無線網路概論
Intro. to Wireless Internet

Lecture 12 –
Cellular Wireless Networks

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YZU CSE

Credit: Partial slides are from Prof. Peter Steenkiste

Lecture Material

- "Wireless Communication Networks and Systems", Corry Beard and William Stallings, 2016.
  - Ch. 13 Cellular Wireless Networks
- Wireless Networks and Applications
  - Prof. Peter Steenkiste, Carnegie Mellon University
  - http://www.cs.cmu.edu/~prs/

Outline

- Cellular History
- Principles of Cellular Networks
- First-Generation Analog
- Second-Generation TDMA
- Second-Generation CDMA
- Third-Generation Systems

Cellular vs. Wi-Fi

	Cellular	WiFi
Spectrum	Licensed	Unlicensed
Service model	Provisioned “for pay”	Unprovisioned “free” – no SLA
MAC services	Fixed bandwidth guarantees	Best effort no guarantees

- SLA: Service Level Agreement

Implications Wi-Fi

	WiFi	Implication
Spectrum	Unlicensed	No control – open, diverse access
Service model	Unprovisioned “free”	No guarantees maximize throughput, fairness
MAC services	Best effort no guarantees	FCC rules to avoid collapse

Implications Cellular

	Cellular	Implication
Spectrum	Licensed	Provider has control over interference
Service model	Provisioned "for pay"	Can and must charge + make commitments
MAC services	Fixed bandwidth SLAs	TDMA, FDMA, CDMA; access control

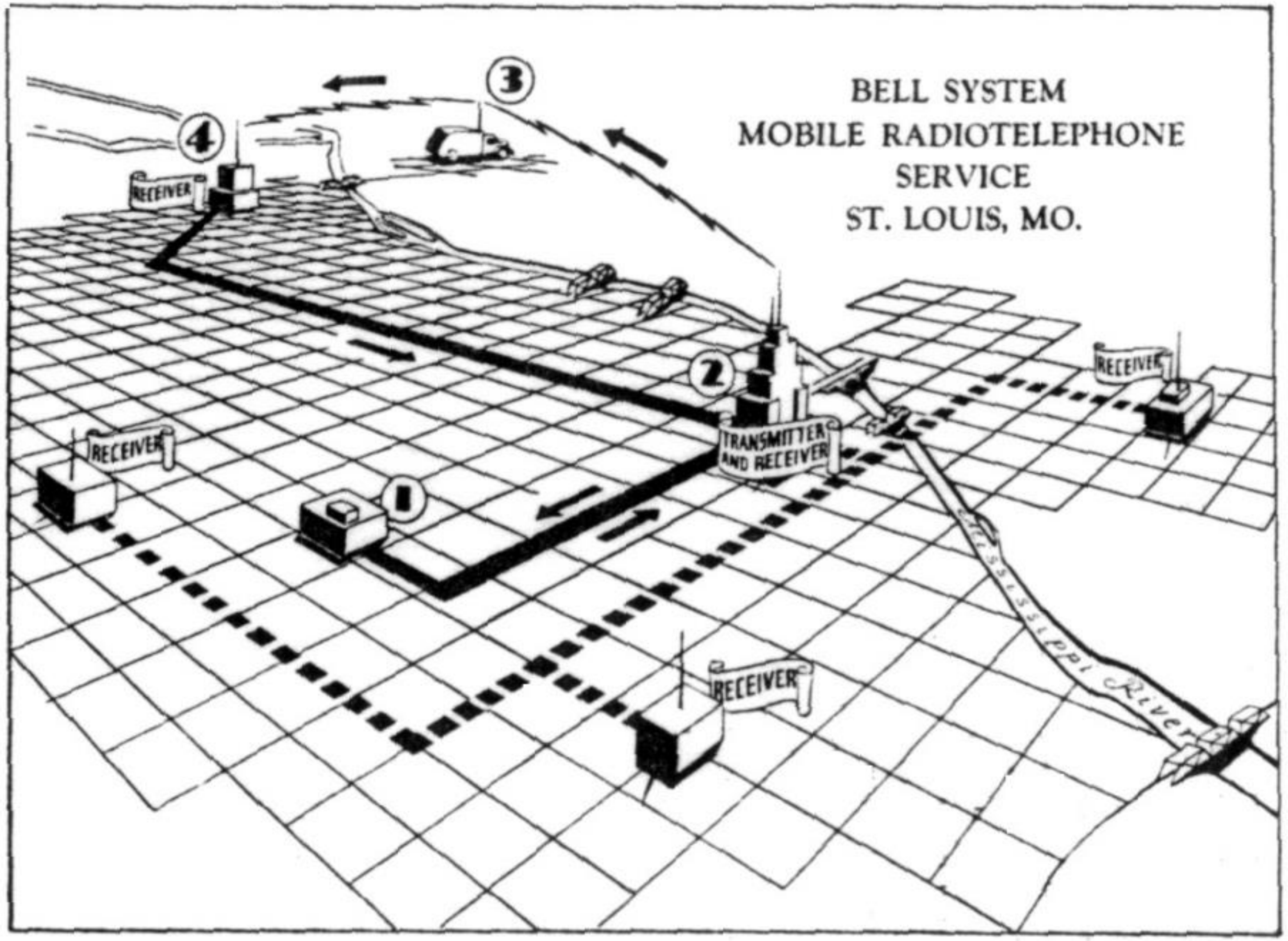
But There are Many Similarities

- Cellular and WiFi face the same fundamental physical layer challenges
  - Interference, attenuation, multi-path, …
- Spatial frequency reuse based on “cells”.
  - Adjacent cells use different frequencies.
- Over time, they use similar modulation schemes.
  - Each generation uses the best technology available at that time.
- Rapid improvements in throughputs
  - Better modulation and coding, increasingly aggressive MIMO, …

The Cellular Idea

- In December 1947, Donald H. Ring outlined the idea in a Bell labs memo.
- Split an area into cells, each with their own low power towers.
- Each cell would use its own frequency.
- Did not take off due to “extreme-at-the-time” processing needs
  - Handoff for thousands of users
  - Rapid switching infeasible – maintain call while changing frequency
  - Technology not ready

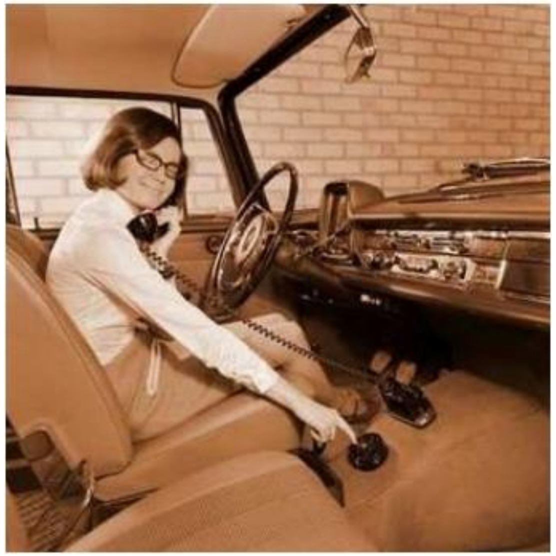
The MTS network



http://www.privateline.com/PCS/images/SaintLouis2.gif

The Early Mobile Phones

- First mobile phones bulky, expensive and hardly portable, let alone mobile
  - Phones weighed ~40 Kg
  - Some early prototypes were much bulkier than shown in the pictures (think: large backpack)
- Operator assisted with maximum 250 users



… the Remaining Components

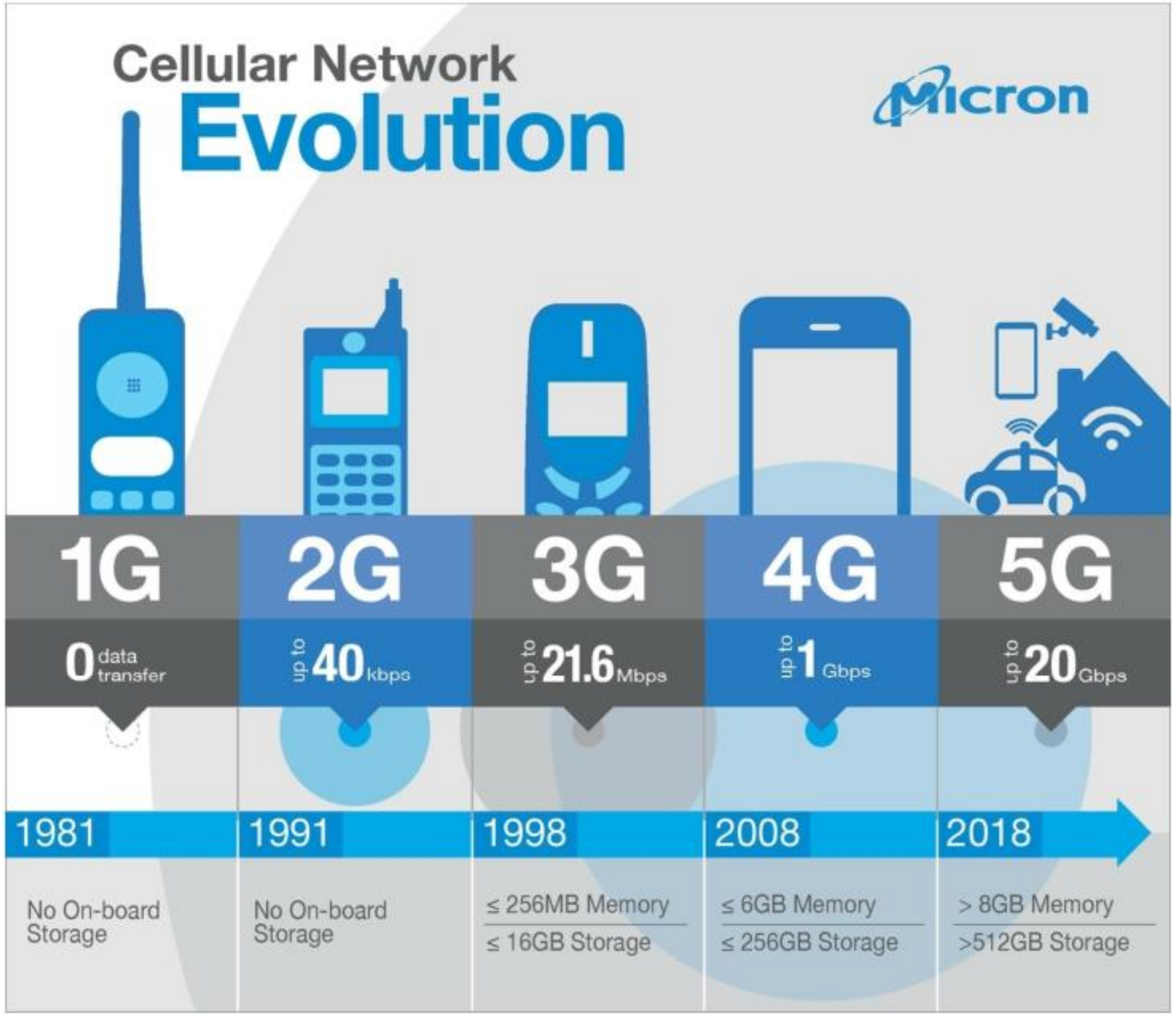
- In December 1947 the transistor was invented by William Shockley, John Bardeen, and Walter Brattain
- Why no portable phones at that time?
- A mobile phone needs to send a signal – not just receive and amplify
- The energy required for a mobile phone transmission still too high for the high power/high tower approach – could only be done with a car battery

DynaTAC8000X: the First Cell Phone

- The "brick":
  - Weighed 2 pounds
  - Offered 30 mins of talk time
  - Sold for $3,995!
- It took 10 years to develop (1973-1983) at a cost of $100 million!
  - Size determined by size of batteries, antennas, keypad, etc.
  - Today size determined by the UI!
- First commercial service in early 80s
  - FCC allocated spectrum in 70s

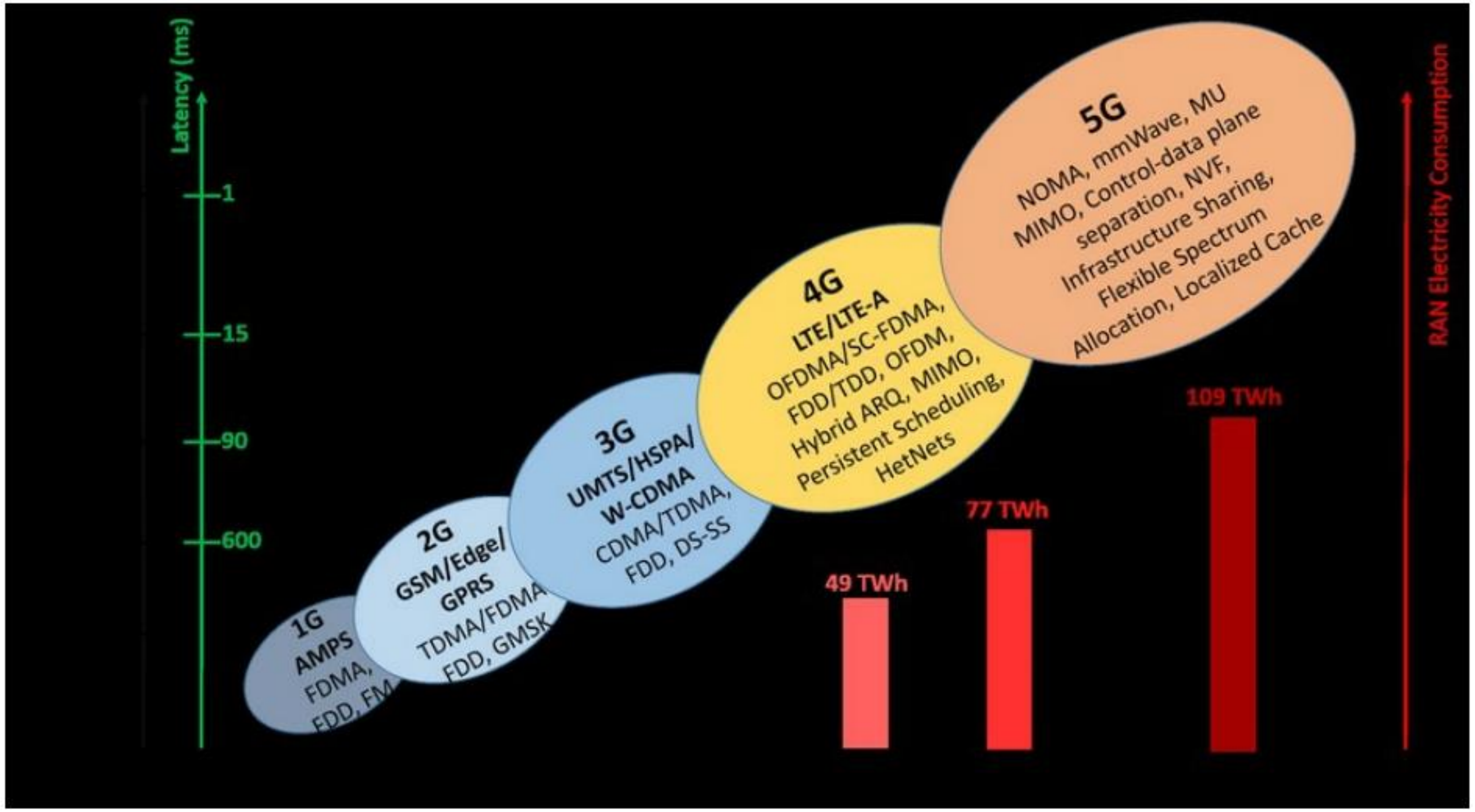
Dr. Martin Cooper of Motorola, made the first US analogue mobile phone call on a larger prototype model in 1973

Cellular Generations



- Roughly one generation every 10 years
- Spectrum allocation for mobile broadband has increased significantly
  - Shift to higher frequencies

Technologies Used



- We have already seen many of these technologies!

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Standardization Process

- Standardization takes as much as 10 years
  - Setting goals, identifying technologies
  - Standardization: many releases
  - Product development and trials

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- Second-Generation CDMA
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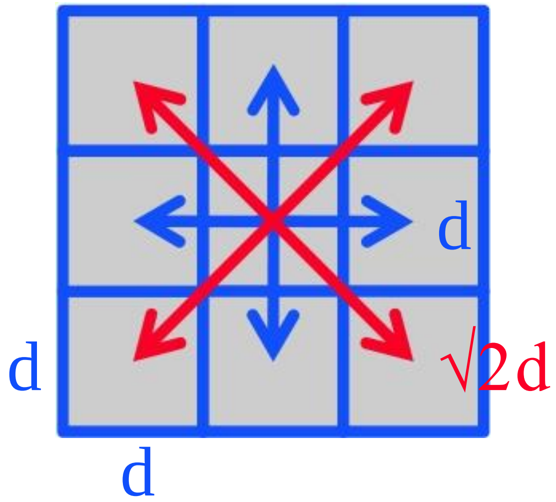
Cellular Network Organization

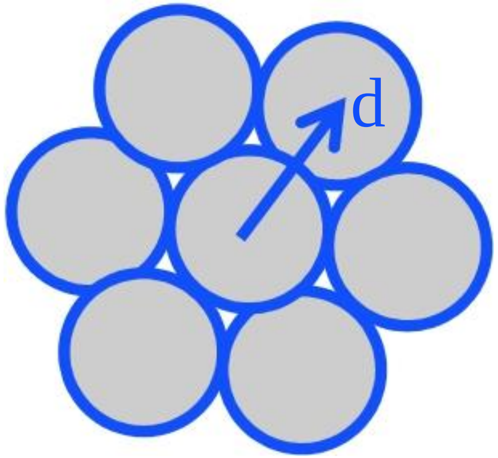
- Use multiple low-power transmitters (100 W or less)
- Areas divided into cells
  - Each served by its own antenna.
  - Served by base station consisting of transmitter, receiver, and control unit.
  - Band of frequencies allocated
  - Cells set up such that antennas of all neighbors are equidistant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

Cellular Network Design Options

- Simplest layout
  - Does not match any propagation model
  - Adjacent antennas not equidistant – how do you handle users at the edge of the cell?

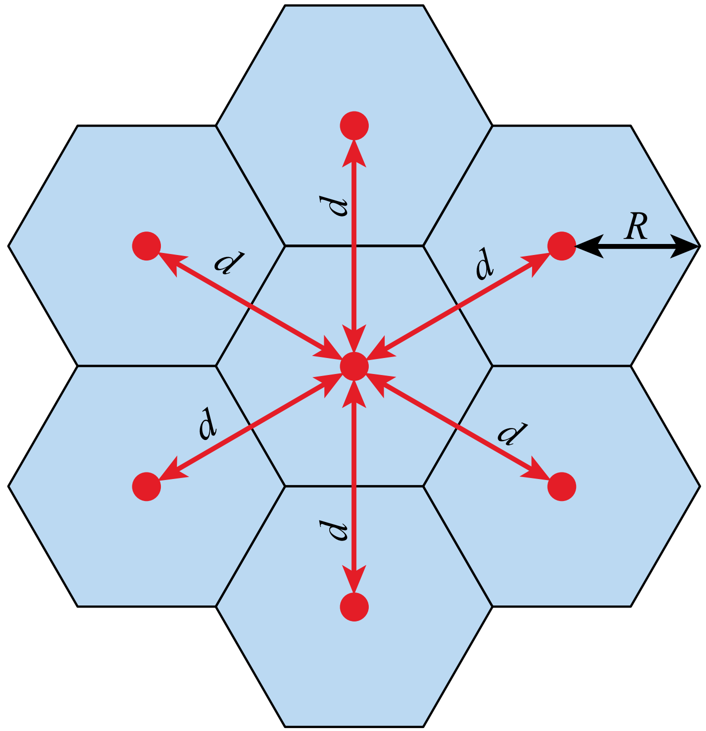


- "Ideal" layout
  - Based on a naïve propagation model – bad approximation but better than squares
  - Does not cover entire area!



The Hexagonal Pattern

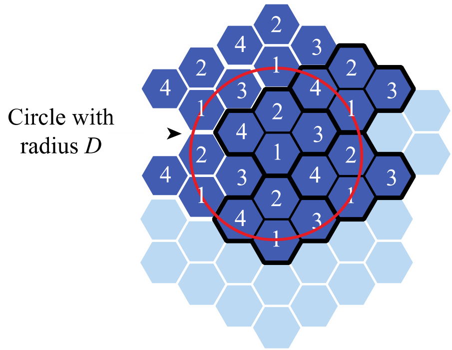
- A hexagon pattern can provide equidistant access to neighboring cell towers
- $d = \sqrt{3}R$
- In practice, variations from ideal due to topological reasons
  - Signal propagation
  - Tower placement



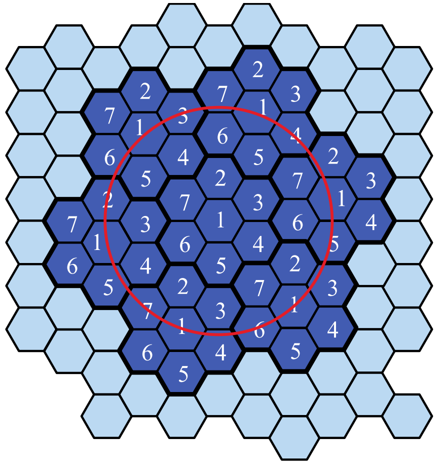
Frequency Reuse

- 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 .

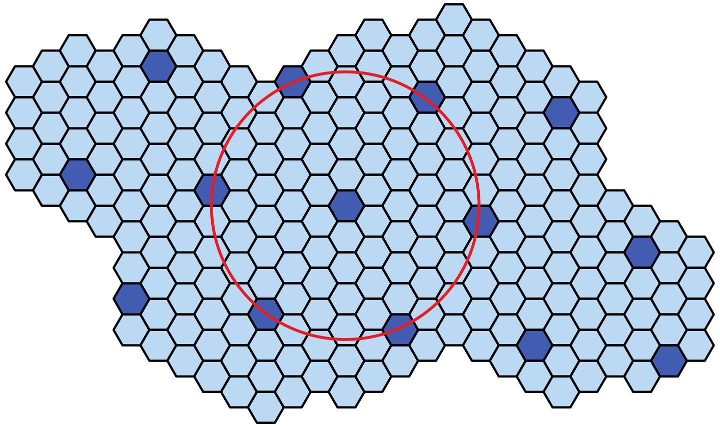
Frequency Reuse Pattern



(a) Frequency reuse pattern for $N = 4$



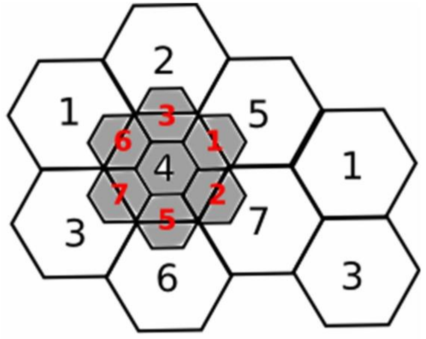
(b) Frequency reuse pattern for $N = 7$



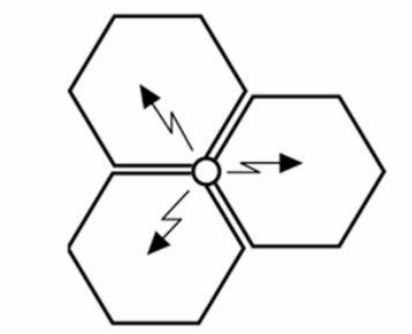
(c) Black cells indicate a frequency reuse for $N = 19$

Increasing Capacity? (1/2)

- 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.



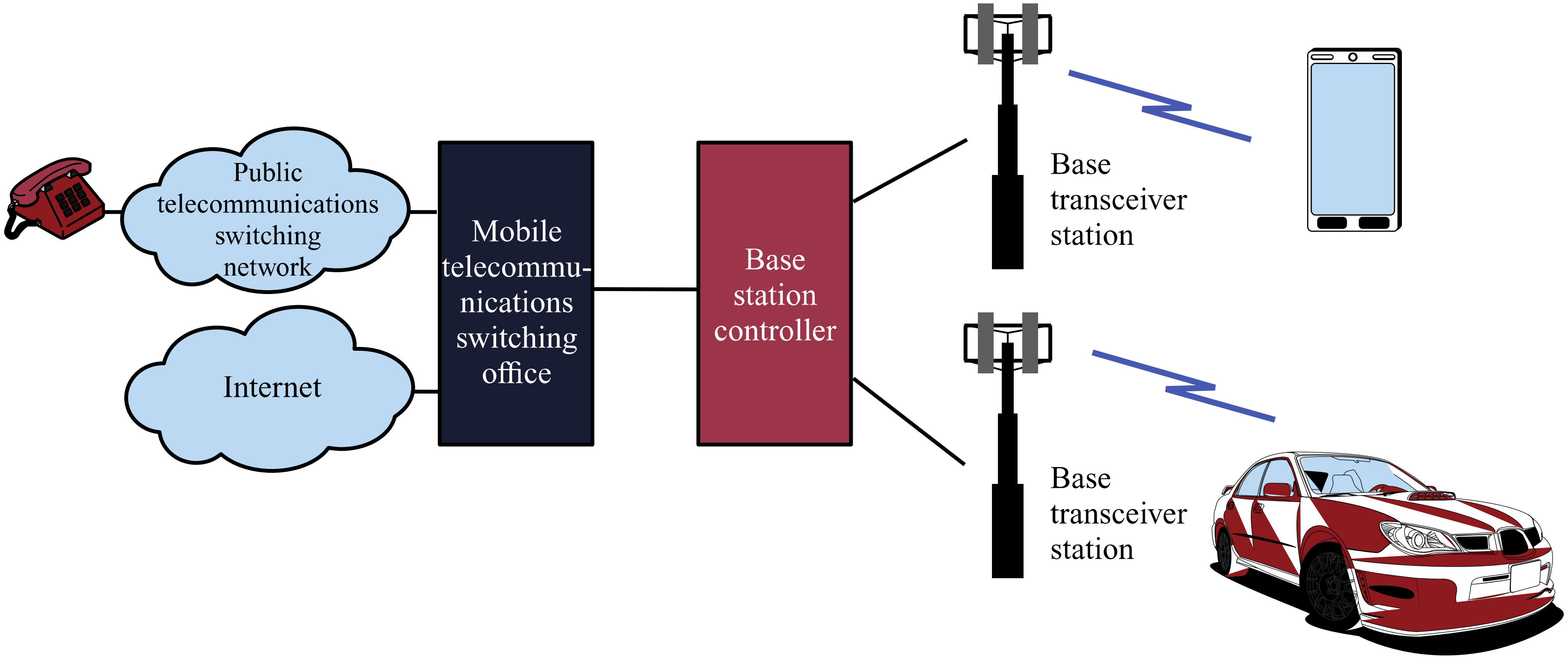
Increasing Capacity? (2/2)

- Network densification
  - More cells and frequency reuse
- Microcells
  - Antennas move to buildings, hills, and lamp posts
- Femtocells
  - Antennas to create small cells in buildings
- Interference coordination
  - Tighter control of interference so frequencies can be reused closer to other base stations
- Inter-cell interference coordination (ICIC)
- Coordinated multipoint transmission (CoMP)

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

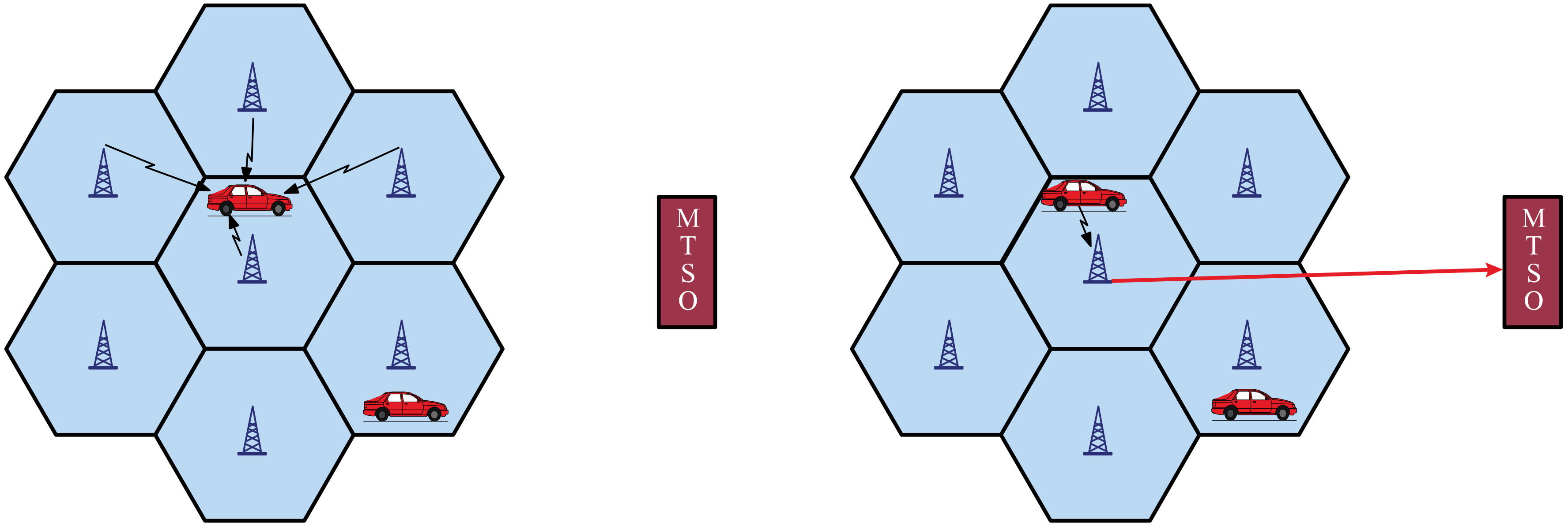
Cellular System



Mobile Cellular Call (1/4)

- Mobile unit initialization
  - Cells broadcast on setup channels
  - Select the strongest channel
- Mobile-originated call
  - Sending the called number.
- Paging
  - Find the called unit.
- Call accepted
- Ongoing call
- Handoff
  - Change cells without interrupting the call.

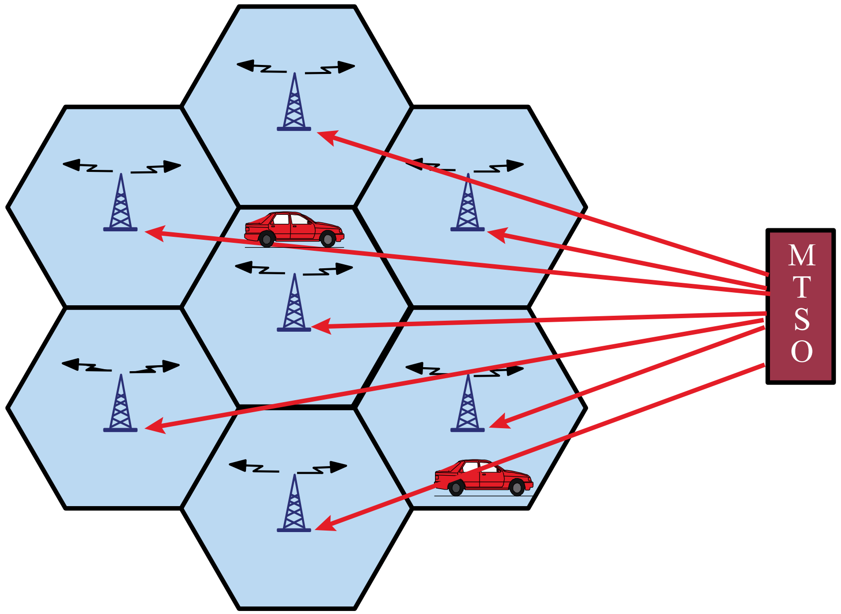
Mobile Cellular Call (2/4)



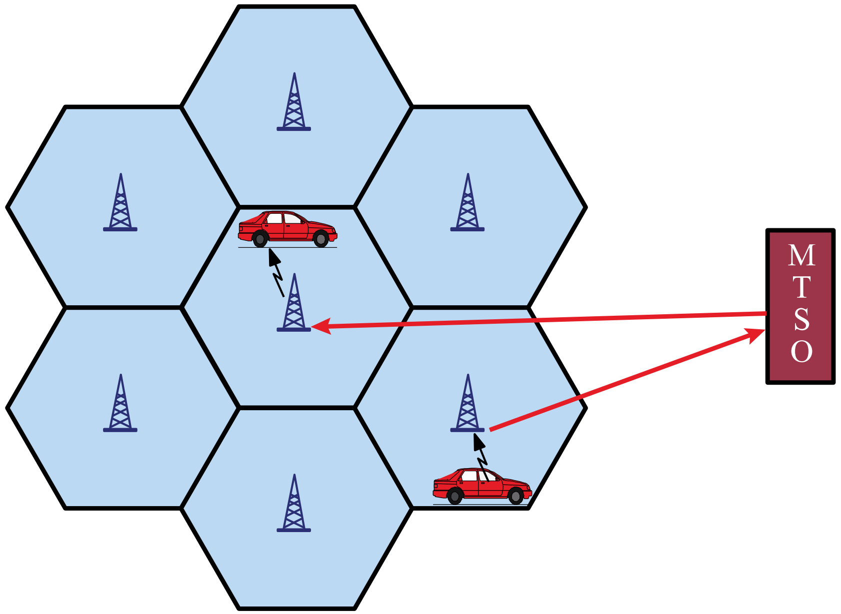
(a) Monitor for strongest signal

(b) Request for connection

Mobile Cellular Call (3/4)

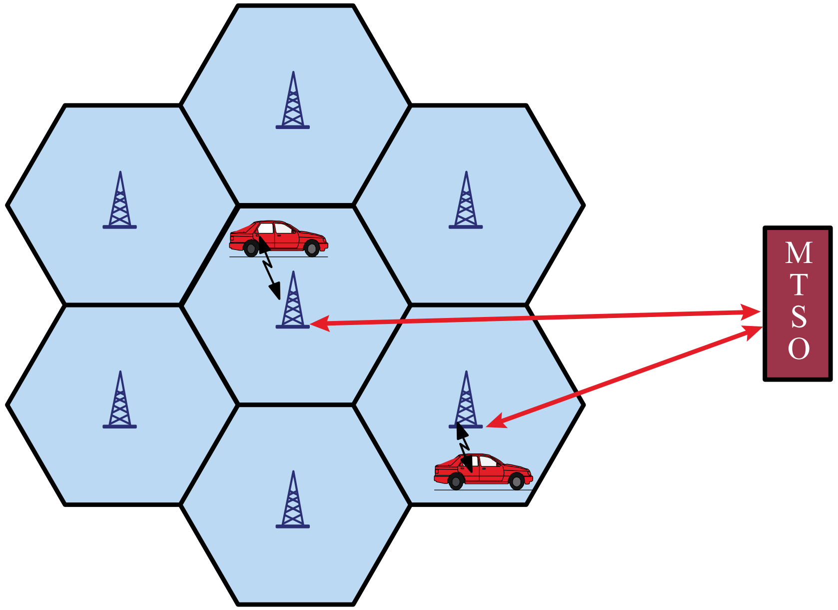


(c) Paging

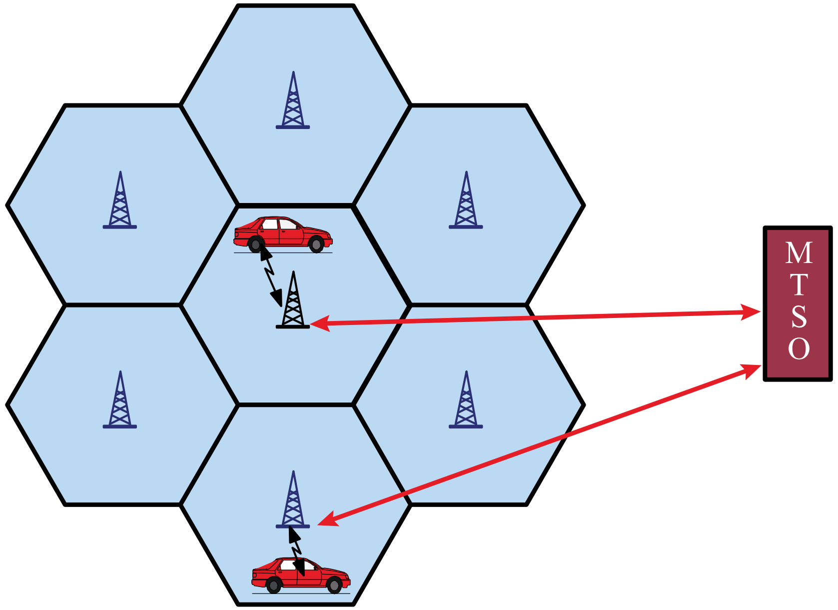


(d) Call accepted

Mobile Cellular Call (4/4)



(e) Ongoing call



(f) Handoff

Additional Functions

- Call blocking
  - Busy tone is returned to the user.
- Call termination
- Call drop
  - BS cannot maintain the minimum required signal strength for a certain period of time.
- Calls to/from fixed and remote mobile subscriber
  - Public switched telephone network (PSTN)
- Emergency call

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 co-channel interference with channels in another cell using the same frequency band.
- Fading
  - Signal propagation effects may disrupt the signal and cause errors.

Handoff

- The procedure for changing the assignment of a mobile unit from one BS to another as it moves from one cell to another.
- Handoff decision
  - Network initiated
  - Mobile unit assisted

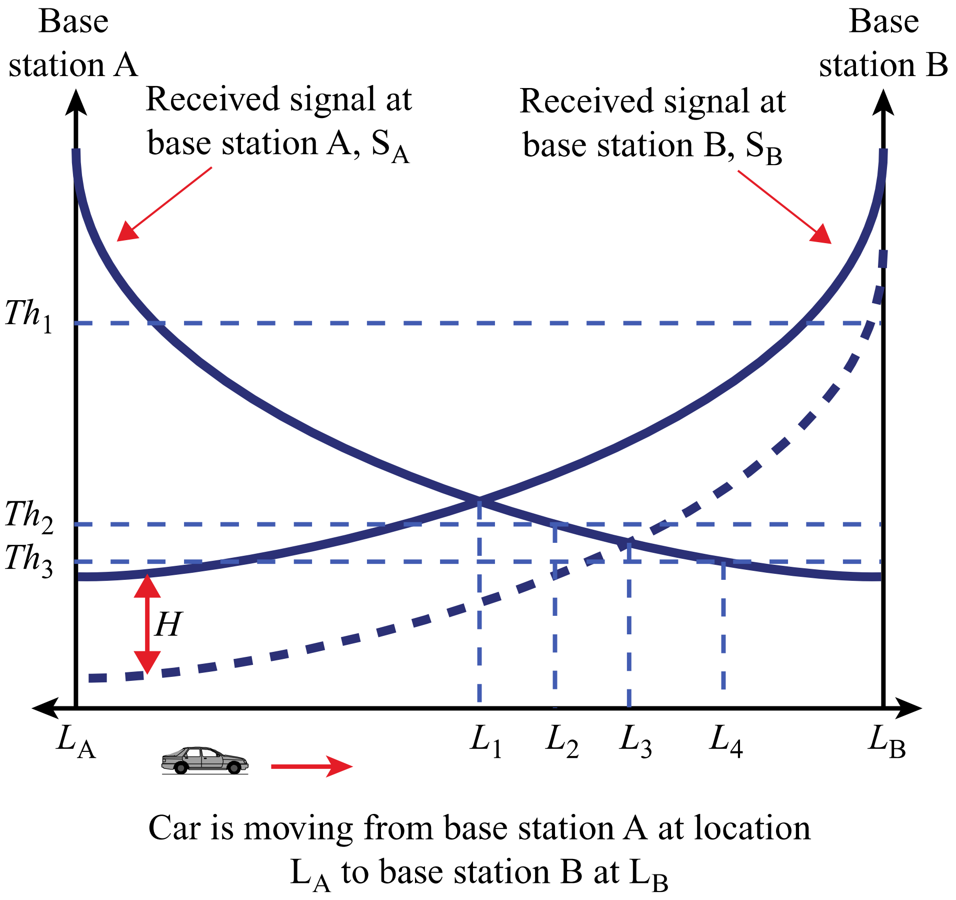
Handoff Performance Metrics

- 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

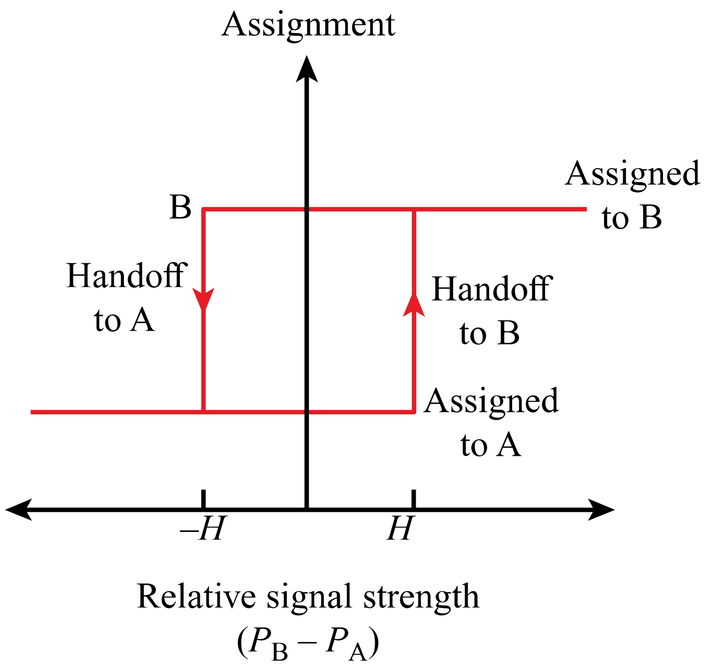
Handoff Strategies (1/2)

- Relative signal strength
  - May lead to ping-pong effect.
  - L_1 in the next slide.
- Relative signal strength with threshold
  - The current BS is sufficiently weak (less than a threshold).
  - With Th_2 -> L_2
- Relative signal strength with hysteresis
  - The new BS is sufficiently strong (by a margin H)
  - L_3 in the next slide.
- Relative signal strength with hysteresis and threshold
  - L_3 if set Th_1 or Th_2
  - L_4 if set Th_3
- Prediction techniques

Handoff Strategies (2/2)



(a) Handoff decision as a function of handoff scheme



(b) Hysteresis mechanism

Power Control

- Reasons to include dynamic power control in a cellular system
  - Received power must be sufficiently above the background noise for effective communication
  - Desirable to minimize power in the transmitted signal from the mobile.
    - Reduce co-channel interference, alleviate health concerns, save battery power
  - In spreading-spectrum systems using CDMA, it's necessary to equalize the received power level from all mobile units at the BS.

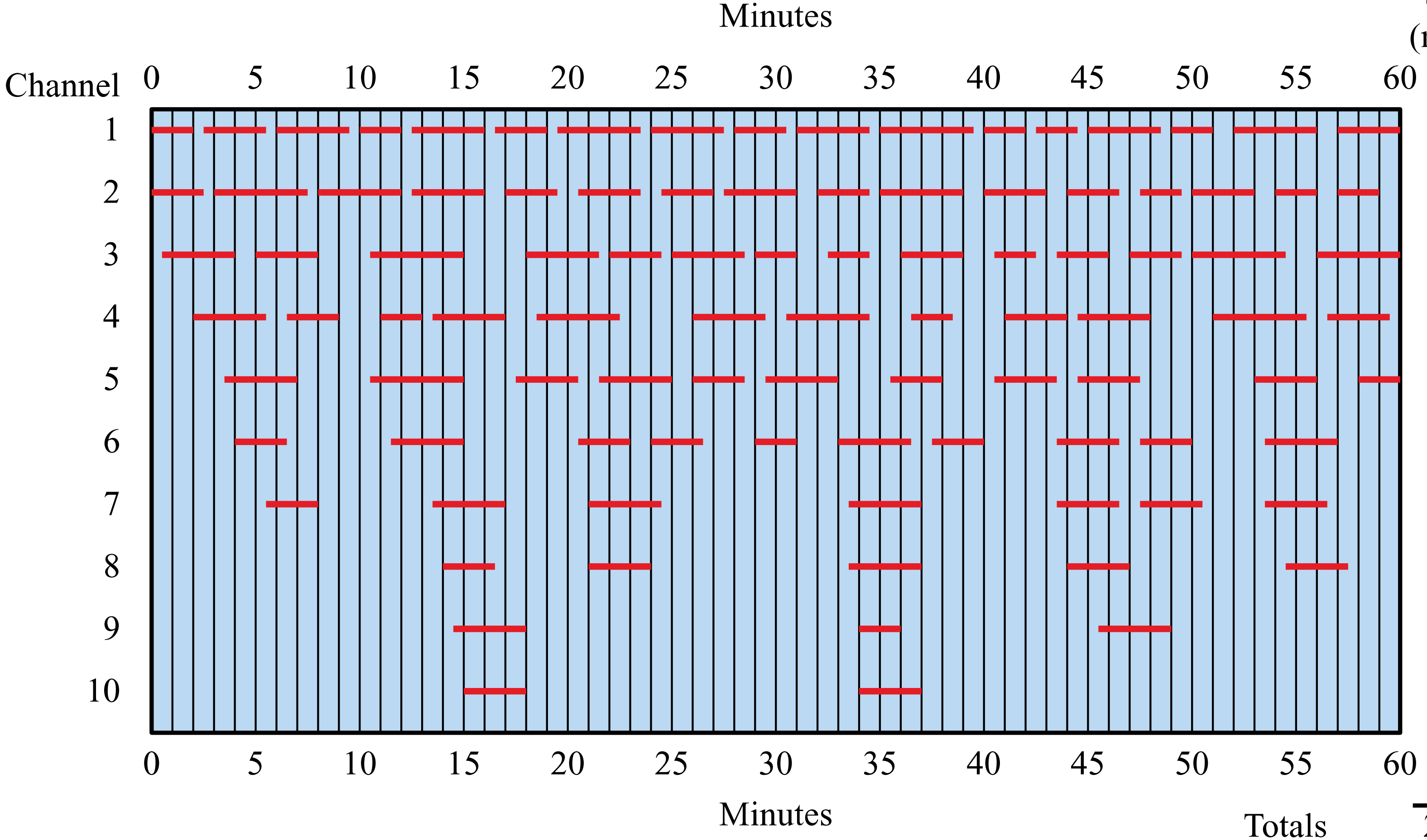
Types of Power Control

- Open-loop power control
  - Depends solely on mobile unit
  - No feedback from BS
  - Set transmission power according to the received power.
  - 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.
    - SNR, BER, PER
  - 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

Traffic in a Cell



Channel	Occupied time (mins)	Number of calls
1	51	17
2	47	16
3	43	14
4	39	12
5	34	11
6	28	10
7	22	7
8	15	5
9	9	3
10	6	2
Totals	294	97

Note: horizontal lines indicate occupied periods to the nearest 1/2 minute

Blocking System Performance

- 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?

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First-Generation Analog

- In North America, two 25-MHz bands were allocated (DL: 869-894 MHz, UP: 824-849 MHz)
  - Deployed since early 80's by two providers
- Channels are spaced by 30 KHz, allowing for 416 channels (21 control, 395 for voice calls)
  - Control channels are full duplex data channels at 10 Kbps
  - Includes preamble, word sync, and Digital Color Code identifying the base station
  - Can send urgent control in data channels
- Voice calls carried in analog using frequency modulation
  - Effectively extends analog telephone over wireless
- Cell size = 2-20Km, frequency reuse is exploited

AMPS

Table 13.2 AMPS Parameters

Base station transmission band	869 to 894 MHz
Mobile unit transmission band	824 to 849 MHz
Spacing between forward and reverse channels	45 MHz
Channel bandwidth	30 kHz
Number of full-duplex voice channels	790
Number of full-duplex control channels	42
Mobile unit maximum power	3 watts
Cell size, radius	2 to 20 km
Modulation, voice channel	FM, 12-kHz peak deviation
Modulation, control channel	FSK, 8-kHz peak deviation
Data transmission rate	10 kbps
Error control coding	BCH (48, 36,5) and (40, 28,5)

AMPS Operation

- When unit wakes up, it sends telephone and serial number to the Mobile Telephone Switching Office (MTSO) over control channel
  - Both stored in read-only memory
  - Used for billing purposes and to detect stolen phones
- Steps in placing a call:
  1. User dials in a number – sent to the MTSO
  2. MTSO verifies validity of service request
  3. MTSO notifies user of channels to use for up/down link
  4. MTSO sends ring signal to the called party
  5. MTSO completes circuit when party picks up
  6. When either party hangs up, MTSO releases circuit and wireless channels, and completes billing

Differences Between First and Second Generation Systems

- Digital traffic channels – first-generation systems are almost purely analog; second-generation systems are digital
  - Using FDMA/TDMA or CDMA
- 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.

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Global System for Mobile (GSM) - Background

- GSM is a set of ETSI standards specifying the infrastructure for a digital cellular service
  - European Telecommunications Standards Institute
  - Developed to provide a common second-generation technology for Europe
- The standard was used in approx. 109 countries around the world including Europe, Japan and Australia
- Order 44 million subscribers
- Process: define a set of requirements, and then develop technologies to meet them

Design Requirements for GSM-like 2G Systems

- Degree of multiplexing: at least 8
  - Not worth adding TDMA complexity otherwise
- Maximum cell radius: ~35km
  - Needed for rural areas
- Frequency: around 900 MHz
- Maximum speed: 250 km/hr – high-speed train
- Maximum coding delay: 20 msec
  - Do not want to add too much to network delay (voice!)
- Maximum delay spread: ~10 msec
- Bandwidth: up to 200 KHz, ~25 kHz/channel

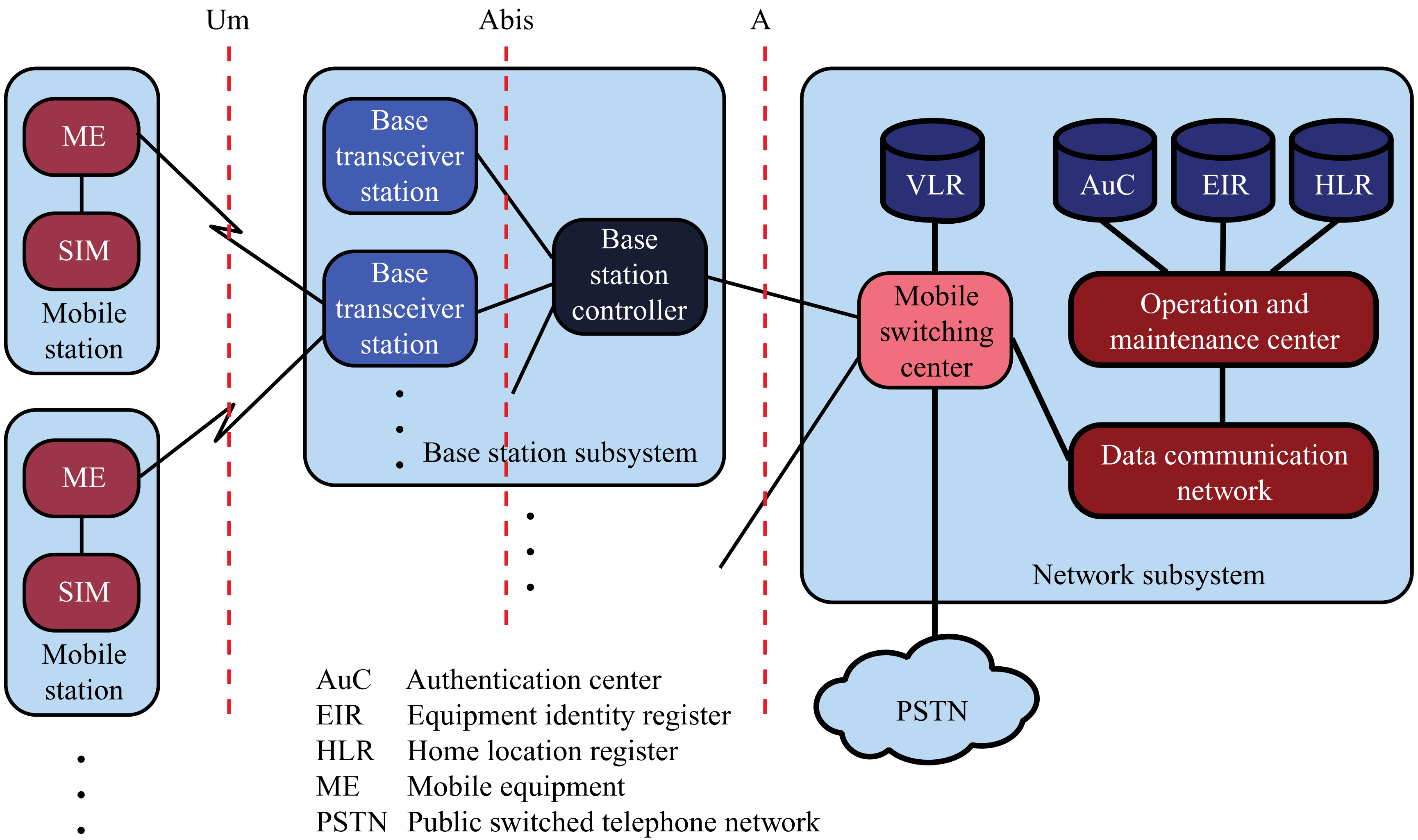
GSM Features

- Hybrid FDMA/TDMA approach
- Mobile station communicates across the air interface with base station in the 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 a SIM is inserted
  - SIMs roam since they are based on single standard
  - Not necessarily the case for subscriber devices – may use different versions of the protocol

GSM SIM

- Users have a Subscriber Identity Module (SIM) – a smart card
- The user identity is associated with a mobile device through the SIM card.
- The SIM is portable and transferable.
- All cryptographic algorithms (for authentication and data encryption) can be realized in the SIM.
- May also store short messages, charging info, ..
- SIM implications:
  - Equipment mobility and user mobility are not the same.
  - International roaming independent of the equipment and network technology.

GSM Architecture



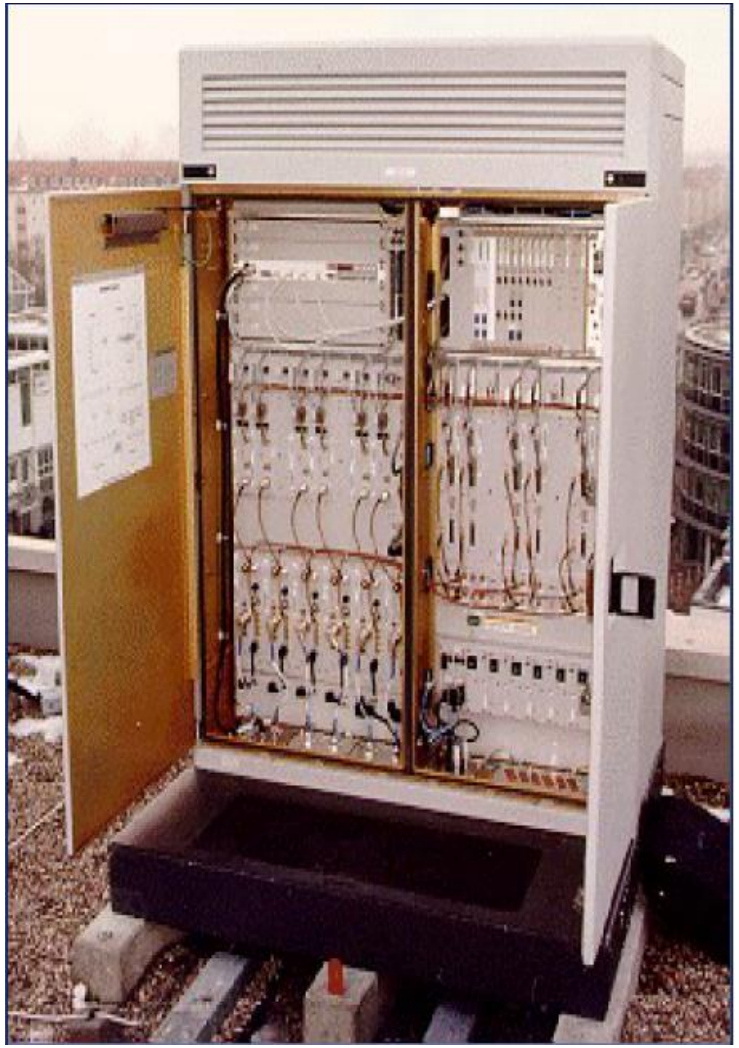
AuC	Authentication center
EIR	Equipment identity register
HLR	Home location register
ME	Mobile equipment
PSTN	Public switched telephone network
SIM	Subscriber identity module
VLR	Visitor location register

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
  - Controls paging

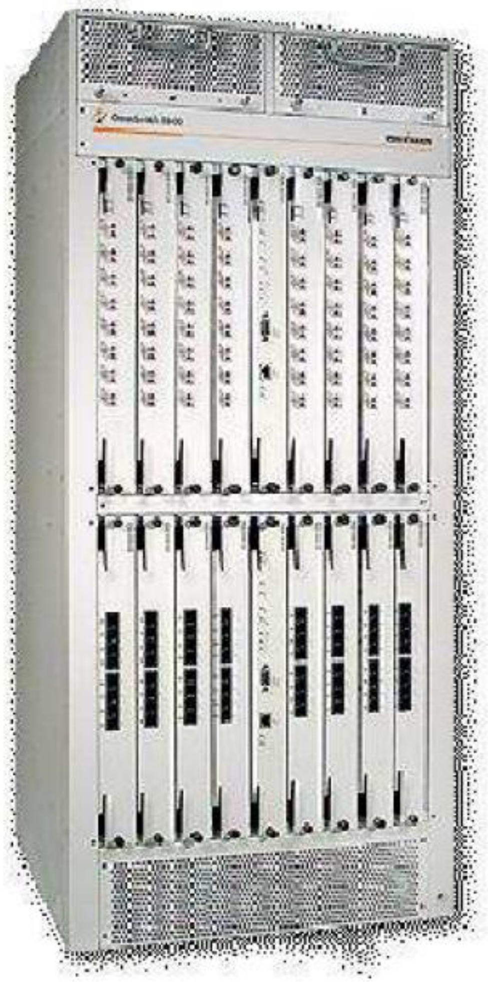
Base Transceiver Station

- Radio transmission/reception management (modulation/demodulation, equalization, interleaving ...)
- Physical layer management (TDMA transmission, SFH, coding, ciphering ...)
- Link layer management
- Received signal quality and power measurement



Base Station Controller

- Interface between MSC and BTSs
  - Forwarding of traffic
  - Coordination of and with BTSs
- Radio resource management for the Base Station Subsystem
  - Channel allocation
  - BTS measures processing
  - BTS and MS power control
  - Handover
  - ...



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

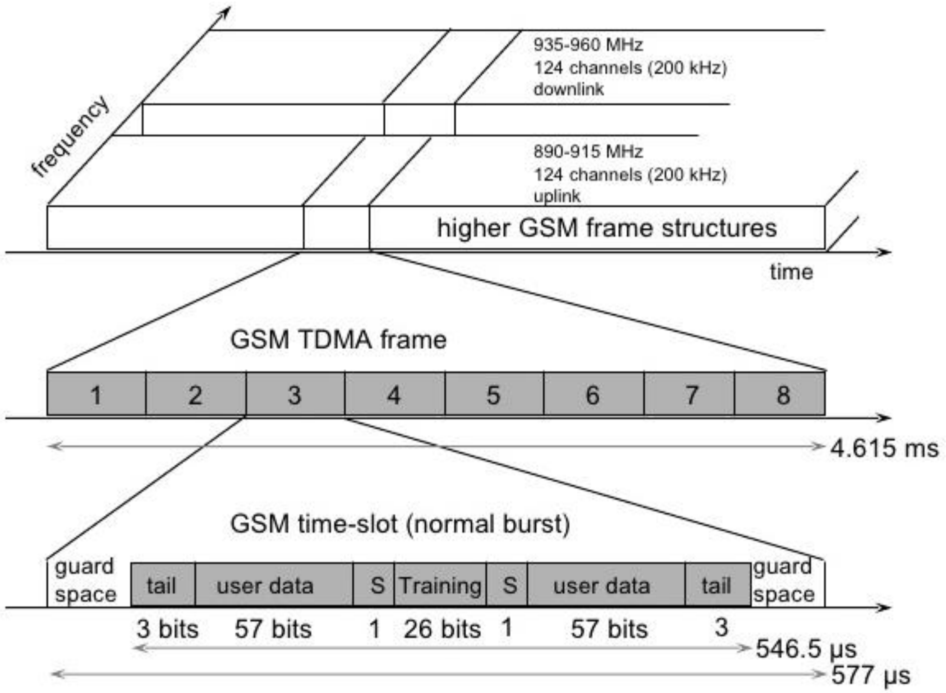
- Management of the communication between mobiles and the fixed network
  - The Gateway Mobile Switching Controller forms the gateway for calls to and from external networks
- MSC is also responsible for mobility management
  - Handover between Base Station Subsystems
  - Roaming across networks

MSC Databases

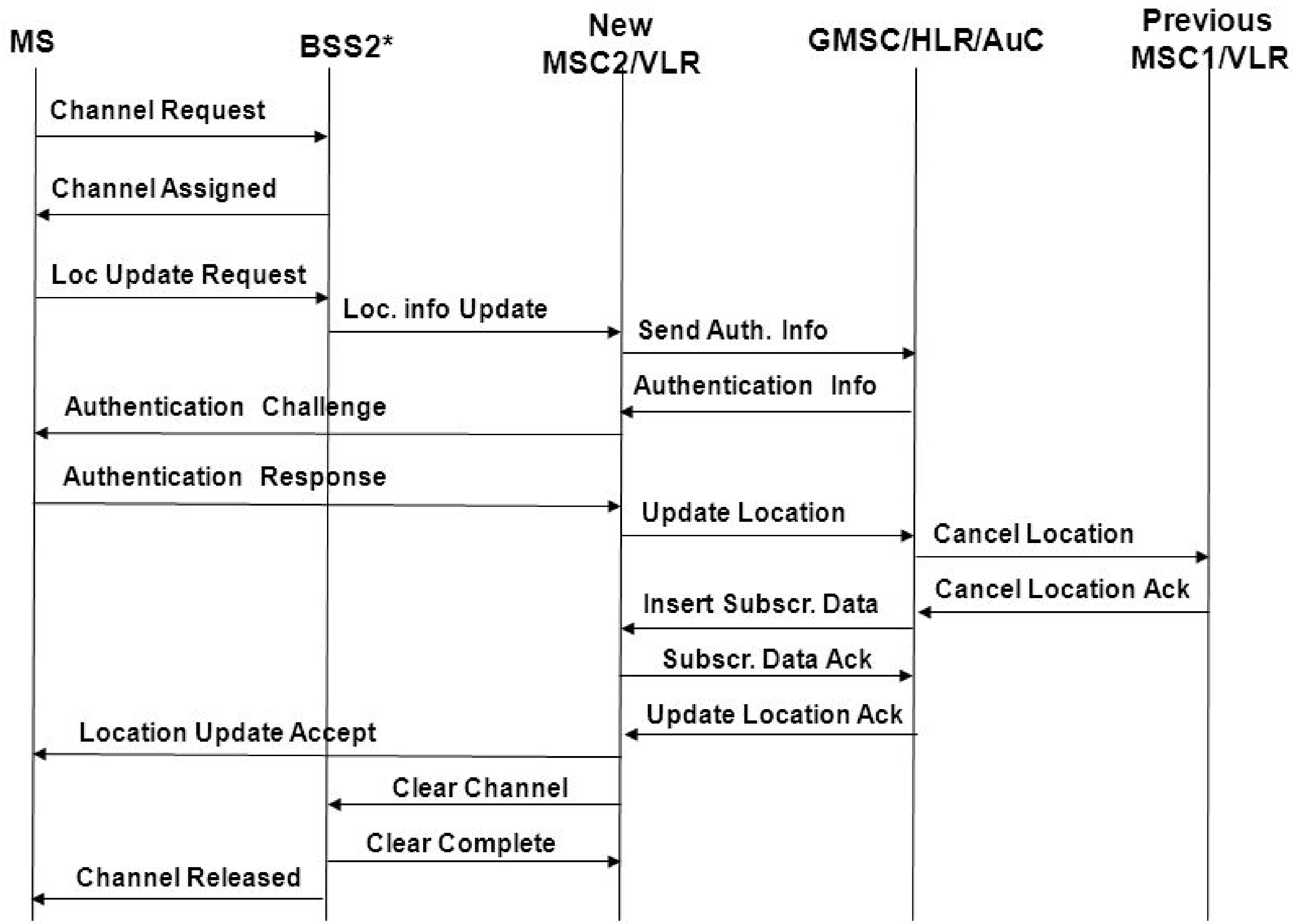
- Home location register (HLR) database
  - Stores information about each subscriber that belongs to it.
- Visitor location register (VLR) database
  - Maintains information about subscribers currently physically in the region.
- Authentication center database (AuC)
  - Used for authentication activities,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

GSM Radio Link

- Combination of FDMA and TDMA
- 200 kHz carriers
- Each with a data rate of 270.833 kbps
- 8 users share each carrier (8 logical channels)



GSM Location Update

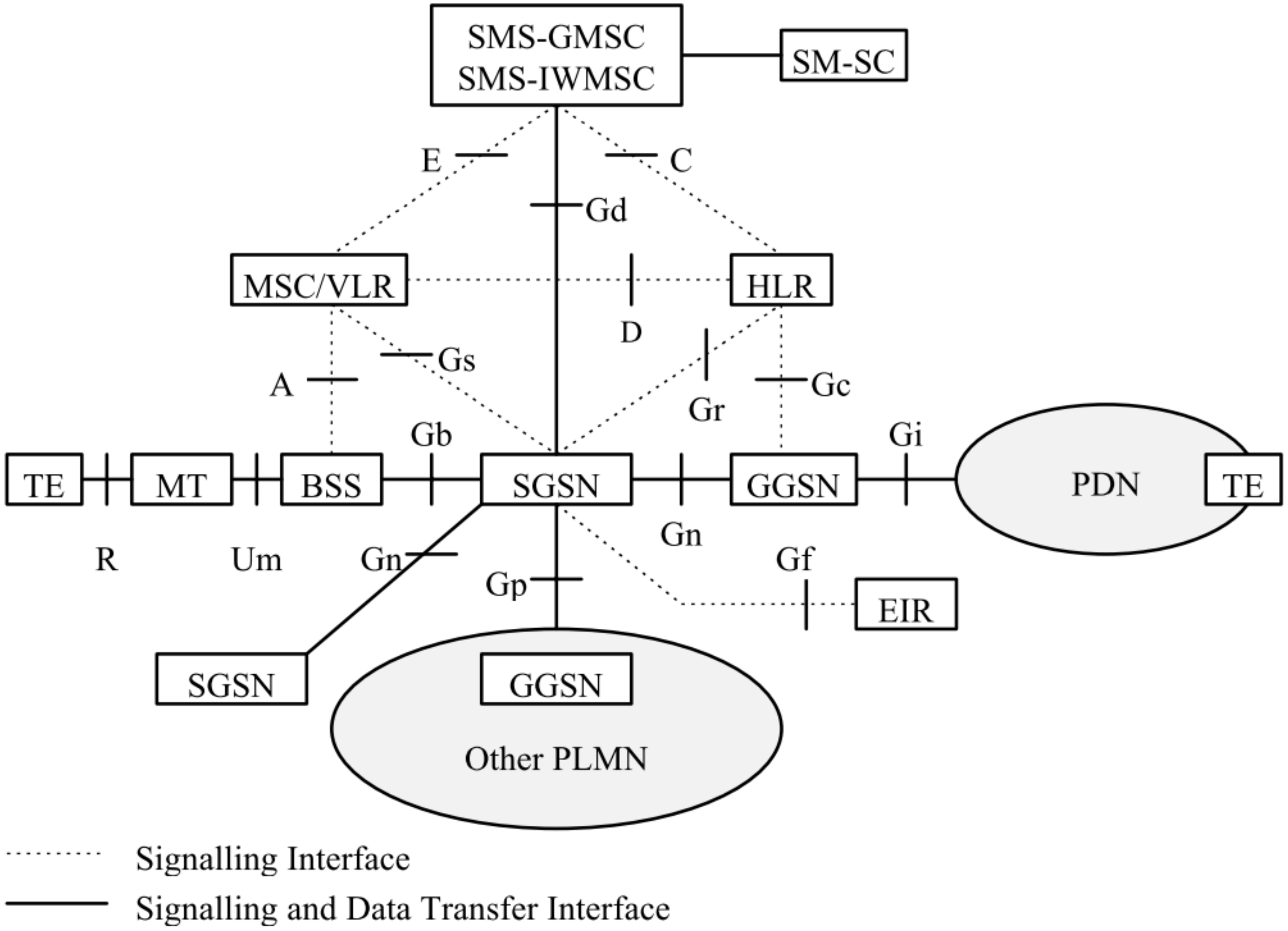


*BSS = BTS + BSC

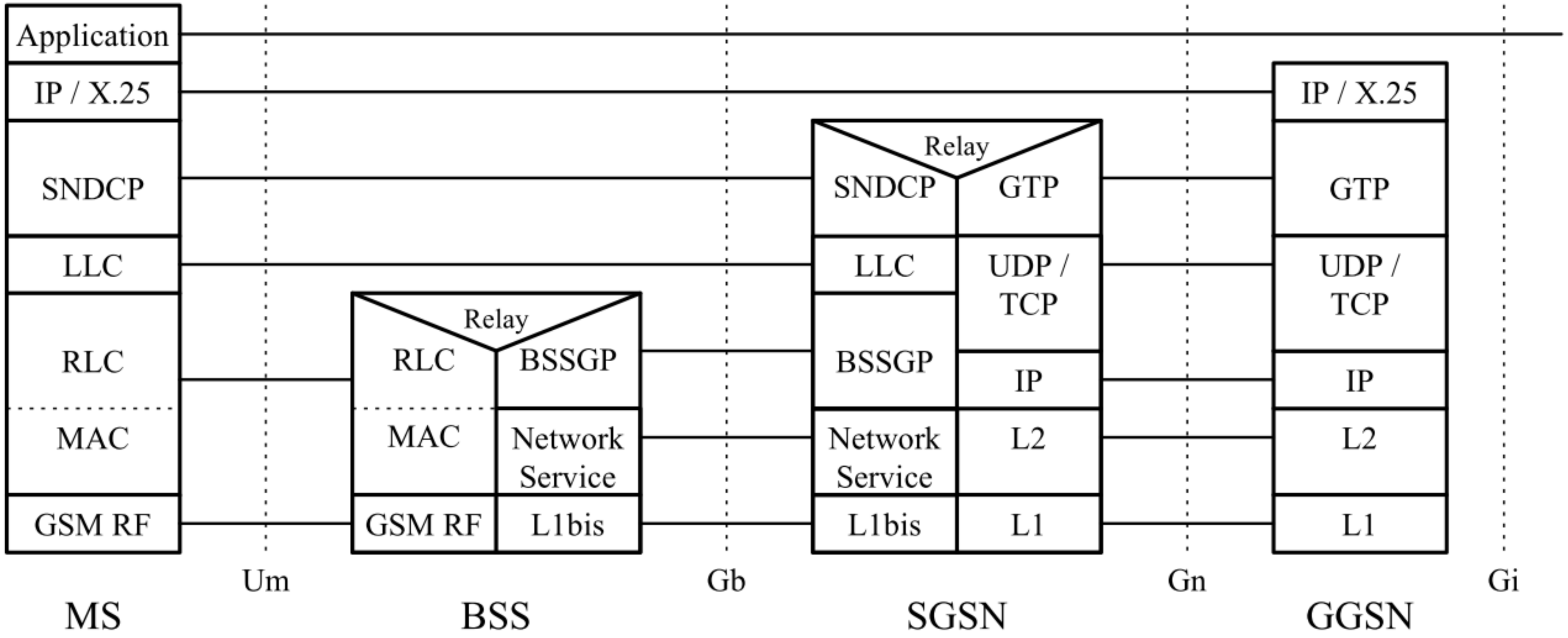
Generalized Packet Radio Service (GPRS)

- Phase 2 of GSM
- Provides a datagram switching capability to GSM
  - Instead of sending data traffic over a voice connection which requires setup, sending data, and teardown
  - GPRS allows users to open a persistent data connection.
  - Also has a new system architecture for data traffic.
  - 21.4 kbps from a 22.8 kbps gross data rate.
  - Can combine up to 8 GSM connections
    - Overall throughputs up to 171.2 kbps

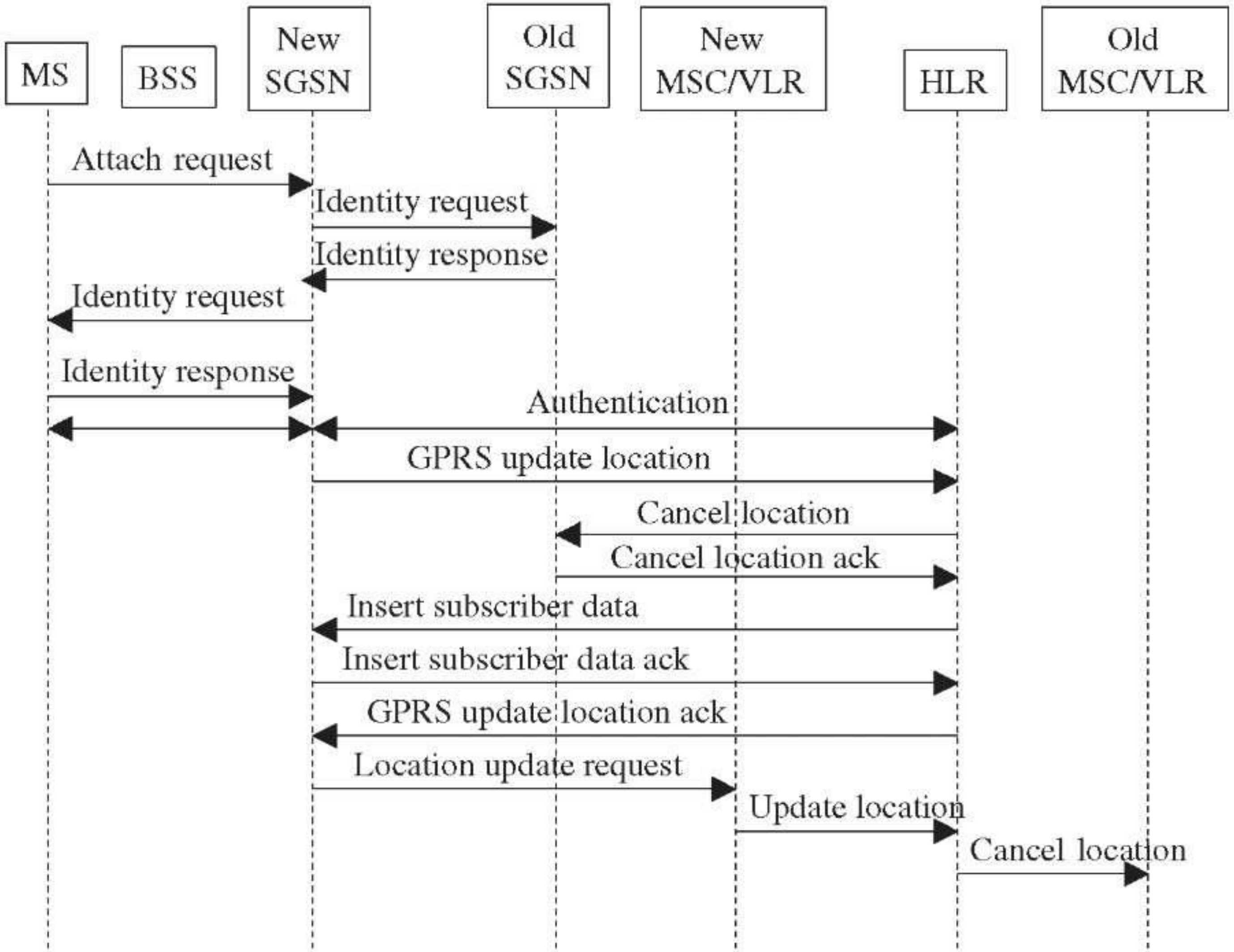
GPRS Architecture



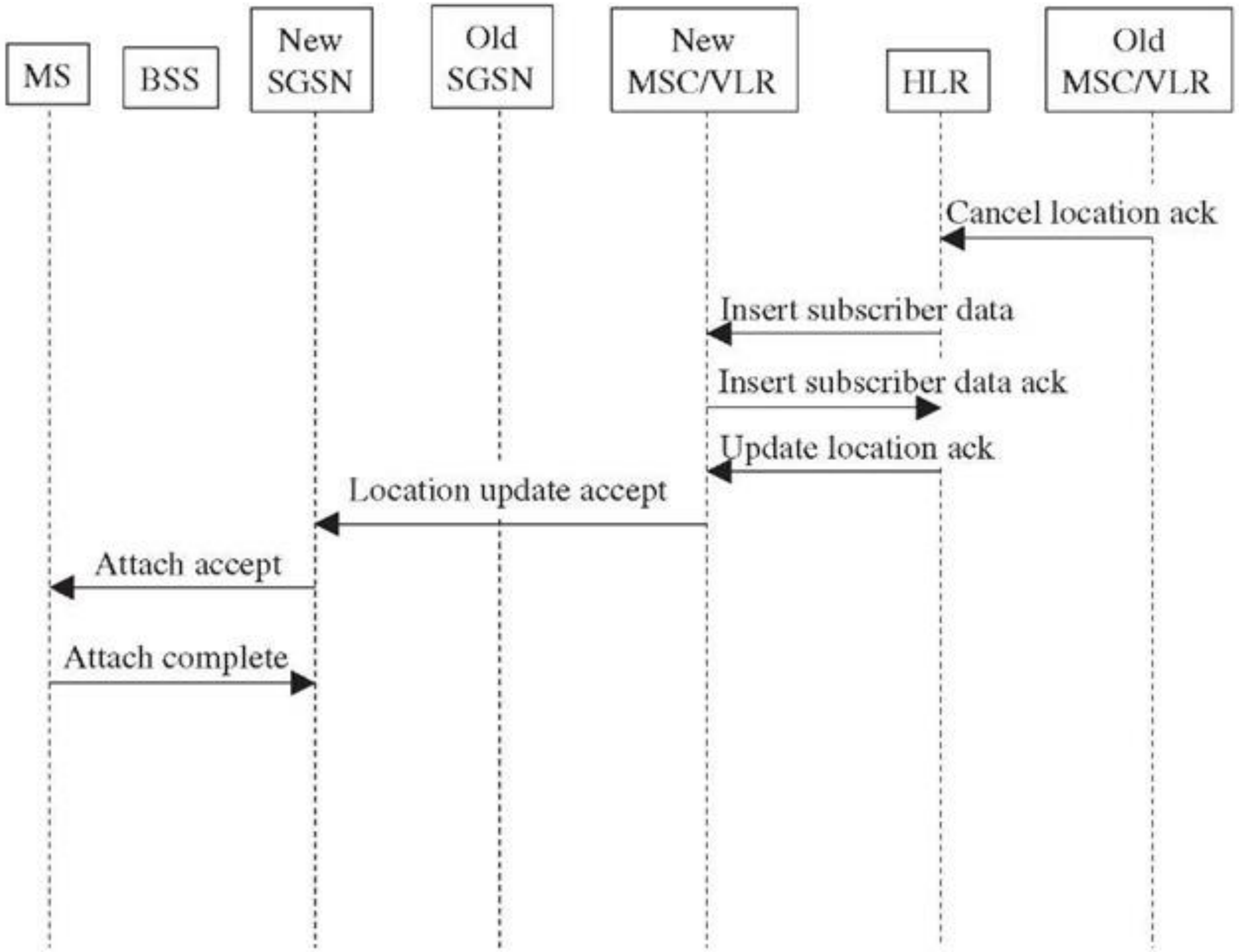
GPRS Transmission Plane



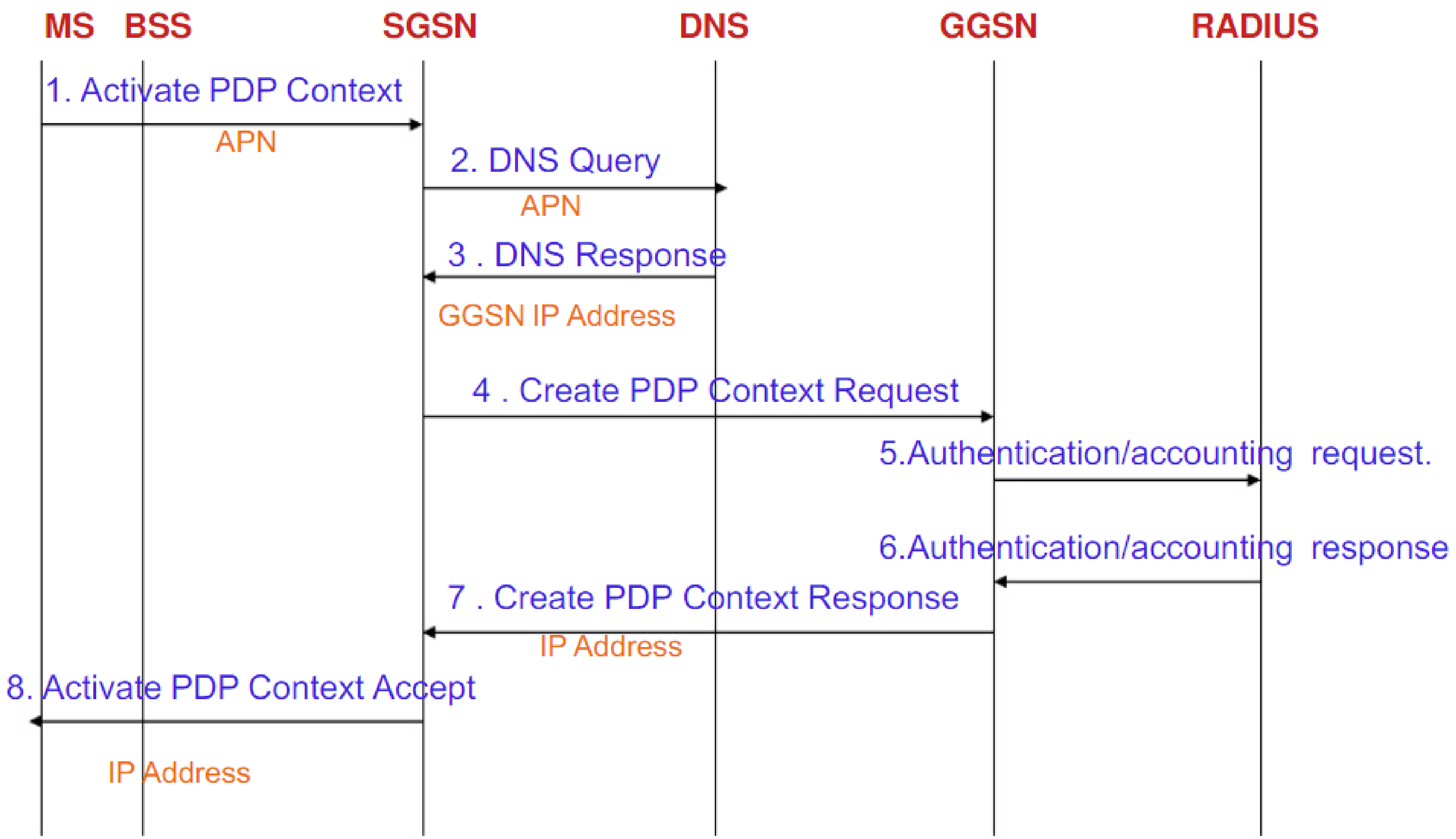
GPRS Attach (1/2)



GPRS Attach (2/2)



PDP Context Activation



Enhanced Data Rates for GSM Evolution (EDGE)

- The next generation of GSM
  - Not yet 3G, so called “2.75G” by some
- Three-fold increase in data rate
  - Up to 3 bits/symbol for 8-PSK from 1 bit/symbol for GMSK for GSM.
  - Max data rates per channel up to $22.8 \times 3 = 68.4$ kbps per channel
  - Using all eight channels in a 200 kHz carrier, gross data transmission rates up to 547.2 kbps became possible
    - Actual throughput up to 513.6 kbps.
- A later release of EDGE (3GPP Release 7) increased downlink data rates over 750 kbps and uplink data rates over 600 kbps

Outline

- Cellular History
- Principles of Cellular Networks
- First-Generation Analog
- Second-Generation TDMA
- Second-Generation CDMA
- Third-Generation Systems

Advantages of CDMA Cellular

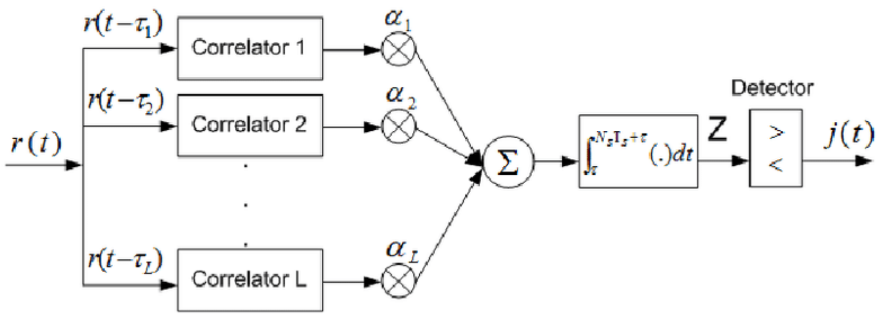
- Frequency diversity
  - Frequency-dependent transmission impairments have less effect on signal.
- Multipath resistance
  - Chipping codes used for CDMA exhibit low cross correlation and low autocorrelation.
- Privacy
  - Privacy is inherent since spread spectrum is obtained by use of noise-like signals.
- 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.

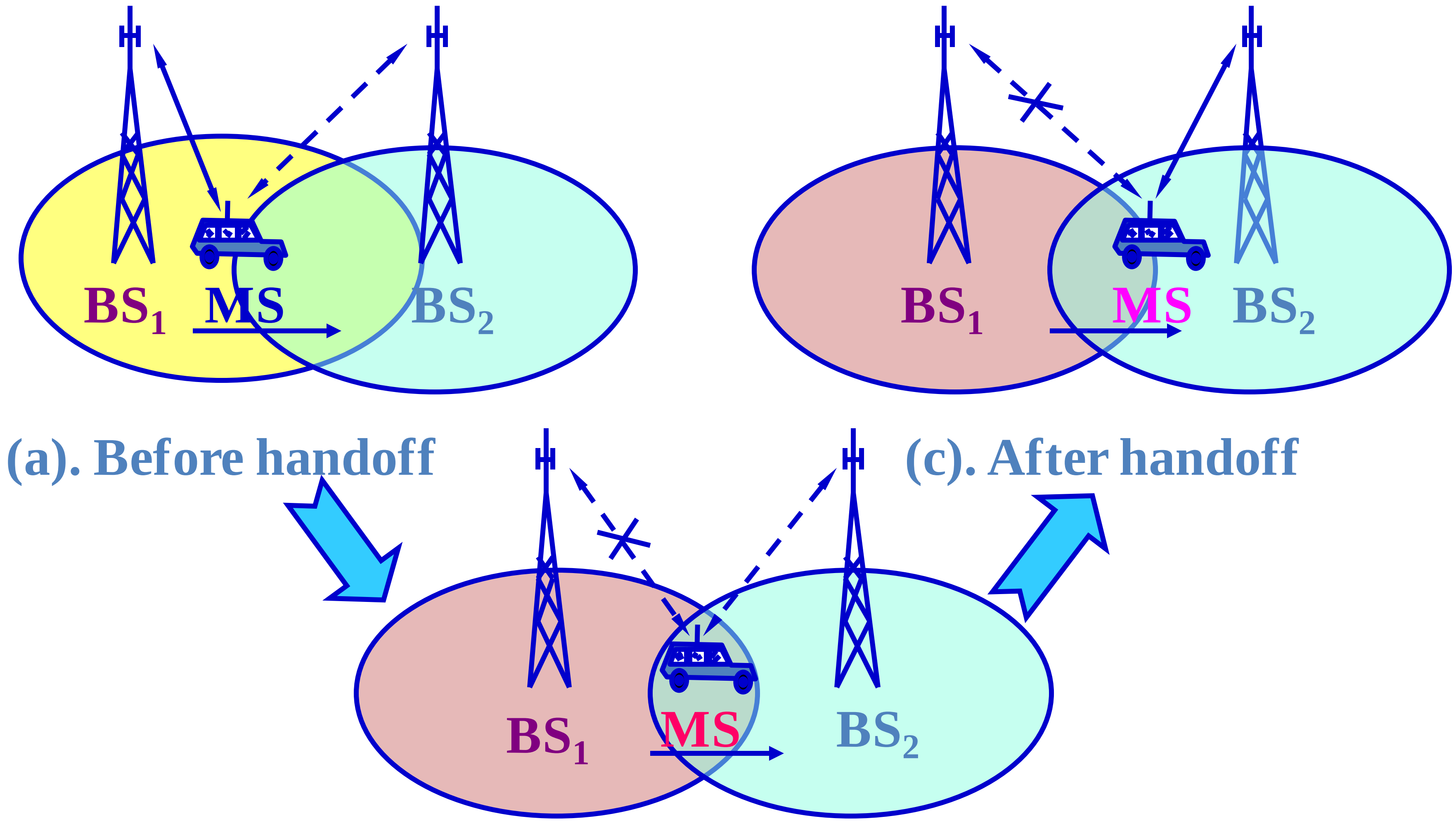
Mobile Wireless CDMA Design Considerations

- 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.



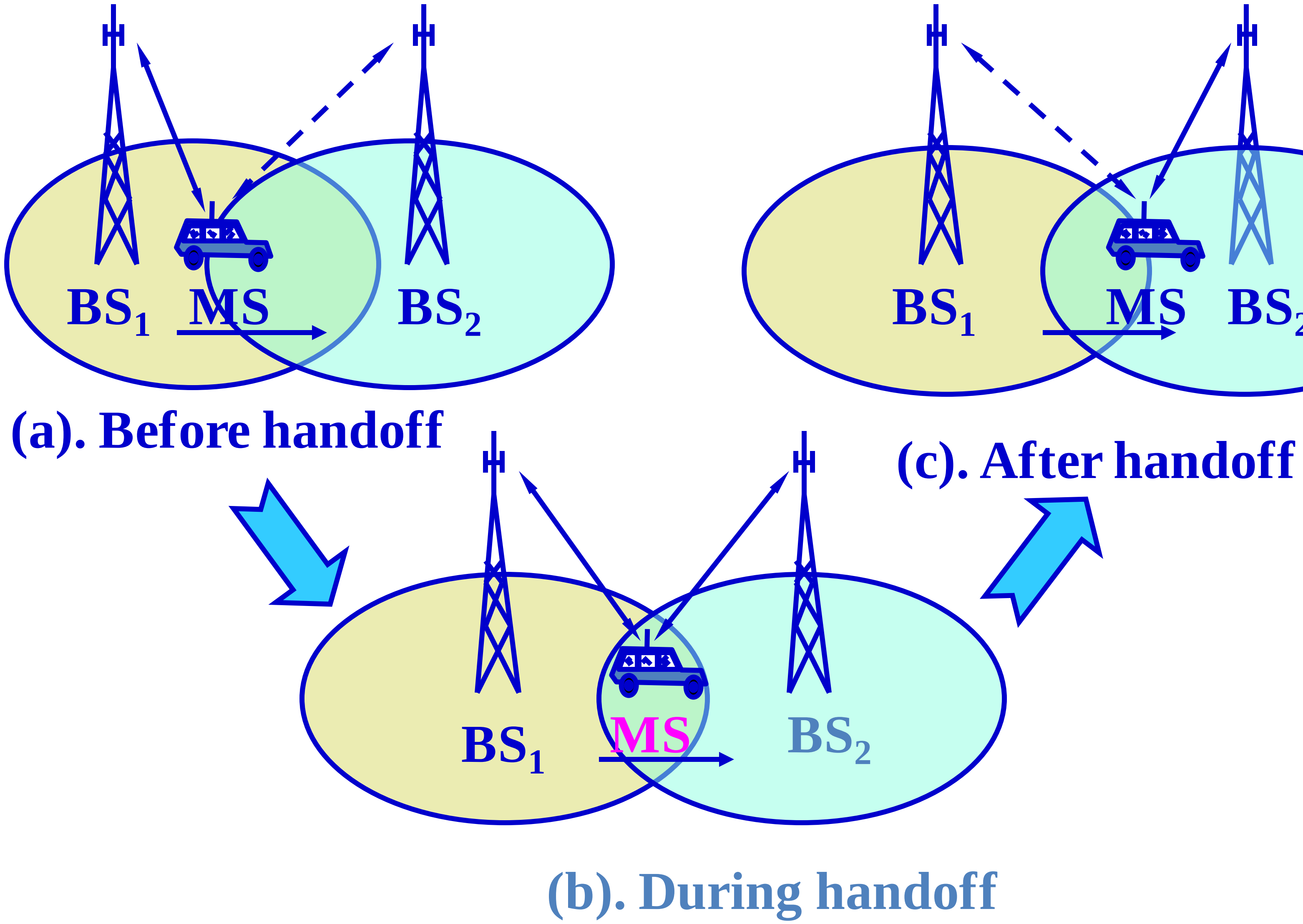
- Soft Handoff
  - Mobile station temporarily connected to more than one base station simultaneously.
  - Using different spreading codes for each base station.

Hard Handoff



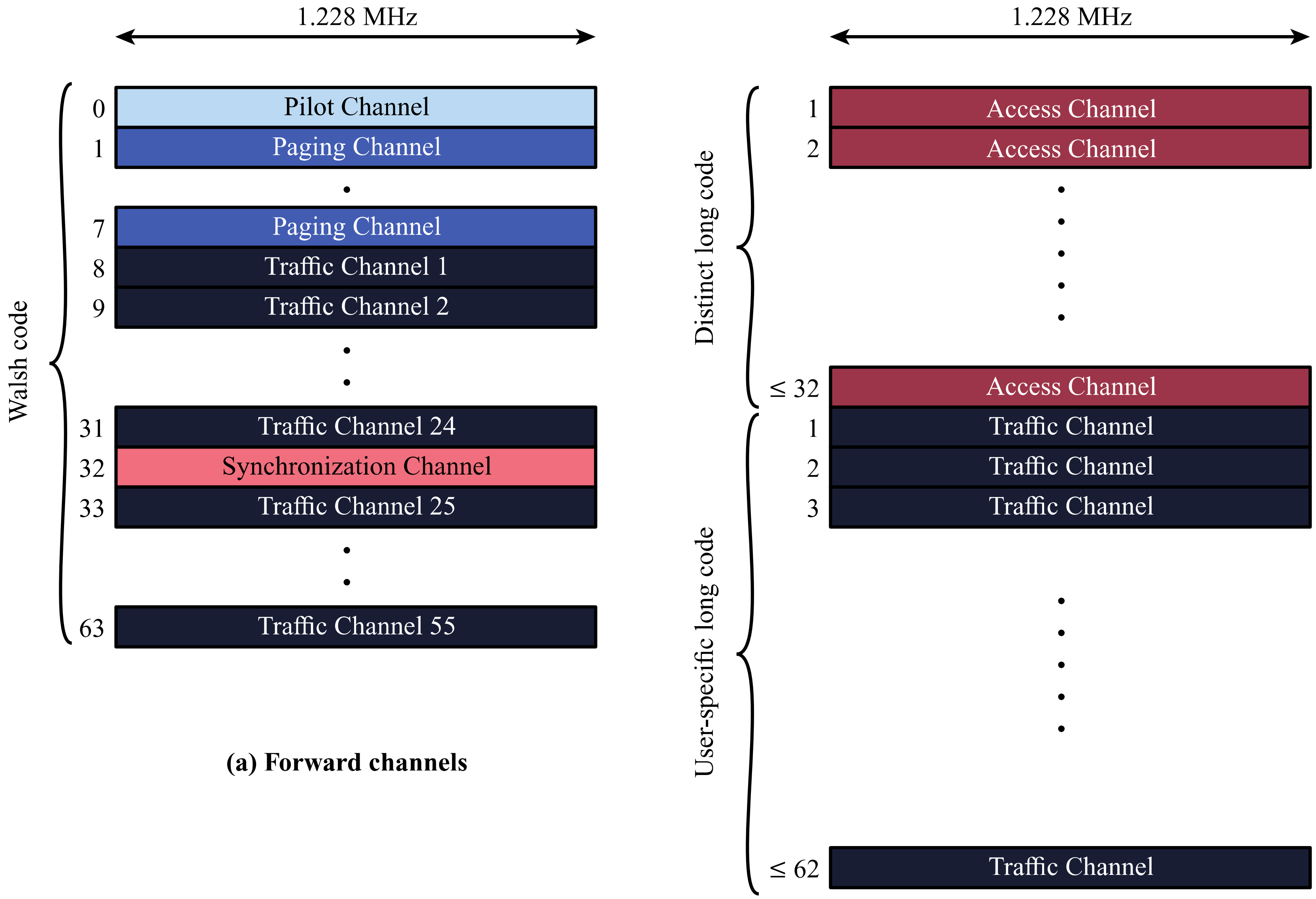
(b). During handoff (**No connection**)

Soft Handoff



IS-95 Forward Link

- Most widely used CDMA cellular standard is IS-95 (cdmaOne), used mainly in North America.
- Forward link channels
  - Pilot (channel 0) - allows the mobile unit to acquire timing information, provides phase reference and provides means for signal strength comparison.
  - Synchronization (channel 32) - used by mobile station to obtain identification information about cellular system.
  - Paging (channels 1 to 7) - contain messages for one or more mobile stations
  - Traffic (channels 8 to 31 and 33 to 63) – the forward channel supports 55 traffic channels
    - 9600 or 14,400 bps



(a) Forward channels

(b) Reverse channels

Outline

- Cellular History
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Third-Generation Capabilities (1/2)

- The ITU's International Mobile Telecommunications for the year 2000 (IMT-2000) initiative
- 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
  - Much higher rates were developed

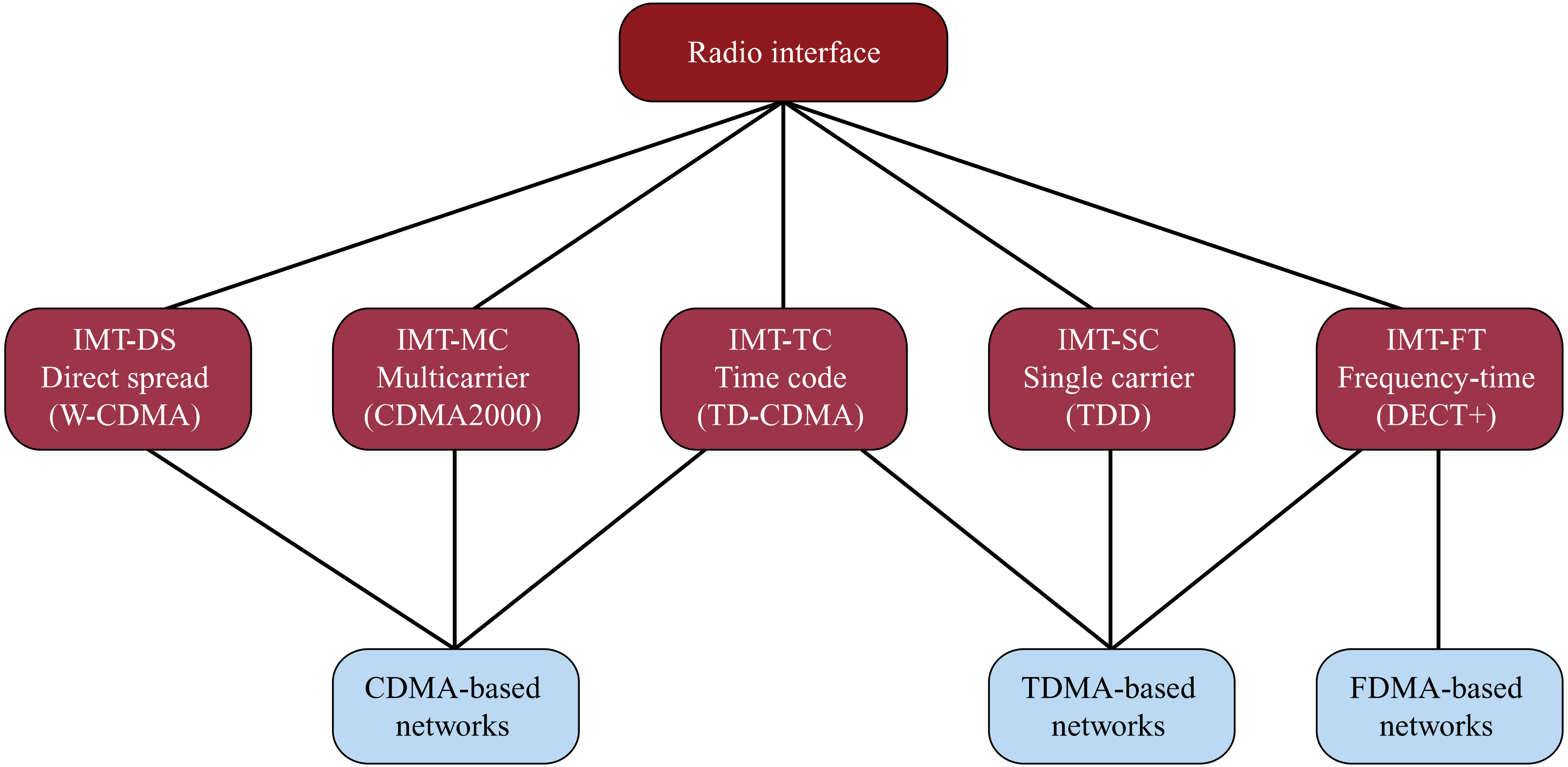
Third-Generation Capabilities (2/2)

- Symmetrical / asymmetrical data transmission rates
- Support for both packet switched and circuit switched data services
- An adaptive interface to the Internet to reflect efficiently the common asymmetry between inbound and outbound traffic
- More efficient use of the available spectrum in general
- Support for a wide variety of mobile equipment
- Flexibility to allow the introduction of new services and technologies

Alternative interfaces (1/2)

- Five alternatives for smooth evolution from 1G and 2G systems
- Two most prevalent
  - Wideband CDMA (WCDMA)
  - CDMA2000
- Both based on CDMA
- Similar to but incompatible with each other

Alternative interfaces (2/2)



CDMA Design Considerations

- Bandwidth – limit channel usage to 5 MHz
- 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

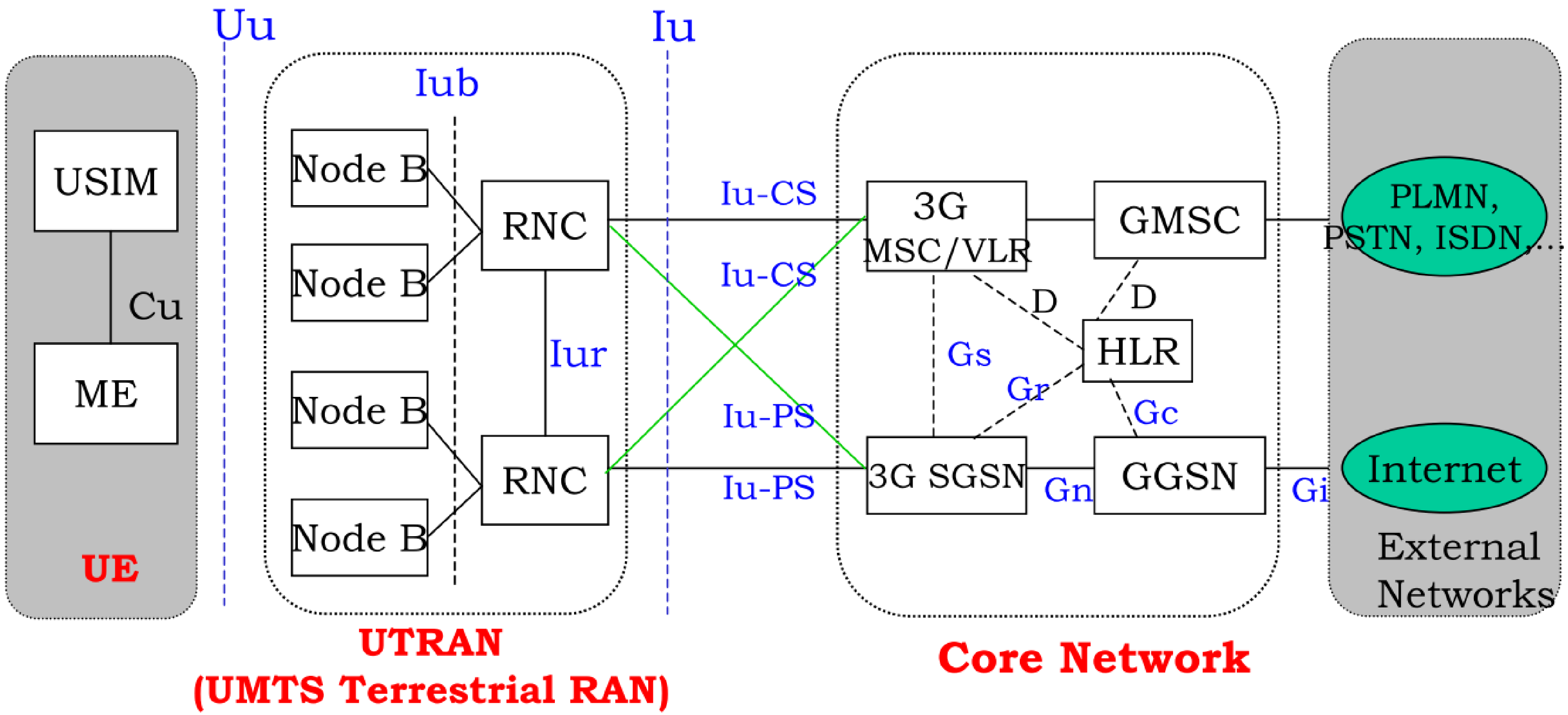
WCDMA and UMTS (1/2)

- WCDMA is part of a group of standards from
  - IMT-2000
  - Universal Mobile Telephone System (UMTS)
  - Third-Generation Partnership Project (3GPP) industry organization
- 3GPP originally released GSM
  - Issued Release 99 in 1999 for WCDMA and UMTS
  - Subsequent releases were "Release 4" and onwards
  - Many higher layer network functions of GSM were carried over to WCDMA

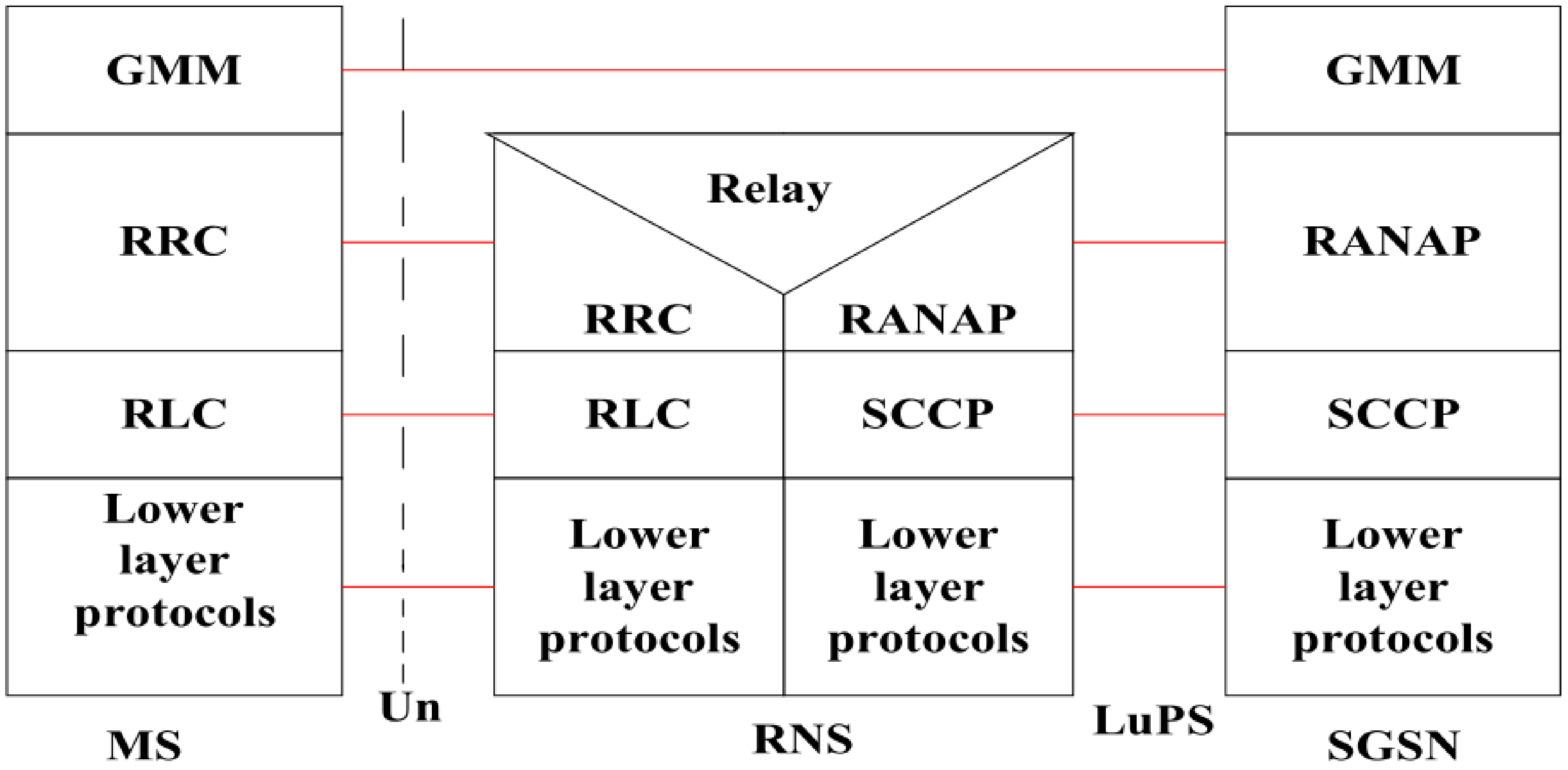
WCDMA and UMTS (2/2)

- 144 kbps to 2 Mbps, depending on mobility
- High Speed Downlink Packet Access (HSDPA)
  - Release 5
  - 1.8 to 14.4 Mbps downlink
  - Adaptive modulation and coding, hybrid ARQ, and fast scheduling
- High Speed Uplink Packet Access (HSUPA)
  - Release 6
  - Uplink rates up to 5.76 Mbps
- High Speed Packet Access Plus (HSPA+)
  - Release 7 and successively improved in releases through Release 11
  - Maximum data rates increased from 21 Mbps up to 336 Mbps
  - 64 QAM, 2×2 and 4×4 MIMO, and dual or multi-carrier combinations
- 3GPP Release 8 onwards introduced Long Term Evolution (LTE)

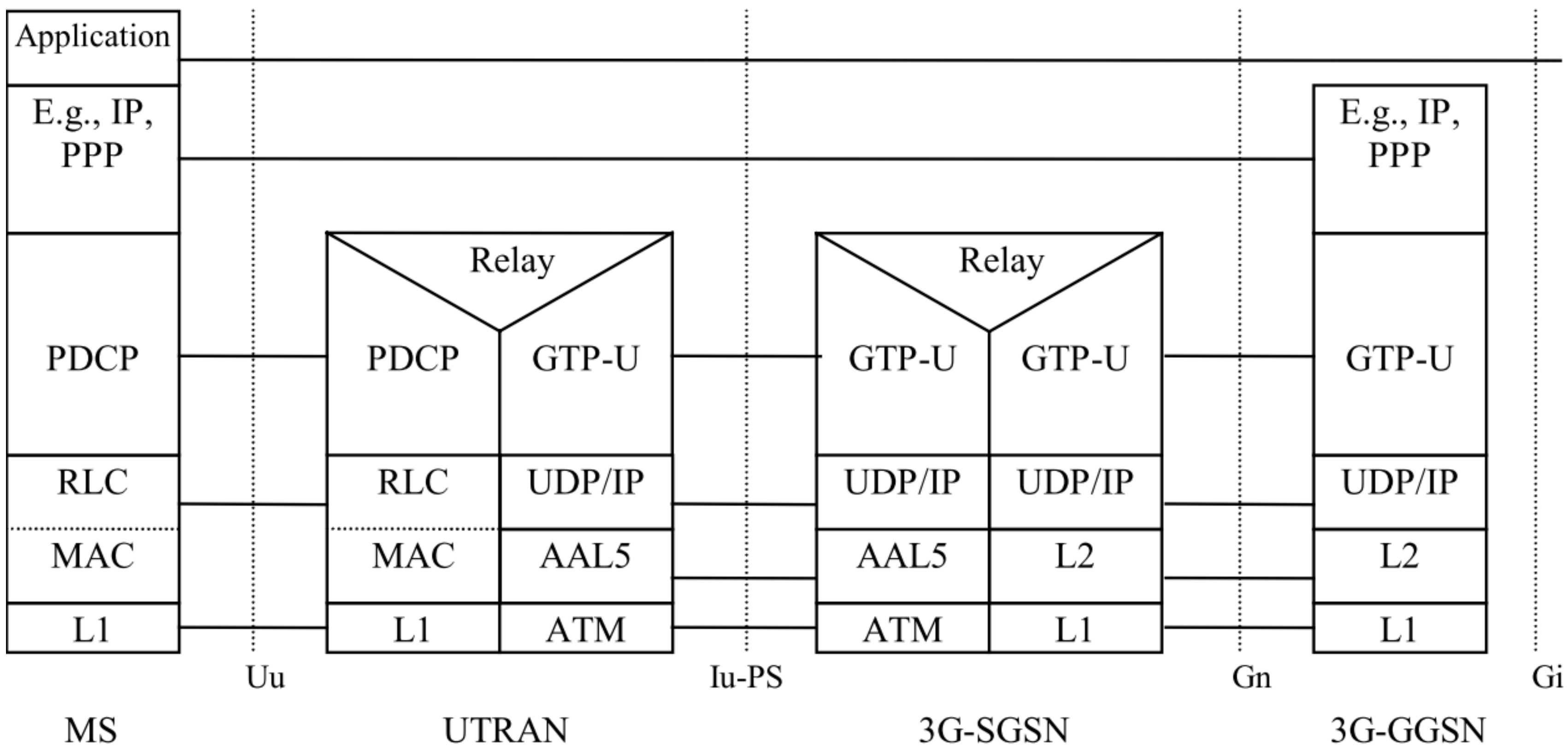
UMTS Architecture



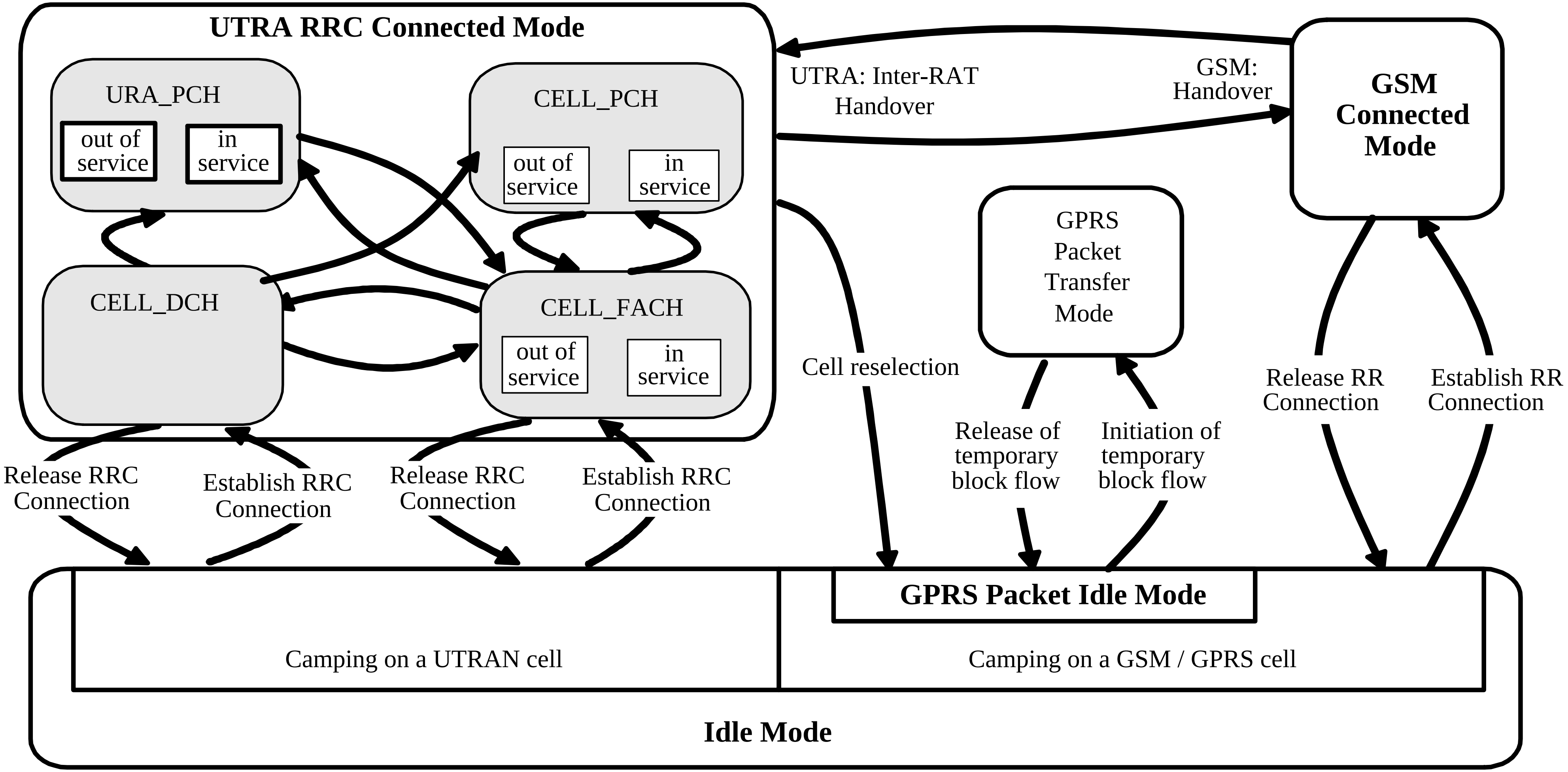
UMTS Control Plane



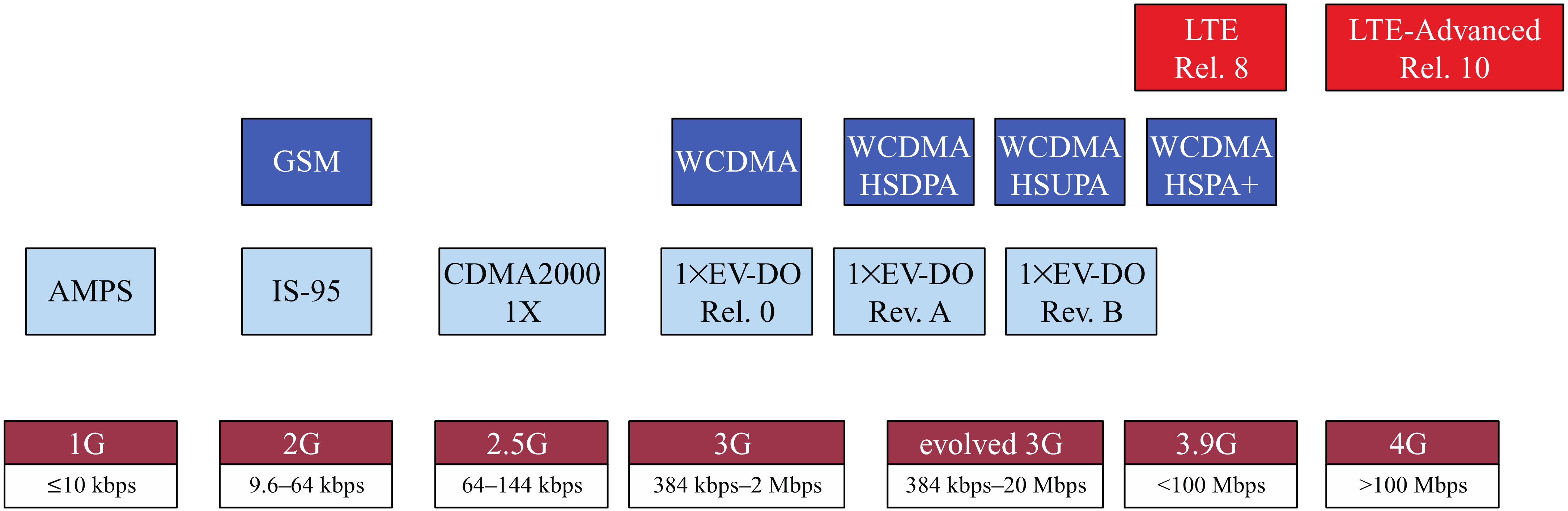
UMTS User Plane



Radio Resource Control



Evolution of Cellular Wireless Systems



CDMA2000 and EV-DO

- CDMA2000 first introduced 1xRTT (Radio Transmission Technology)
  - 1 times the 1.2288 Mcps spreading rate of a 1.25 MHz IS-95 CDMA channel
  - Not 3G, so considered by some as “2.5G”
- Evolution-Data Only (1×EV-DO)
  - Also 1×EV-DV (data/voice) which never succeeded
  - 1×EV-DO Release 0
    - 2.4 Mbps uplink, 153 kbps downlink
    - Only using 1.25 MHz of 5 MHz required of CDMA
  - 1×EV-DO Release A
    - 3.1 Mbps downlink, 1.8 Mbps uplink, QoS
  - 1×EV-DO Release B
    - 5 MHz bandwidth, 14.7 Mpbs uplink, 5.4 Mbps downlink
- EV-DO uses only IP, but VoIP can be used for voice