Cellular Wireless Networks

Cellular Network Organization

- Use multiple low-power transmitters (100 W or less)
- Areas divided into cells, because the range of each transmitter is small.
  - Each served by its own antenna
  - Served by base station consisting of transmitter, receiver, and control unit.
  - Band of frequencies allocated
  - Adjacent cells assigned different frequencies to avoid interference/crosstalk.
  - However, cells fairly distant from each other use the same frequency.
  - Cells set up such that antennas of all neighbors are equidistant (hexagonal pattern). Hence, hexagonal pattern used. Not true for other patterns such as square pattern.
    - Radius of the hexagon is the radius of the circumscribing circle.
    - For a cell radius R, the distance between the cell center and each adjacent cell center is d = (square root of 3) * R.

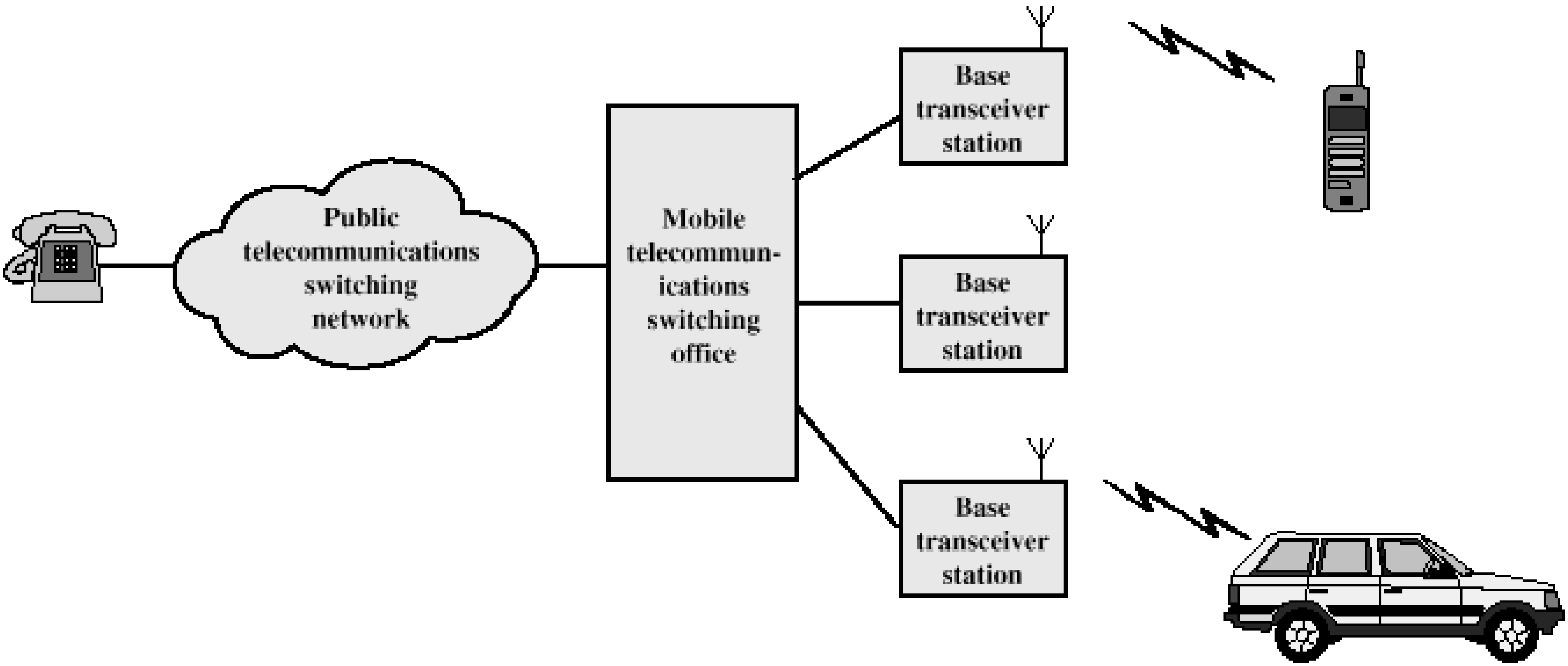
Frequency Reuse

- 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.
  - If the pattern consists of N cells, and each cell is assigned the same number of frequencies, each cell can have K/N frequencies.
    - For example: For AMPS, K = 395, and N = 7 is the smallest pattern that can provide sufficient isolation

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. Decrease in cell size, radiated power.

Cellular System Overview



Cellular Systems Terms

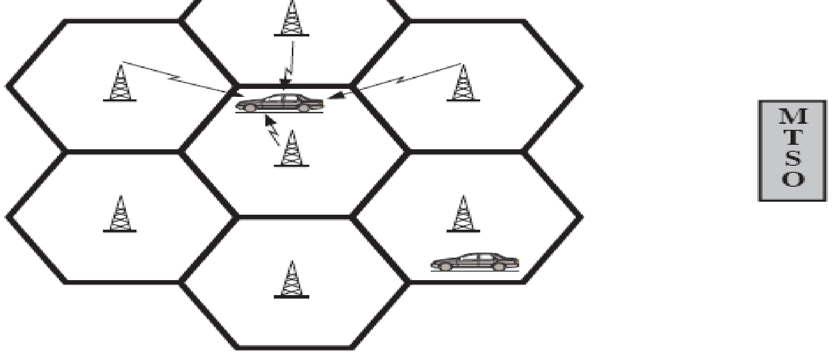
- Base Station (BS) – includes an antenna, a controller, and a number of receivers
- Mobile telecommunications switching office (MTSO) – connects calls between mobile units
- Two types of channels available between mobile unit and BS
  - Control channels – used to exchange information having to do with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

Steps in an MTSO Controlled Call between Mobile Users (1)

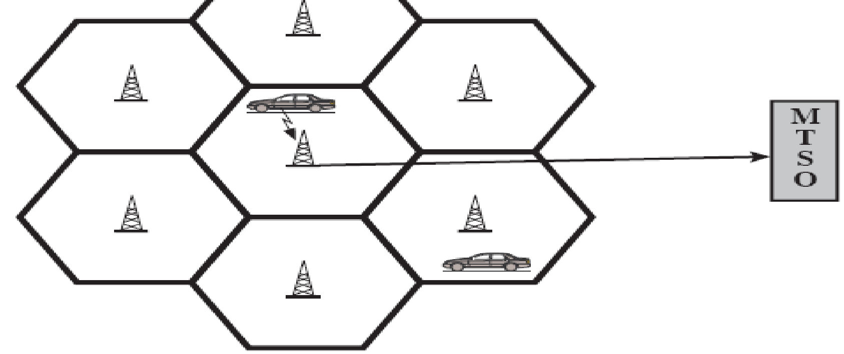
- Mobile unit initialization
  - When the mobile unit is turned on, it scans and selects the strongest setup control channel used for this system.
  - Cells with different frequency bands repetitively broadcast on different setup channels.
  - The receiver selects the strongest setup channel and monitors that channel.
  - Mobile unit has automatically selected the BS antenna of the cell within which it will operate.
  - Then a handshake takes place between the mobile unit and the MTSO controlling this cell, through the BS in this cell. The handshake is used to identify the user and register its location.
  - This scanning procedure is repeated to account for the mobility of the device.
- Mobile-originated call
  - Mobile unit originates the call by sending the number of the called unit on the preselected setup channel.
  - The receiver at the mobile unit first checks that the setup channel is idle by examining information in the forward (from the BS) channel.
  - When an idle is detected, the mobile unit may transmit on the corresponding reverse (from the BS) channel.
  - The BS sends the request to the MTSO.

Steps in an MTSO Controlled Call between Mobile Users (2)

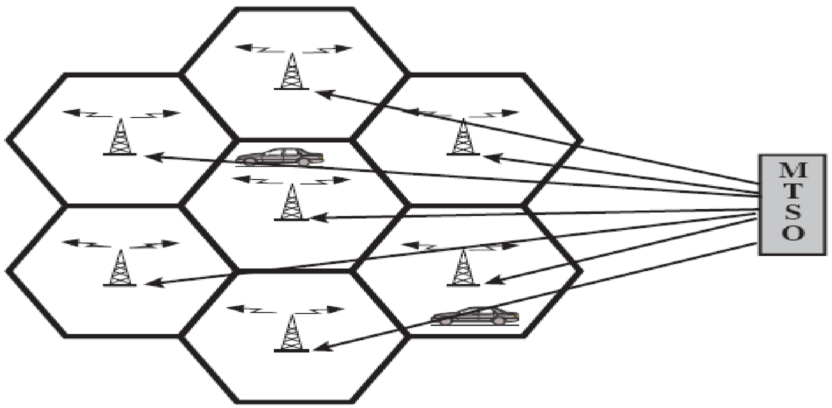
- Paging
  - The MTSO then attempts to complete the connection to the called unit.
  - The MTSO sends a paging message to certain BSs depending on the called mobile unit number.
  - Each BS transmits the paging signal on its own assigned setup channel.
- Call accepted
  - The called mobile unit recognizes its number on the setup channel being monitored and responds to that BS, which sends the response to the MTSO.
  - The MTSO sets up a circuit between the calling and the called BSs. At the same time, the MTSO selects an available traffic channel within each BS's cell and notifies each BS, which in turn, notifies its mobile unit.
- Ongoing call
  - While the connection is maintained, the two mobile units exchange voice or data signals, going through their respective BSs and the MTSO.
- Handoff
  - If a mobile unit moves out of range of one cell and into the range of another during a connection, the traffic channel has to change to one assigned to the BS in the new cell.



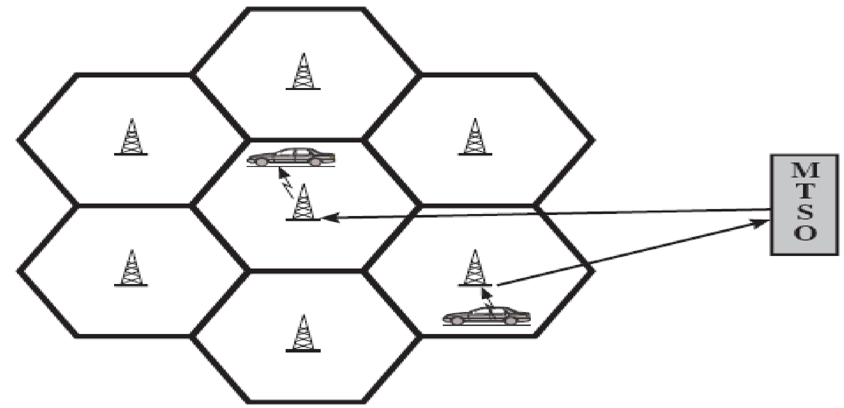
(a) Monitor for strongest signal



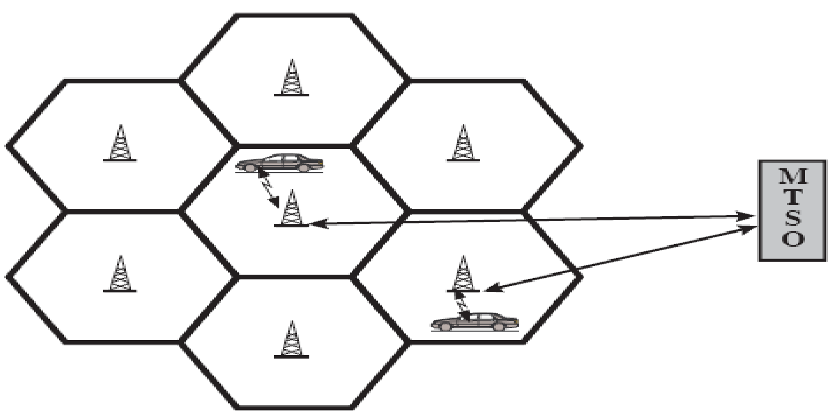
(b) Request for connection



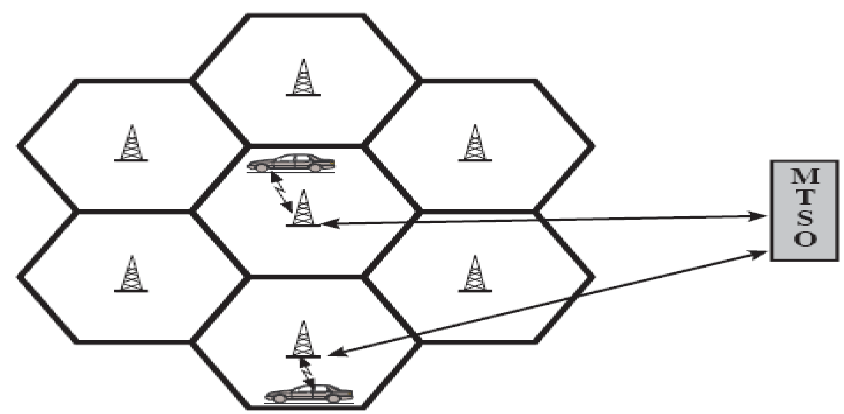
(c) Paging



(d) Call accepted



(e) Ongoing call



(f) Handoff

Additional Functions in an MTSO Controlled Call

- Call blocking
  - During the mobile-initiated call stage, if all the traffic channels assigned to the nearest BS are busy, then the mobile unit makes a preconfigured number of repeated attempts.
  - After a certain number of failed tries, a busy tone is returned to the user.
- Call termination
  - When one of the two users hangs up, the MTSO is informed and the traffic channels at the two BSs are released.
- Call drop
  - During a connection, because of interference or weak signal spots in certain areas, if the BS cannot maintain the minimum required signal strength for a certain period of time, the traffic channel to the user is dropped and the MTSO is informed.
- Calls to/from fixed and remote mobile subscriber
  - The MTSO connects to the public switched telephone network, enabling the mobile user to connect with a fixed subscriber via the telephone network.

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

- Is the procedure for changing the assignment of a mobile unit from one BS to another as the mobile unit moves from one cell to another.
- Two types:
  - Network Initiated: Decision is made solely by the network measurements of received signals from the mobile unit.
  - Mobile unit assisted handoff: Enables the mobile unit to participate in the handoff decision by providing feedback to the network concerning signals received at the mobile unit.

Handoff Performance Metrics

- Cell blocking probability – probability of a new call being blocked due to heavy load on the BS traffic capacity. In this case, the mobile unit is handed off to a neighboring cell based not on signal quality, but on traffic capacity.
- 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

Power Control

- Design issues making it desirable to include dynamic power control in a cellular system
  - Received power must be sufficiently above the background noise for effective communication.
    - As the mobile unit moves away from the transmitter, the received power declines due to normal attenuation.
    - Additionally, effects of reflection, diffraction and scattering can cause rapid changes in received power levels over small distances.
  - Desirable to minimize power in the transmitted signal from the mobile
    - To reduce cochannel interference, alleviate health concerns, save battery power
  - In Spread Spectrum 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
  - Depends solely on mobile unit
  - No feedback from BS
  - Not as accurate as closed-loop, but can react quicker to fluctuations in signal strength
- Closed-loop power control
  - Adjusts signal strength in reverse channel based on metric of performance (such as received signal power level, received signal to noise ration, or received bit-error rate).
  - BS makes power adjustment decision and communicates a power adjustment command to mobile on the control channel
  - Also, used to adjust power in the forward cannel.

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, for normalized λ

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 BS to mobile unit (869 – 894 MHz).
    - One for transmission from mobile unit to BS (824 – 849 MHz).
  - Each band split in two to encourage competition
    - In each market, two operators can operate.
    - Each operator is allocated is allocated 12.5 MHz in each direction for its system.
    - The channels are spaced 30 kHz apart, which allows a total of 416 operators per channel.
    - 21 channels allocated for control, leaving 395 to carry calls.
    - The control channels are data channels operating at 10 kbps.
    - The conversation channels carry the conversations.
    - This number of channels was found to be inadequate for most major markets.
  - Frequency reuse was exploited.

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

Second Generation TDMA

- Higher quality signals.
- Higher data rates for support of digital services.
- Greater capacity.

Differences Between First and Second Generation Systems

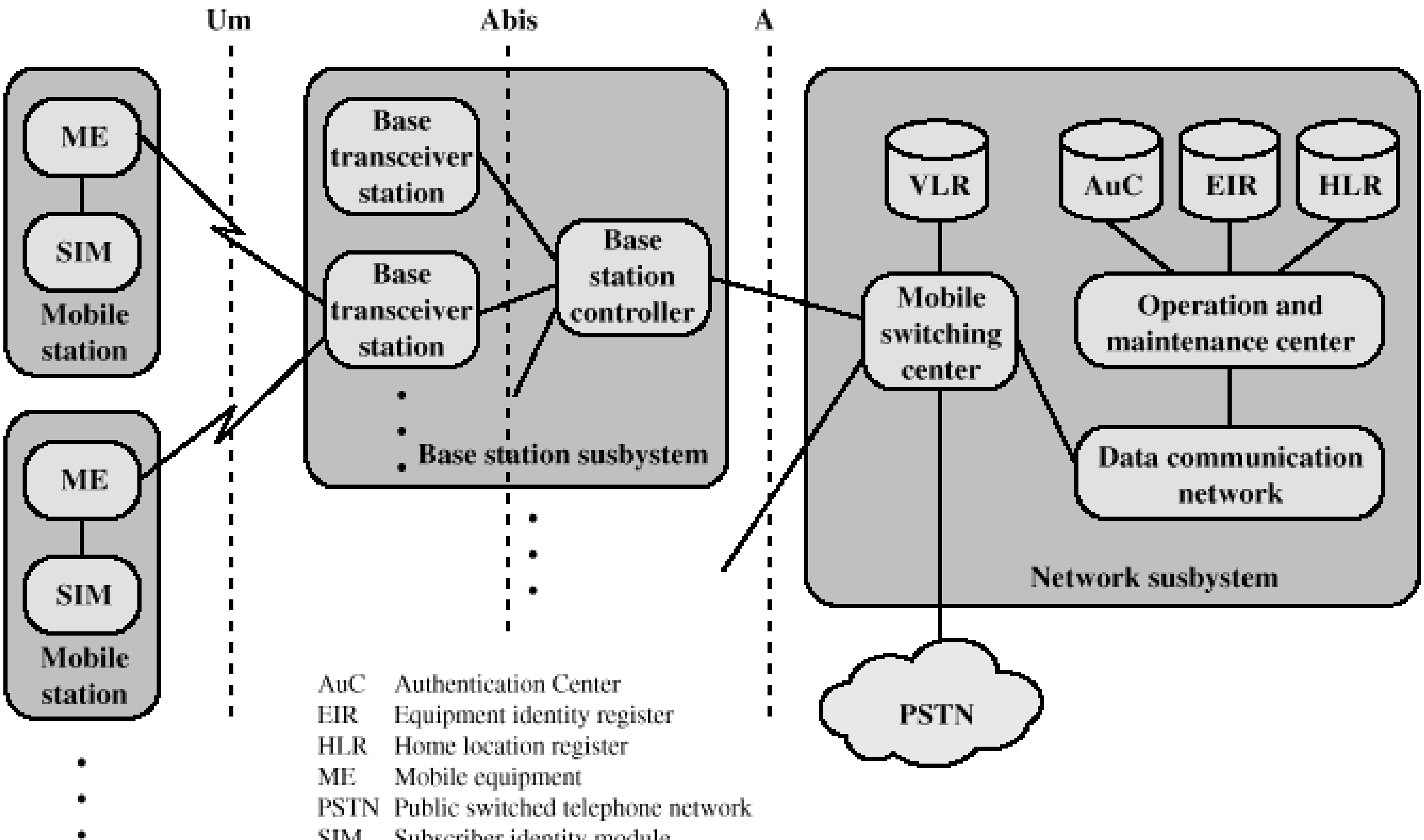
- Digital traffic channels – first-generation systems are almost purely analog; second-generation systems are digital
- Encryption – all second generation systems provide encryption to prevent eavesdropping (relatively easy, as both user/control traffic digitized in second generation systems).
- Error 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. In first generation systems a channel is allocated to only one user at any given time.

Mobile Wireless TDMA Design Considerations

- Number of logical channels (number of time slots in TDMA frame): 8
- Maximum cell radius (R): 35 km, to give a sufficient high traffic level in rural areas.
- Frequency: region around 900 MHz; This is commonly allocated to radio applications.
- Maximum vehicle speed (V_m):250 km/hr, to accommodate mobile units on high speed trains.
- Maximum coding delay: approx. 20 ms. To avoid adding unduly to delays within the fixed network, which may involve satellite links. Above 20 ms, voice conversation becomes difficult.
- Maximum delay spread (Δ_m): 10 μs (in mountainous regions). This is the difference in propagation delay among different multipath signals arriving at the same antenna.
- Bandwidth: Not to exceed 200 kHz (corresponding to 25 kHz per channel)

GSM

- Global system for mobile communication (GSM).
- Access method is TDMA.
- Became popular in Europe (first appeared in 1990), Asia-Pacific. Also used in other parts of the world.
- Very successful standard. Very popular worldwide for new implementations.
- The GSM association claimed over a billion subscribers worldwide by early 2004.



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

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 PCS
  - 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 Subsystem (NS)

- NS provides link between cellular network and public switched telecommunications networks
  - 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

GSM TDMA Format – Time Slot Fields

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

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

CDMA

- Code Division Multiple Access (CDMA).
- Spread Spectrum based technique for multiplexing.
- Alternative to TDMA for 2nd generation cellular networks.
- Transmission is in the form of direct sequence spread spectrum (DS-SS).
  - DS-SS uses a chipping code (each transmitter is assigned a code) to increase the data rate of the transmission, resulting in an increased signal bandwidth.
  - Multiple access is provided by assigning orthogonal chipping codes to multiple users, so that the receiver can recover the transmission of individual unit from multiple transmissions.

Advantages of CDMA Cellular

- Frequency diversity – Because the transmission is spread out over a larger bandwidth, frequency-dependent transmission impairments, such as noise bursts and selective fading, 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, where each user has a unique code.
- Graceful degradation – system only gradually degrades as more users access the system. However, in TDMA or FDMA, a fixed number of users can access the system simultaneously.

Drawbacks of CDMA Cellular

- Self-jamming – arriving transmissions from multiple users will not be aligned on chip boundaries, unless users are perfectly synchronized.
  - Thus, the spreading sequence of the different users are not orthogonal and there is some level of cross-correlation.
  - In FDMA, or TDMA, for reasonable time or frequency guard bands, the received signals are orthogonal or nearly so.
- 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.
  - Soft Handoff – Make before break.
  - Hard Handoff – Break before make.

Mobile Wireless 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

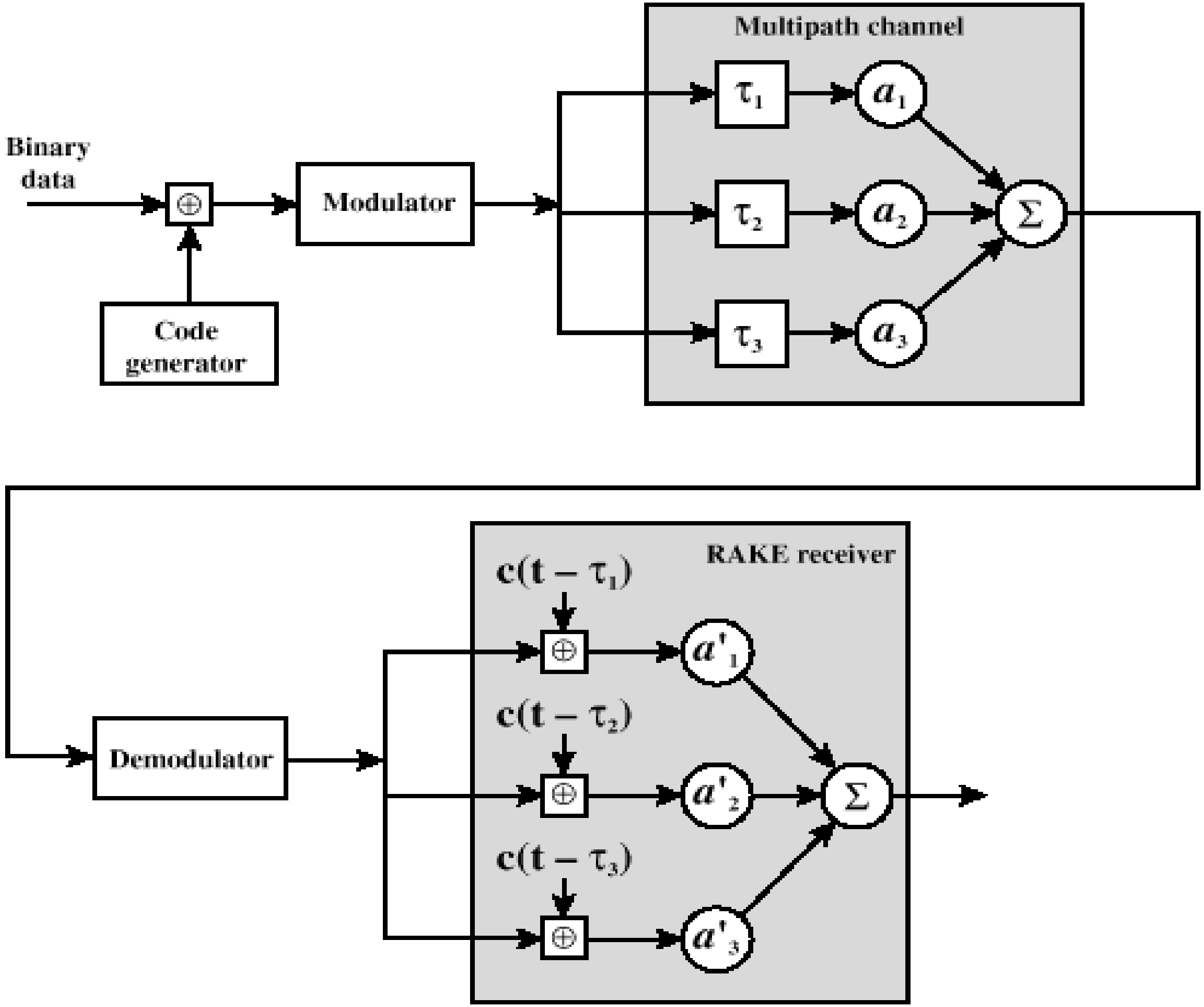


Figure 10.18 Principle of RAKE Receiver [PRAS98]

CDMA Design Considerations

- CDMA – Dominant technology for 3G systems.
- Bandwidth – limit channel usage to 5 MHz.
  - 5 MHz improves receiver's ability to resolve multipath.
  - Supports 3G target data rates.
- Chip rate – depends on desired data rate, need for error control, and bandwidth limitations; 3 Mcps or more is reasonable
- Multirate – advantage is that the system can flexibly support multiple simultaneous applications from a given user and can efficiently use available capacity by only providing the capacity required for each service