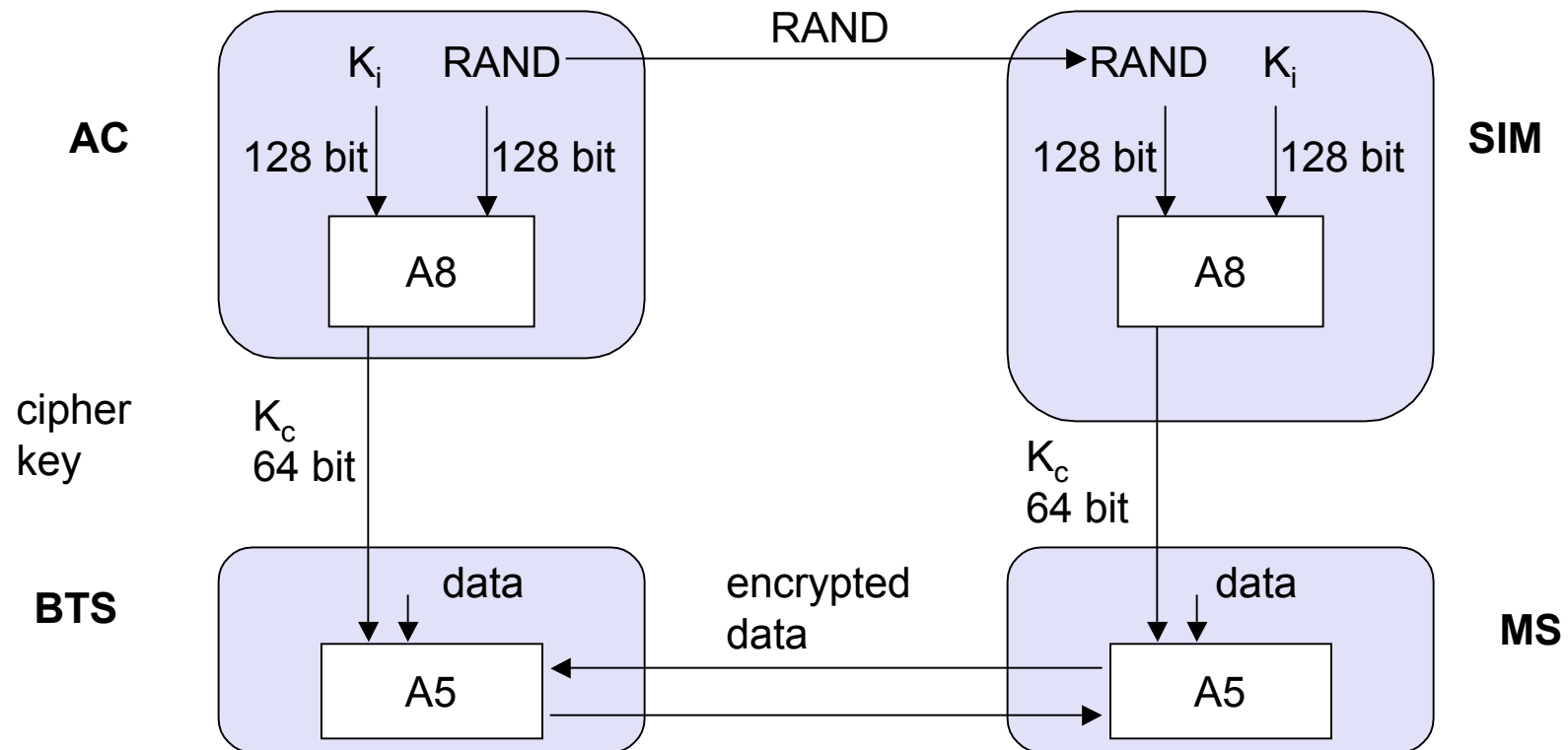
GSM - key generation and encryption



mobile network (BTS)



MS with SIM



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
 - o 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

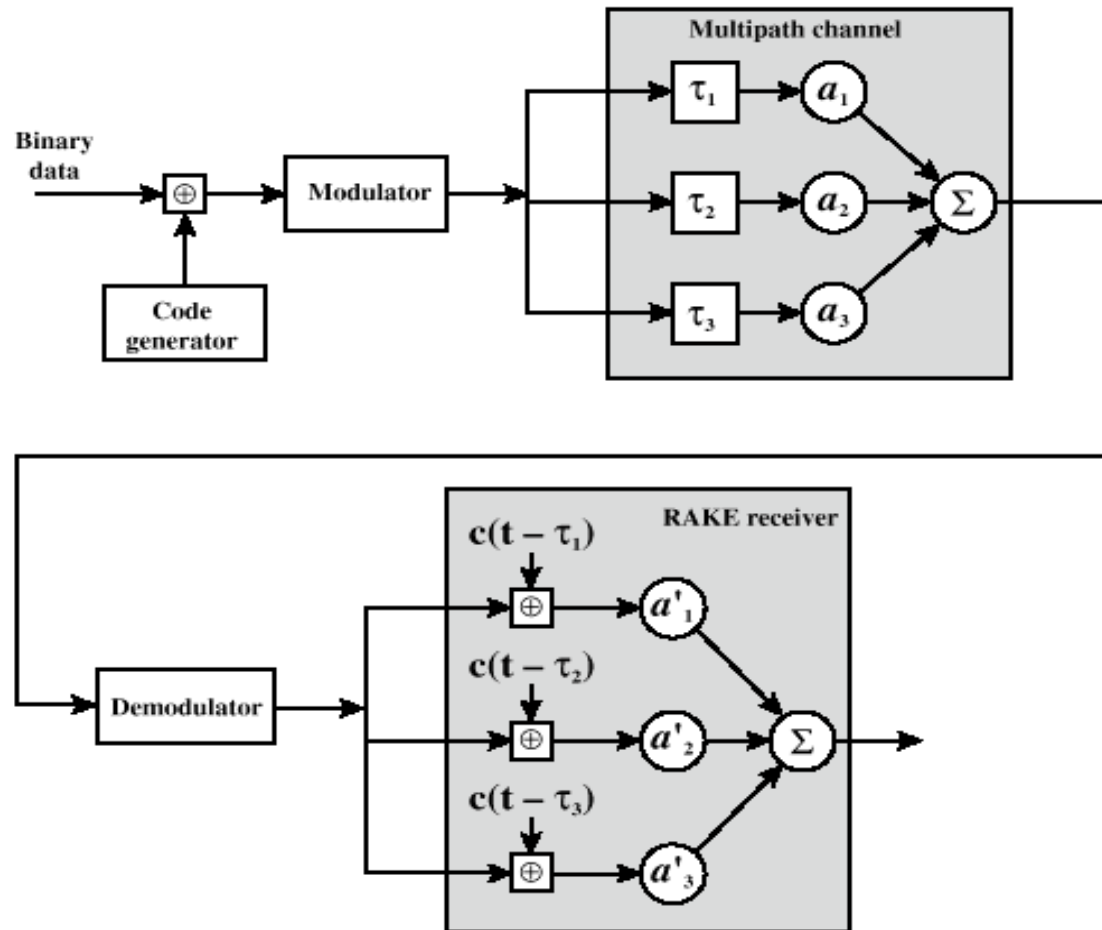


Figure 10.18 Principle of RAKE Receiver [PRAS98]

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
 - o 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
 - o Use a 6-bit piece of data as an index to the Walsh matrix
 - o 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