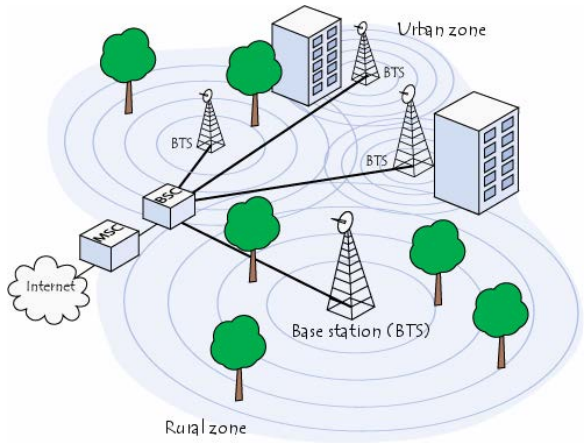
Introduction to Cellular Networks: 1G/2G/3G



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Audio/Video recordings of this class lecture are available at:

http://www.cse.wustl.edu/~jain/cse574-22/

Student Questions

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Overview

1. Cellular Telephony
2. Cellular Frequency Reuse
3. 2G: GSM
4. 2.5G: GPRS, EDGE
5. 3G: W-CDMA
6. 3.5G: High-Speed Packet Access (HSPA)

Note: This is the 1st lecture in a series of lectures on 1G to 5G. 4G, 4.5G, and 5G are covered in subsequent modules.

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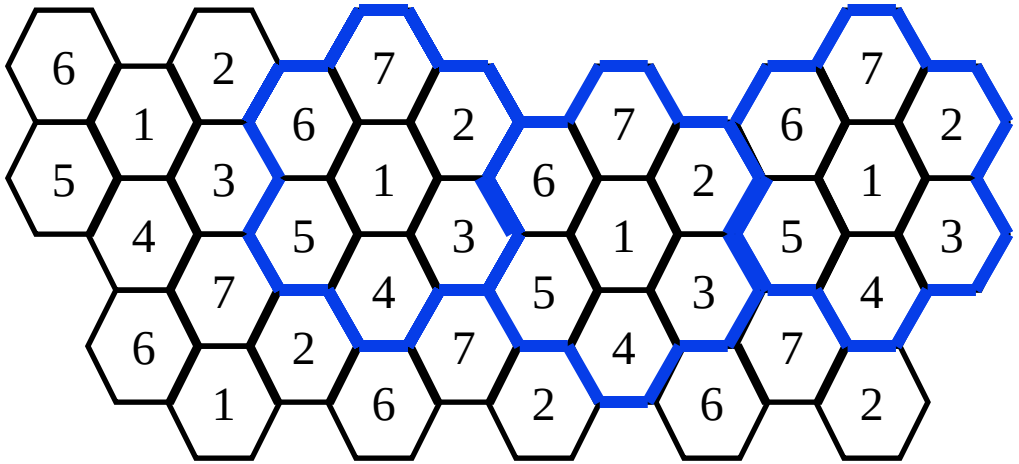
Cellular Network Beginnings

- AT&T Bell Labs designed a cellular structure to reuse frequency. No two adjacent cells use the same frequency.
- 1977: FCC authorized two commercial deployments
  - Chicago: Illinois Bell
  - Washington, DC: American Radiotelephone Service
  - Both services started in 1983



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Ref: P. Bedell, "Cellular Networks: Design and Operation, A real World Perspective," Outskirts Press, 2014, ISBN:9781478732082

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Initial Cellular System in US

- US was divided into
  - 306 metropolitan service areas (MSAs)
    75% of the US population, 20% of the area
    Densely populated ⇒ Small cell size
  - 428 rural service areas (RSAs)
    Less populated ⇒ Larger cell size
- Each area was initially allowed two competing carriers: A, B
  - Bell (B)
  - Alternative (A)
- 832 channel pairs in each area. 416 pairs per carrier.
  45 MHz between transmit and receive frequencies
  30 kHz per channel
  1:7 Frequency reuse with hexagonal cells
- Too many applicants ⇒ FCC started a lottery system
- At least one system in every market by 1990

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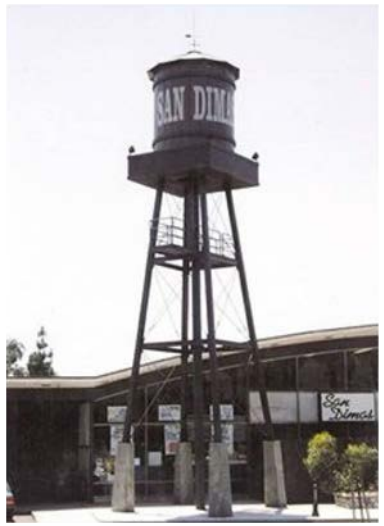
Cell Sites

- On towers, rooftops, water tanks, utility poles, …
  - Good source of income for utility companies, cities, schools, churches, hotels, …
  - With a base station for electronics
  - NIMBY (Not in my backyard)
    ⇒ Mostly hidden, shared towers





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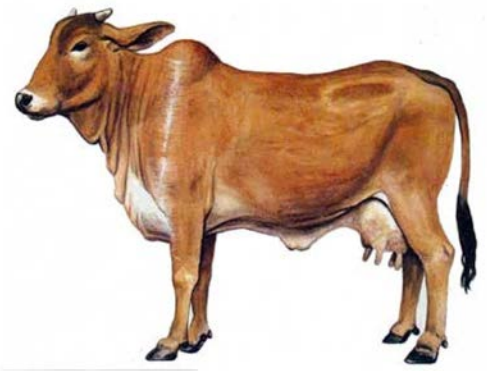
Cells on Wheels (CoWs)

- Used for a temporary surge in traffic, e.g., games, fares, …



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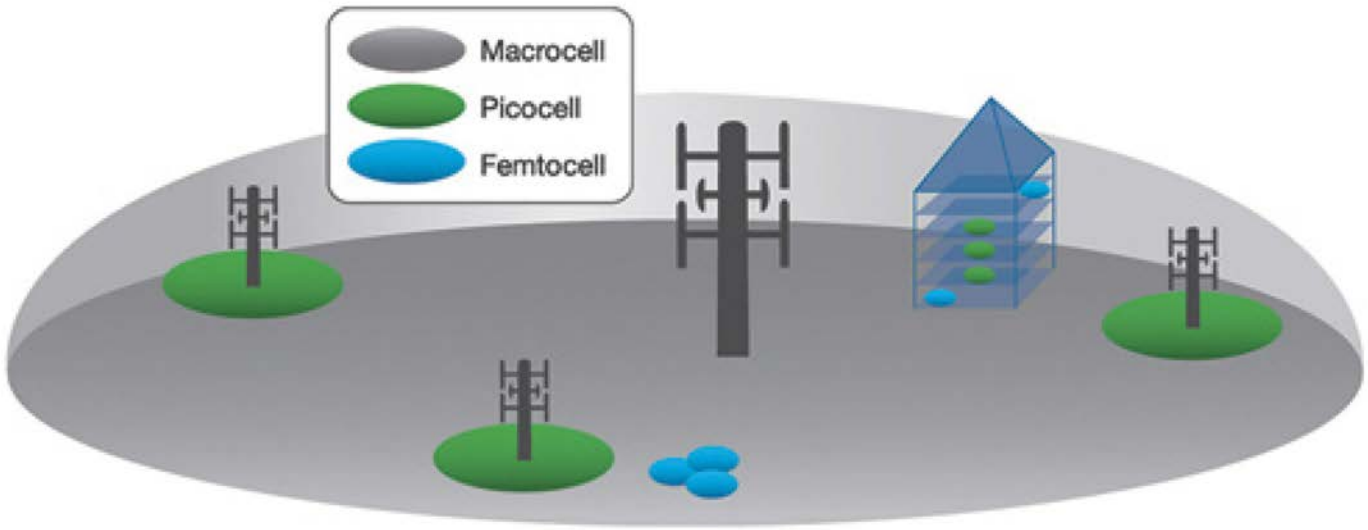
Macro, Micro, Pico, Femto Cells

- Macro: Sections of a city, more than a 1 km radius
- Micro: Neighborhoods, less than 1 km
- Pico: Busy public areas: Malls, airports, …, 200 m
- Femto: Inside a home, 10 m



Ref: http://www.microwavejournal.com/articles/print/22784-high-efficiency-amplifier-for-picocells

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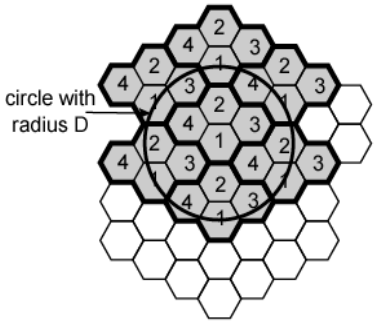
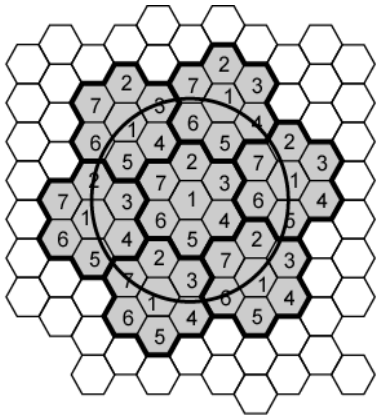
Cellular Frequency Reuse

Cluster Size =4

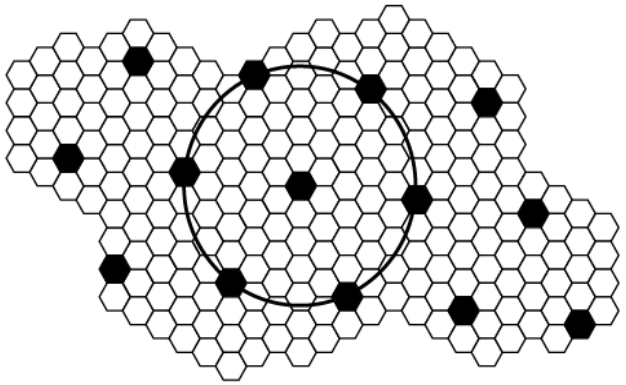


(a) Frequency reuse pattern for N = 4



(b) Frequency reuse pattern for N = 7

Cluster Size =7



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

Cluster Size =19

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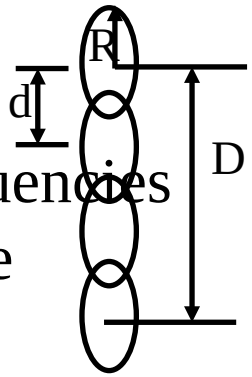
Characterizing Frequency Reuse

- D = minimum distance between centers of cells that use the same band of frequencies (called co-channels)
- R = radius of a cell
- d = distance between centers of adjacent cells ($d = R\sqrt{3}$)
- N = number of cells in repetitious pattern (**Cluster**)
  - Reuse factor
  - Each cell in the pattern uses a unique band of frequencies
- Hexagonal cell pattern, following values of N possible
  - $N = I^2 + J^2 + (I \times J)$, $I, J = 0, 1, 2, 3, \ldots$
- Possible values of N are 1, 3, 4, 7, 9, 12, 13, 16, 19, 21, …
- Reuse Ratio = Distance/Radius = $D/R = \sqrt{3N}$
- $D/d = \sqrt{N}$



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Ref: C. Siva Ram Murthy; B. S. Manoj, "Ad Hoc Wireless Networks Architectures and Protocols," Prentice Hall, 2004, ISBN: 013147023X, 880 pp., Safari Book, Section 3.2.

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Frequency Reuse Example

What would be the minimum distance between the centers of two cells with the same band of frequencies if the cell radius is 1 km and the reuse factor is 12?

$$D/R = \sqrt{3N}$$

$$D = (3\times12)^{1/2} \times 1 \text{ km}$$

$$= 6 \text{ km}$$

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Homework 16A

- The distance between cell centers with the same frequency band is required to be more than 6 km. What is the cell radius for the cluster size of 12?

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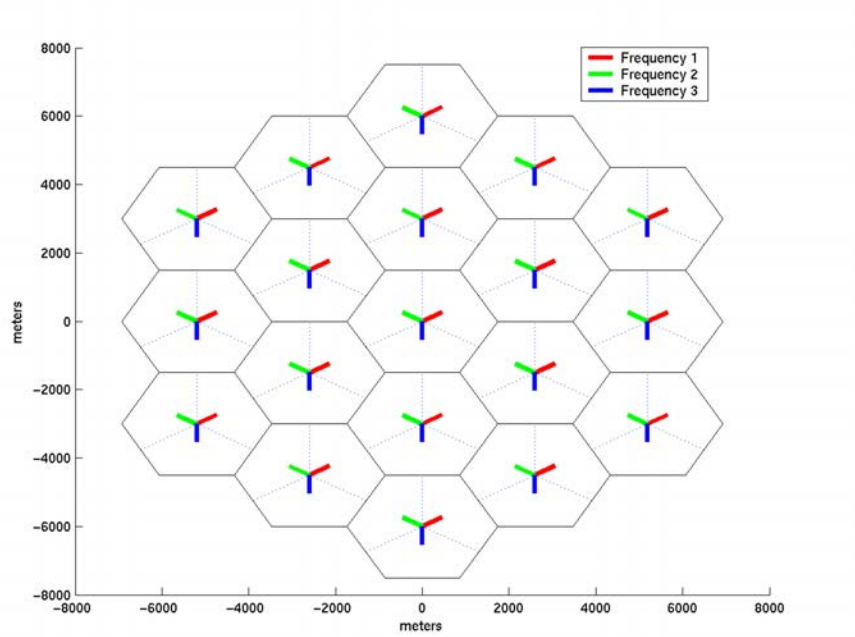
Frequency Reuse Notation

- N×S×K frequency reuse pattern
- N=Number of cells per cluster
- S= Number of sectors in a cell
- K = Number of frequency allocations per cell



1X3X3

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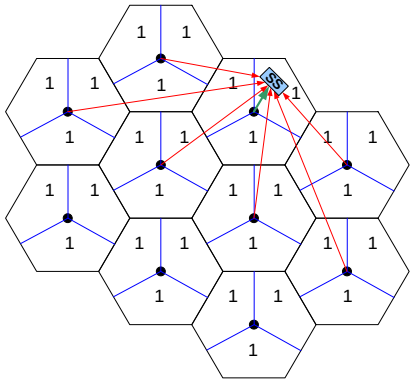
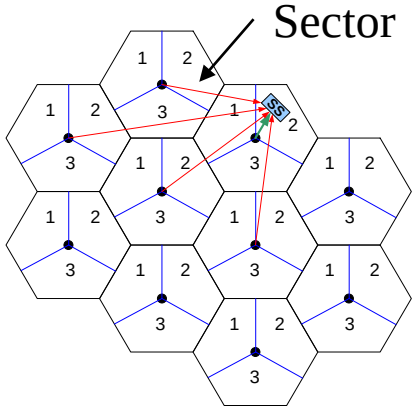
Frequency Reuse Notation (Cont)

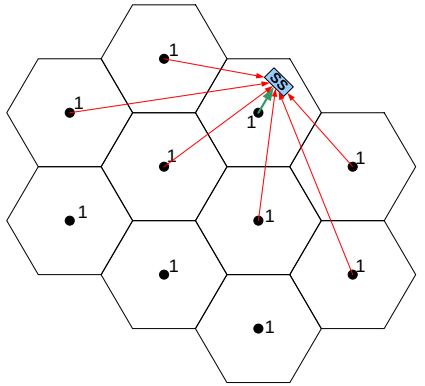
1x3x1



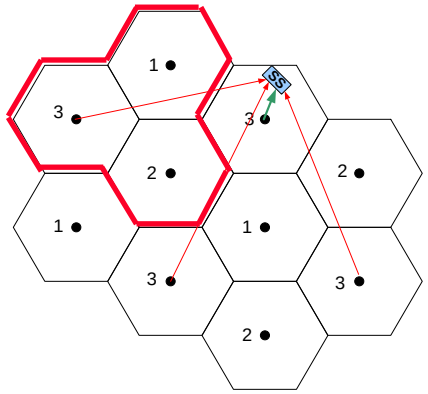
1x3x3



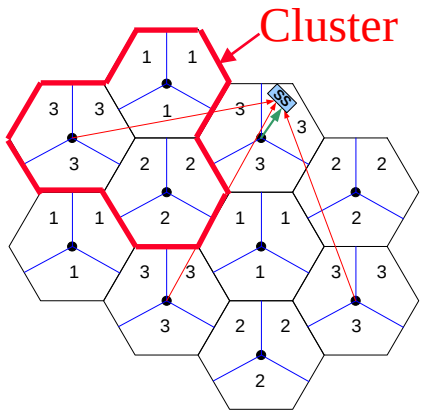
1x1x1



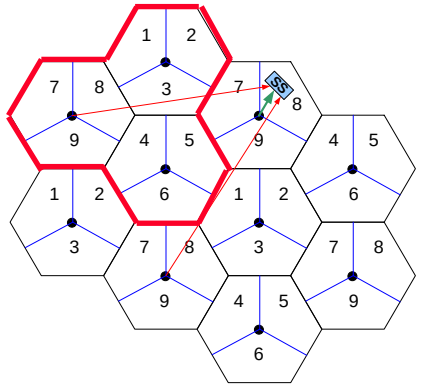
3x1x1



3x3x1



3x3x3



Sector

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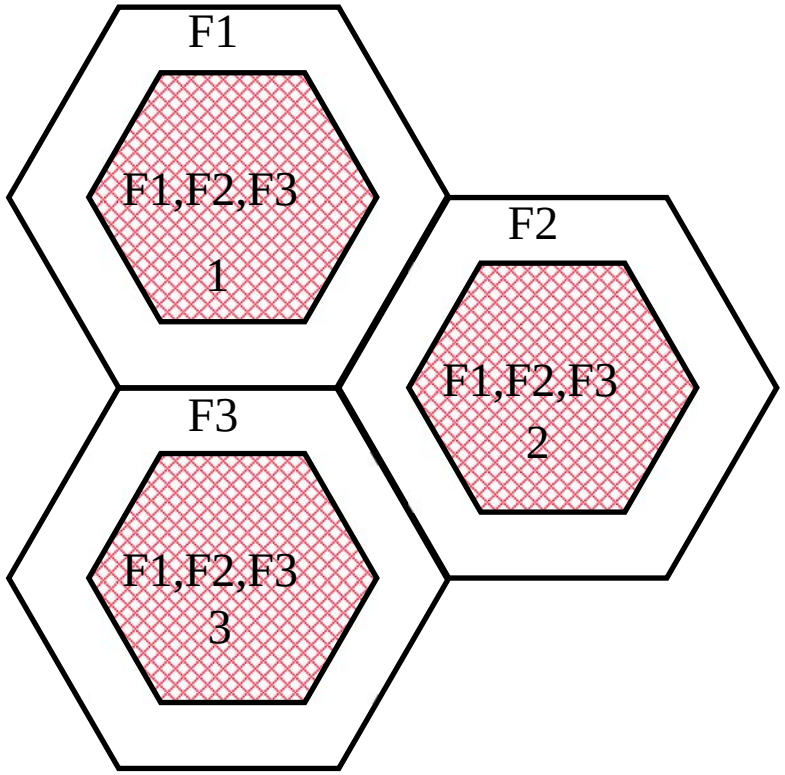
Fractional Frequency Reuse

- Users close to the BS use all frequency subchannels
- Users at the cell boundary use only a fraction of available subchannels



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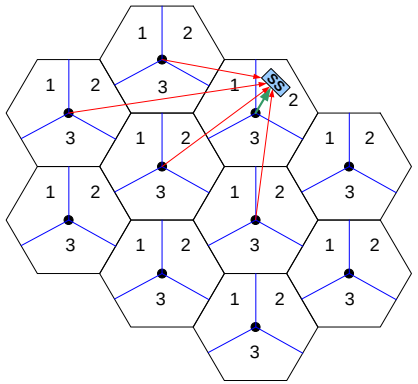
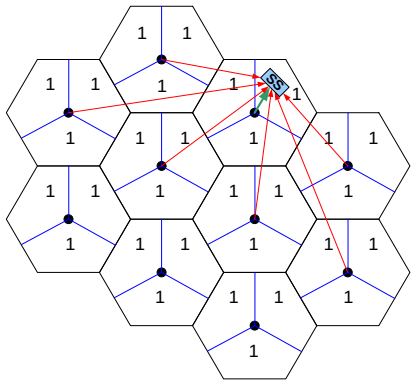
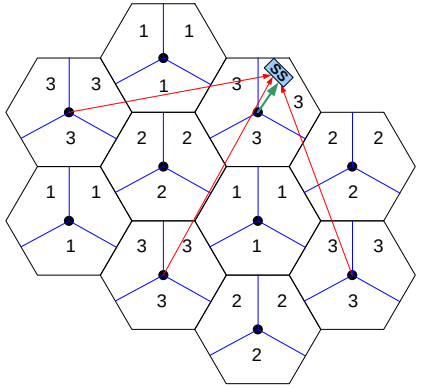
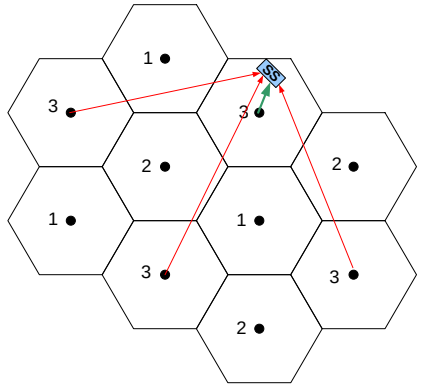
Homework 16B

- Label the frequency reuse patterns below.









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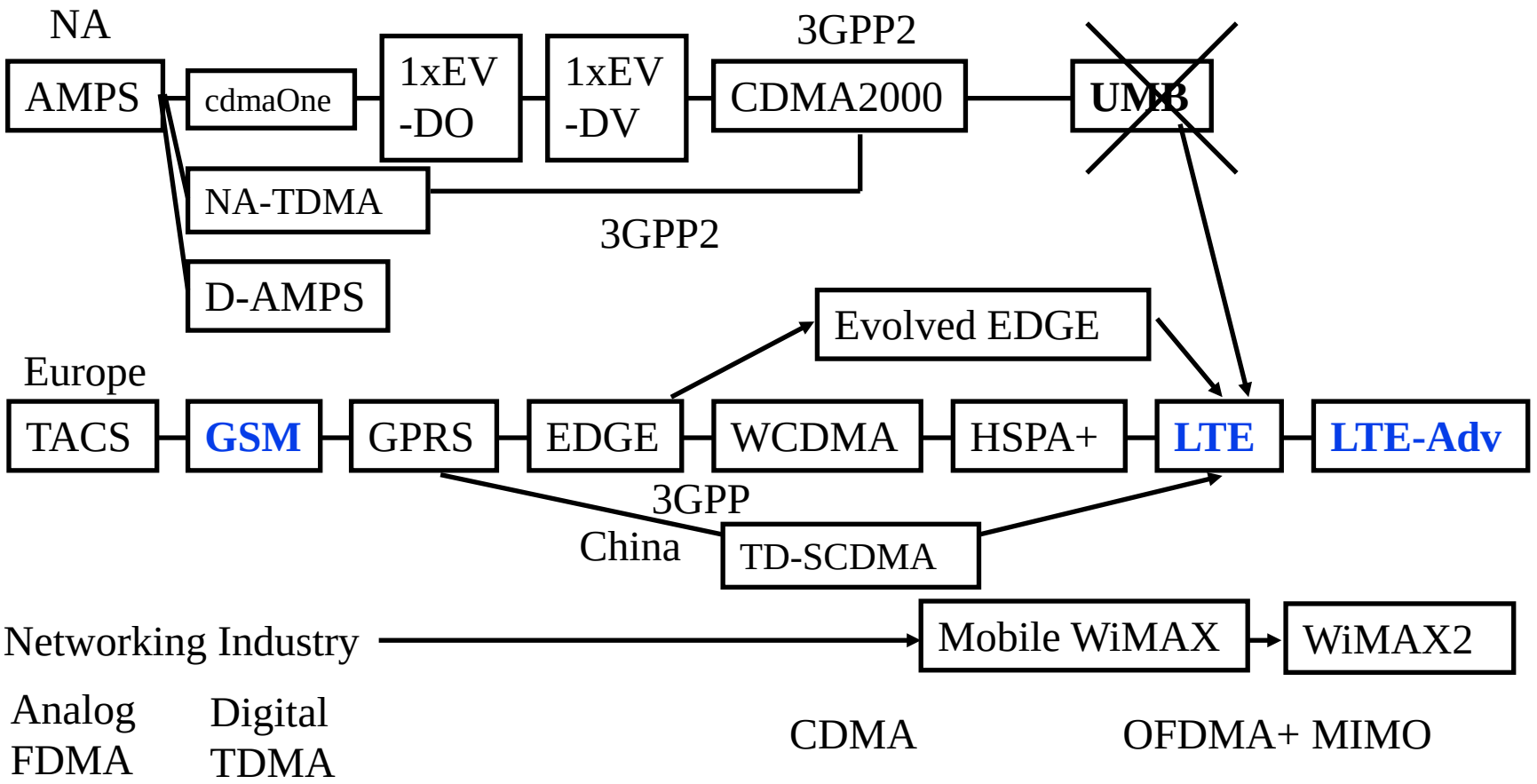
Cellular Telephony Generations



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Cellular Generations (Cont)

- **1G: Analog Voice. FDMA. 1980s**
  - AMPS: Advanced Mobile Phone System
  - TACS: Total Access Communications System
- **2G: Digital Voice. TDMA. 1990**
  - cdmaOne: Qualcomm. International Standard IS-95.
  - NA-TDMA
  - Digital AMPS (D-AMPS)
  - **GSM**: Global System for Mobile Communications
- **2.5G: Voice + Data. 1995.**
  - 1xEV-DO: Evolution-Data Optimized
  - 1xEV-DV: Evolution Data and Voice
  - General Packet Radio Service (GPRS)
  - Enhanced Data Rate for GSM Evolution (EDGE)

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Cellular Generations (Cont)

- **3G: Voice + High-speed data. All CDMA. 2000.**
  - CDMA2000: Qualcomm. International Standard IS-2000.
  - W-CDMA: Wideband CDMA
  - TD-SCDMA: Time Division Synchronous Code Division Multiple Access (Chinese 3G)
  - 384 kbps to 2 Mbps
- **3.5G: Voice + Higher-speed data**
  - EDGE Evolution
  - High-Speed Packet Access (HSPA)
  - Evolved HSPA (HSPA+)
  - Ultra Mobile Broadband (UMB)

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Cellular Generations (Cont)

- Two Tracks for 1G/2G/3G:
  - Europe 3GPP (3rd Generation Partnership Project)
  - North America 3GPP2
- **3.9G: High-Speed Data. VOIP. OFDMA.**
  - WiMAX 16e (Worldwide Interoperability for Microwave Access)
  - Long Term Evolution (LTE)
- **4G: Very High-Speed Data. 2013.**
  - WiMAX 16m or WiMAX2
  - LTE-Advanced
  - 100 Mbps – 1 Gbps
- **5G: Ultra High-Speed Data. 2020.**
  - IP based

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3.9G vs. 4G

- 3G = International Mobile Communications 2000 (IMT-2000) = W-CDMA, CDMA2000
- 4G = IMT-Advanced = LTE-Advanced, IEEE 802.16m
- WiMAX forum officially declared WiMAX to be 3G technology so they can use spectrum allocated to 3G.
- WiMAX and LTE are at most 3.9G or "near-4G." Some telecom companies are selling them as 4G

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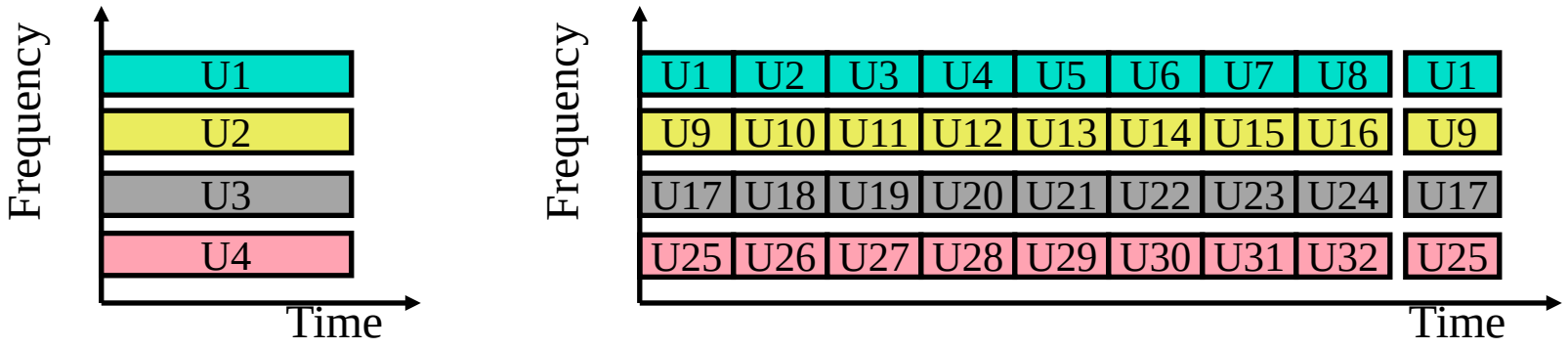
GSM

- Global System for Mobile Communications
- Implemented in 90% of cell phones worldwide.
- 1990 Technology using Time-Division Multiple Access (**TDMA**) instead of Frequency Division Multiple Access (FDMA) used in 1G
- 850/900/1800/1900 MHz (quad-band)
- **Subscriber Identity Module (SIM)** card contained user data. The user could use any phone with their SIM card



(a) FDMA (B) TDMA

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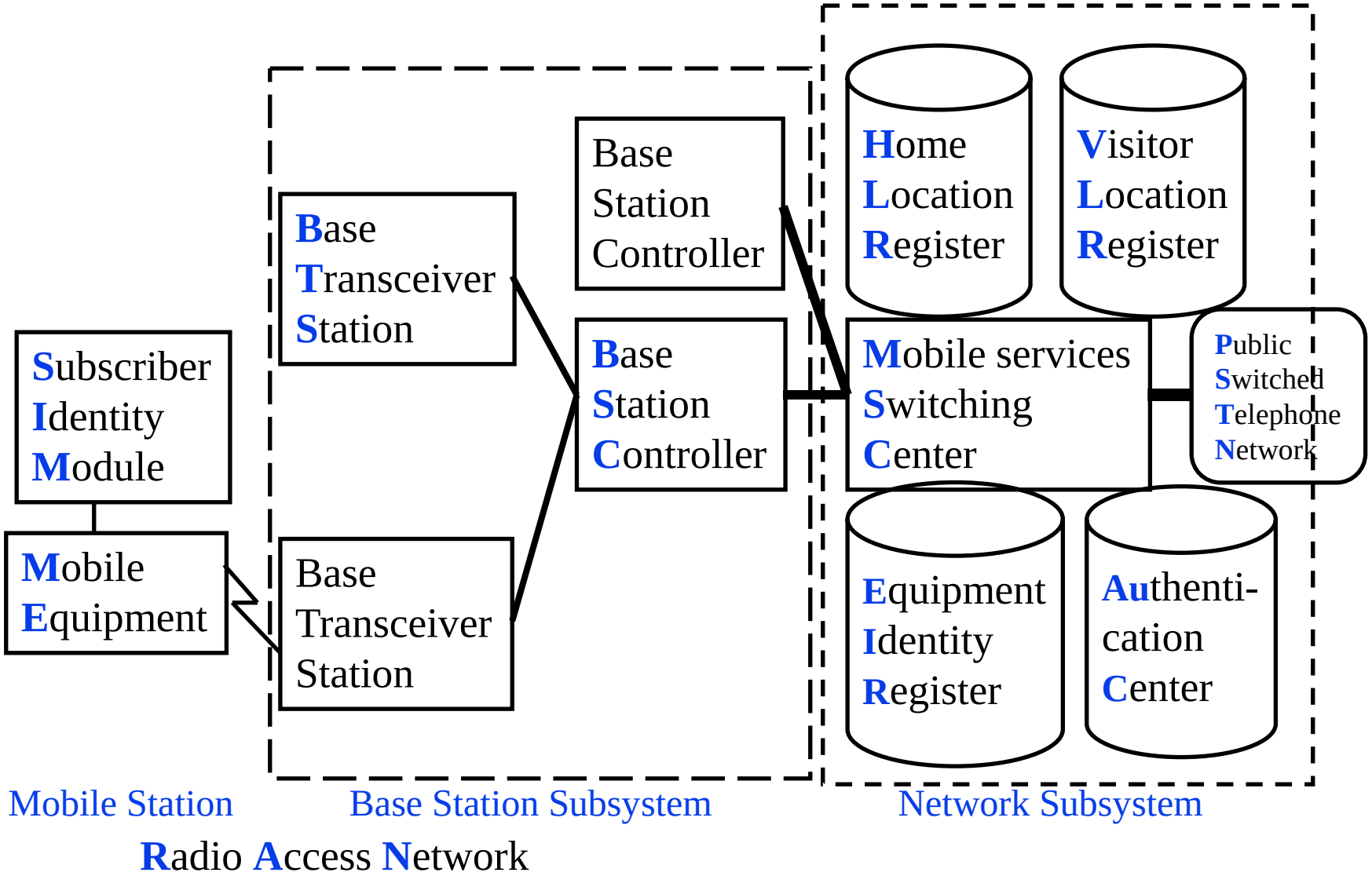
GSM Cellular Architecture



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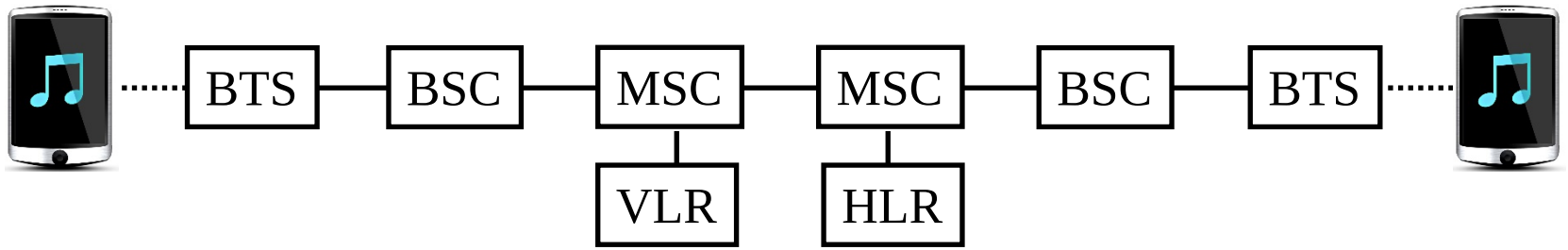
Cellular Architecture (Cont)

- One Base transceiver station (BTS) per cell.
- One Base Station Controller (BSC) can control multiple BTS.
  - Allocates radio channels among BTSs.
  - Manages call handoffs between BTSs.
  - Controls handset power levels
- Mobile Switching Center (MSC) connects to PSTN and switches calls between BSCs. Provides mobile registration, location, and authentication. Contains Equipment Identity Register.



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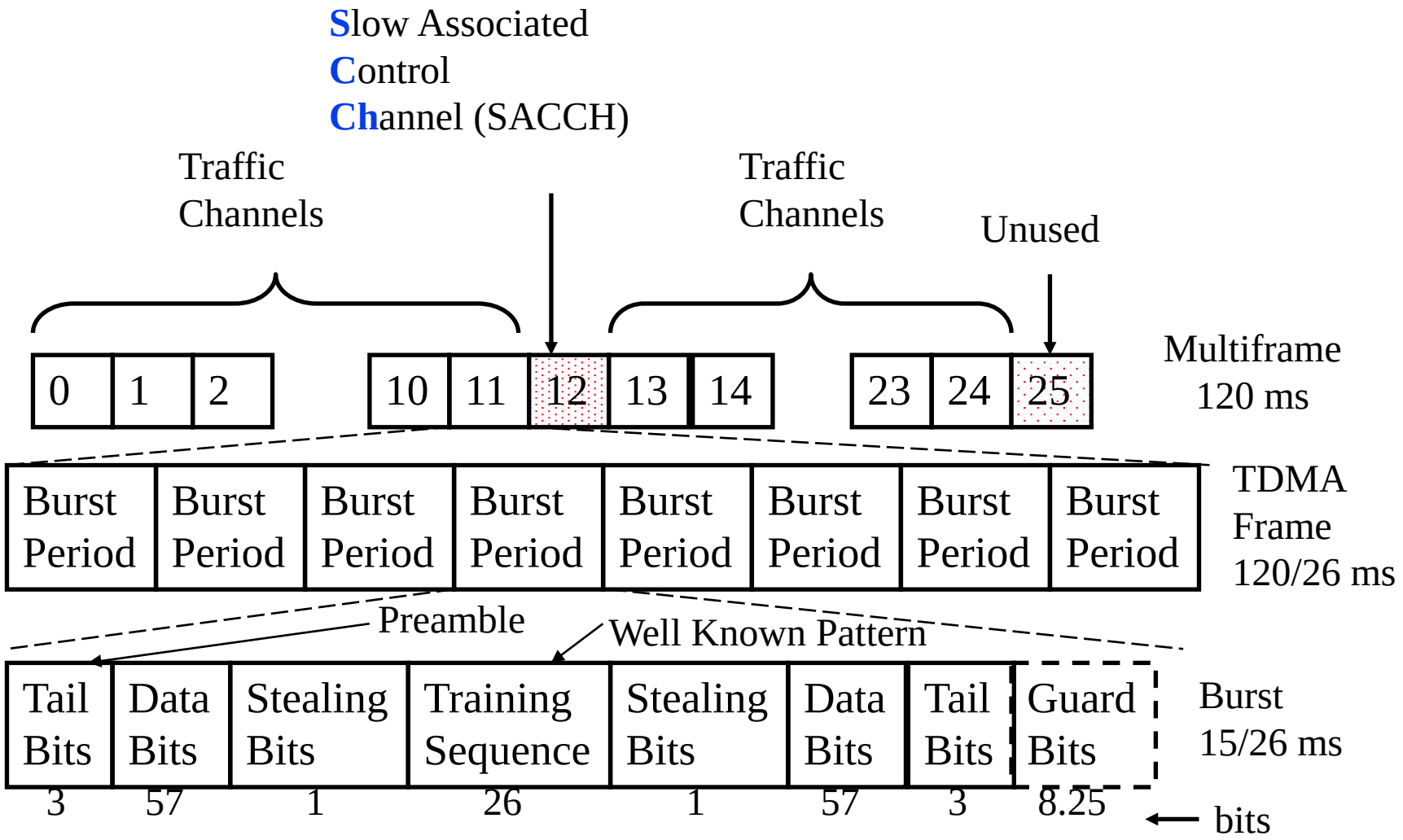
Cellular Architecture (Cont)

- **Home Location Register (HLR)** and Visitor Location Register (VLR) provide the call routing and roaming
- VLR+HLR+MSC functions are generally in one equipment
- Equipment Identity Register (EIR) contains a list of all valid mobiles.
- Authentication Center (AuC) stores the secret keys of all SIM cards.
- Each handset has an International Mobile Equipment Identity (IMEI) number.

Student Questions

GSM Radio Link



Ref: Martin Sauter, "From GSM to LTE-Advanced: An Introduction to Mobile Networks and Mobile Broadband, Revised Second Edition," John Wiley & Sons, August 2014, 456 pp., ISBN:978-1-118-86195-0 (Safari Book).

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Student Questions

GSM Radio Link (Cont)

- 890-915 MHz uplink, 935-960 MHz downlink
- 25 MHz ⇒ 125 × 200kHz frequency channels
- Each frequency channel is TDMA with a burst (slot) period of 15/26 ms.
- Eight burst periods = TDMA frame of 120/26 ms.
- One user traffic channel = one burst period per TDMA frame.
- 26 TDMA frames ⇒ one multiframe
  24 are used for traffic, 1 for control, and 1 is unused.
  Slow Associated Control Channel (SACCH)
  If SACCH does not have sufficient capacity, Fast Associated Control Channel (FACCH) is used by stealing ½ of some bursts.
- **Stealing bits** identify whether the 1/2-slot carries data or control
- 200 kHz = 270.8 kbps over 26 slots
  ⇒ 9.6 kbps/user after encryption and FEC overhead

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GSM Specs

- Full rate vocoders ⇒ Voice is sampled at 64 kbps compressed to 16 kbps.
- Subscriber Identify Module (SIM) contains a microcontroller and storage. It contains authentication, encryption, and accounting info.
  Owners need a 4-digit PIN.
- SIM cards can contain additional info, such as emergency medical info.
- Mobile Assisted Handoff: Mobile sends identities of six candidate base stations for handoff. MSC selects.
- Short Message Service (SMS)
  - Up to 160 characters
  - Sent over the control channel
  - Unicast or broadcast

Student Questions

Cellular System Capacity Example

- A particular cellular system has the following characteristics: cluster size =7, uniform cell size, user density=100 users/sq km, allocated frequency spectrum = 900-949 MHz, bit rate required per user = 10 kbps uplink and 10 kbps downlink, and modulation code rate = 1 bps/Hz.

A. Using FDMA/FDD:
   1. How much bandwidth is available per cell using FDD?
   2. How many users per cell can be supported using FDMA?
   3. What is the cell area?
   4. What is the cell radius assuming circular cells?

B. If the available spectrum is divided into 35 channels and TDMA is employed within each channel:
   1. What is the bandwidth and data rate per channel?
   2. How many time slots are needed in a TDMA frame to support the required number of users?
   3. If the TDMA frame is 10ms, how long is each user slot in the frame?
   4. How many bits are transmitted in each time slot?

Student Questions

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Cellular System Capacity (Cont)

- A particular cellular system has the following characteristics: cluster size =7, uniform cell size, user density=100 users/sq km, allocated frequency spectrum = 900-949 MHz, bit rate required per user = 10 kbps uplink and 10 kbps downlink, and modulation code rate = 1 bps/Hz.
- A. Using FDMA/FDD:
  1. How much bandwidth is available per cell using FDD?
     49 MHz/7 = 7 MHz/cell
     FDD $\Rightarrow$ 3.5 MHz/uplink or downlink
  2. How many users per cell can be supported using FDMA?
     10 kbps/user = 10 kHz $\Rightarrow$ 350 users per cell
  3. What is the cell area?
     100 users/sq km $\Rightarrow$ 3.5 Sq km/cell
  4. What is the cell radius assuming circular cells?
     $\pi r^2 = 3.5 \Rightarrow r = 1.056$ km

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Cellular System Capacity (Cont)

B. If the available spectrum is divided into 35 channels and TDMA is employed within each channel:

1. What is the bandwidth and data rate per channel?

   3.5 MHz/35 = 100 kHz/Channel = 100 kbps

2. How many time slots are needed in a TDMA frame to support the required number of users?

   Ten kbps/user $\Rightarrow$ 10 users/channel

3. If the TDMA frame is 10ms, how long is each user slot in the frame?

   10 ms/10 = 1ms

4. How many bits are transmitted in each time slot?

   1 ms x 100 kbps = 100 b/slot

Student Questions

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Homework 16C

- A particular cellular system has the following characteristics: Cluster size =9, uniform cell size, user density=100 users/sq km, allocated frequency spectrum = 900-945 MHz, bit rate required per user = 10 kbps uplink and 10 kbps downlink, and modulation code rate = 2 bps/Hz.
- A. Using FDMA/FDD:
  - 1. How much bandwidth is available per cell using FDD?
  - 2. How many users per cell can be supported using FDMA?
  - 3. What is the cell area
  - 4. What is the cell radius assuming circular cells?

B. If the available spectrum is divided into 100 channels and TDMA is employed within each channel:

1. What is the bandwidth and data rate per channel?
2. How many time slots are needed in a TDMA frame to support the required number of users?
3. If the TDMA frame is 10ms, how long is each user slot in the frame?
4. How many bits are transmitted in each time slot?

Student Questions

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GPRS

- General Packet Radio Service (GPRS). 2.5G Technology
- Standard GSM has eight slots per 200 kHz channel
  One slot/user ⇒ 9.6 kbps data/user
- GPRS allows any number of slots to a user
  - four different codings used depending upon channel condition
  - 9.6 kbps to 21.4 kbps per slot
  - 76-171 kbps using all 8 slots.
- GPRS user can hop frequency channels

Gi = GSM User
Gpi = GPRS User

	t_0	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_0	t_1	t_2	
Uplink 1	G1		G2		GP2			GP1	G1		G2	
Uplink 2				GP1			GP2					
Downlink 1	G1	GP1	G2		GP2			GP1	G1		G2	
Downlink 2	GP1				GP1					GP2		

Student Questions

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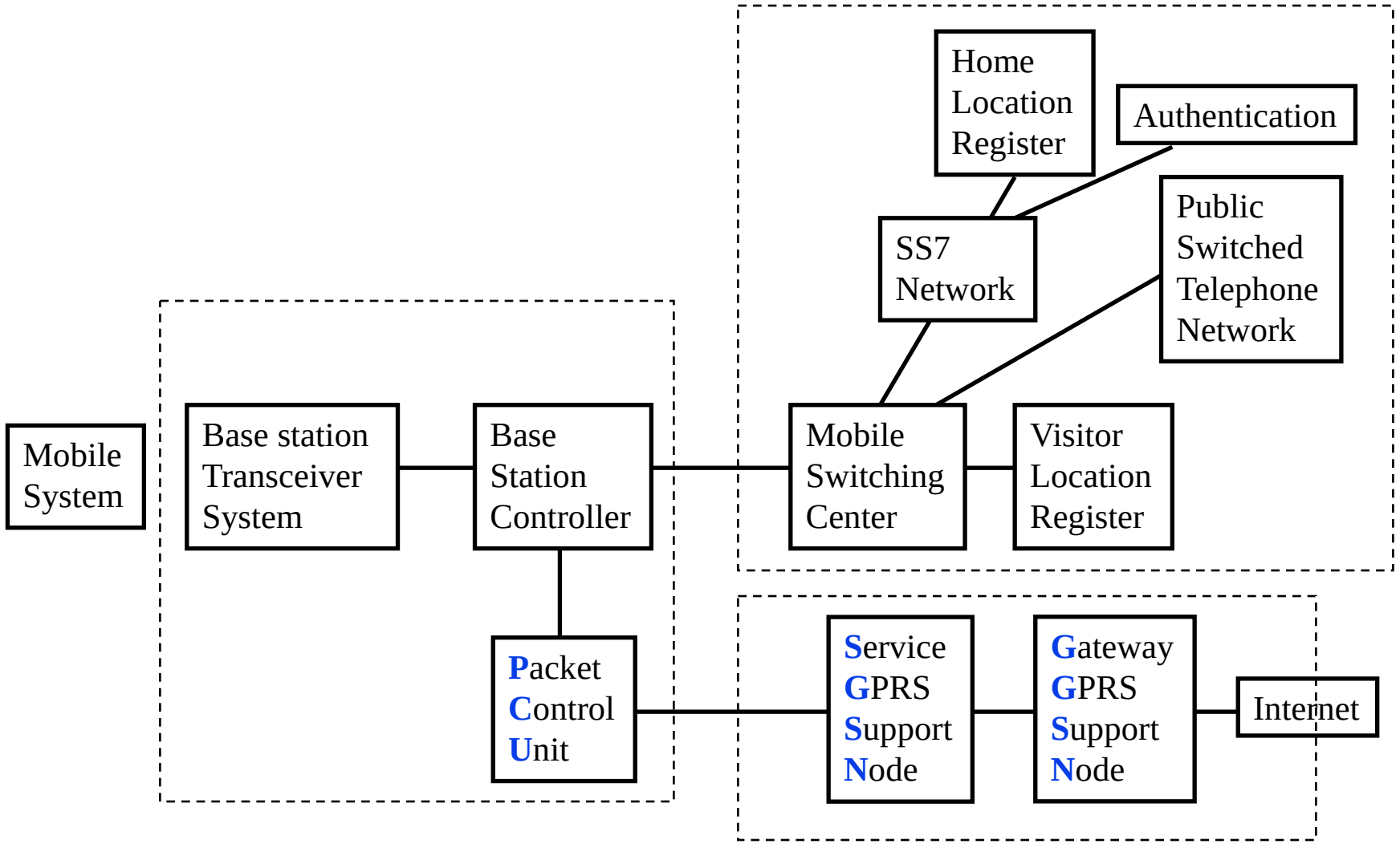
GPRS (Cont)

- Supports intermittent and bursty data transfers
  Point-to-multipoint also supported
- Need to add two new elements to GSM networks:
  - **Service** GPRS support node (SGSN)
    – Security, Mobility, and Access control for data packet
  - **Gateway** GPRS support node (GGSN)
    – Connects to external packet-switched networks
- Standardized by ETSI

Student Questions

GSM/GPRS Network Architecture



Ref: A. Ghosh, J. Zhang, J. G. Andrews, R. Muhamed, "Fundamentals of LTE," Prentice Hall, 2010, ISBN: 0137033117 464 pp. Safari book.

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EDGE

- **E**nhanced **D**ata Rates for **G**SM **E**volution (EDGE)
- Standard GSM uses Gaussian Minimum Shift Keying (GMSK) modulation.
  - Data stream is shaped with a Gaussian filter before frequency modulation
- EDGE changes to 8-PSK modulation ⇒ three bps/Hz
- GPRS+EDGE ⇒ 384 kbps
- Need better radio signal quality
- GSM-EDGE Radio Access Network (GERAN)

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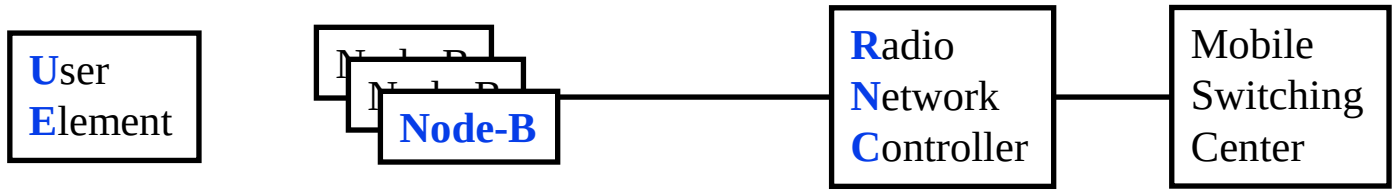
W-CDMA

- Wideband Code Division Multiple Access
- European 3G
- Aka Universal Mobile Telecommunications System (UMTS)
- Uses Direct Sequence Spread Spectrum over two 5 MHz FDD channels
- Radio access network is called "UMTS Terrestrial Radio Access Network (UTRAN)."
- Air interface is called "UMTS Terrestrial Radio Access (UTRA)."



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- What is Air interface?

Mobile-tower communication
= wireless communication
= Radio part of the system
as opposed to the central system

High-Speed Packet Access (HSPA)

- Evolution (extension) of W-CDMA
- High-Speed Downlink **Packet** Access (HSDPA):
  - Adaptive modulation and coding
  - Channel-dependent scheduling
  - Higher order modulations, e.g., 16-QAM
- High-Speed Uplink Packet Access (HSUPA):
  - Parallel transmissions from multiple users
- HSPA = HSDPA+HSUPA
  - Up to 64-QAM
- HSPA+: Evolution of HSPA. Up to 168 Mbps down, 22 Mbps up using MIMO and multiple carriers

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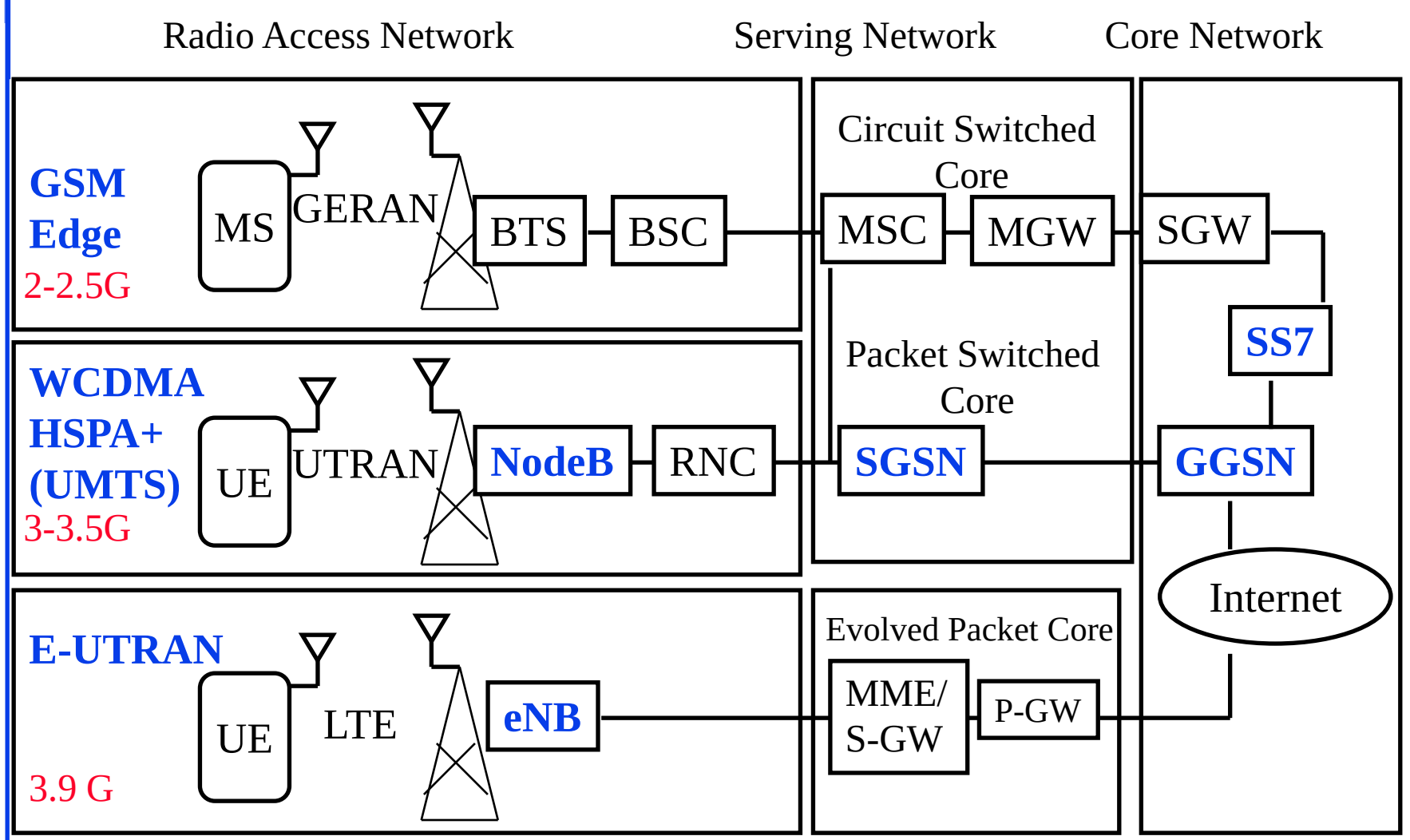
Evolved Packet System (EPS)



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Evolved Packet System (Cont)

- CS = Circuit Switched
- EPC = Evolved Packet Core
- EPS = Evolved Packet System
- GERAN = GSM Enhanced Radio Access Network
- GGSN = Gateway GPRS Support Node
- LTE = Long Term Evolution
- MGW = Media Gateway
- MME = Mobility Management Utility
- MSC = Mobile Switching Center
- P-GW = Packet Gateway
- PS = Packet Switched
- RNC = Radio Network Control
- S-GW = Serving Gateway
- SGSN = Service GPRS Support Node
- SS7 = Signaling System 7
- eNB = Evolved NodeB

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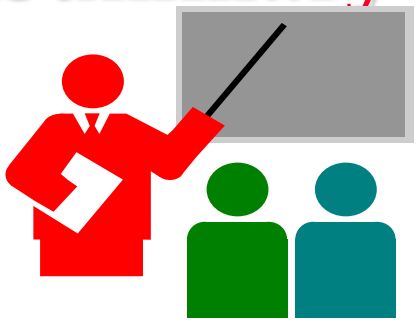
Summary



1. In a cellular cluster of size N, the same distance between cells with the same frequencies is R$\sqrt{3N}$. Here R is the cell radius.
2. 1G was an analog voice with FDMA
3. 2G was digital voice with TDMA. The most widely implemented 2G is GSM. GPRS and EDGE improved the data rate.
4. 3G was voice+data with CDMA. The most widely implemented 3G is W-CDMA using two 5 MHz FDD channels.
5. Data rate was improved later using HSPA and HSPA+.

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Reading List

- Martin Sauter, "From GSM to LTE-Advanced: An Introduction to Mobile Networks and Mobile Broadband, Revised Second Edition," John Wiley & Sons, August 2014, 456 pp., ISBN:978-1-118-86195-0 (Safari Book).
- C. Siva Ram Murthy; B. S. Manoj, "Ad Hoc Wireless Networks Architectures and Protocols," Prentice Hall, 2004, ISBN: 013147023X, 880 pp., Safari Book.

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Wikipedia Links

- http://en.wikipedia.org/wiki/Advanced_Mobile_Phone_System
- http://en.wikipedia.org/wiki/CDMA
- http://en.wikipedia.org/wiki/IS-2000
- http://en.wikipedia.org/wiki/IS-95
- http://en.wikipedia.org/wiki/W-CDMA
- http://en.wikipedia.org/wiki/Evolution-Data_Optimized
- http://en.wikipedia.org/wiki/EV-DV#Potential_competing_standards
- http://en.wikipedia.org/wiki/GSM
- http://en.wikipedia.org/wiki/GPRS
- http://en.wikipedia.org/wiki/EDGE
- http://en.wikipedia.org/wiki/Evolved_EDGE
- http://en.wikipedia.org/wiki/TD-SCDMA
- http://en.wikipedia.org/wiki/High_Speed_Packet_Access
- http://en.wikipedia.org/wiki/Ultra_Mobile_Broadband
- http://en.wikipedia.org/wiki/IMT-2000

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- P. Bedell, "Cellular Networks: Design and Operation, A real World Perspective," Outskirts Press, 2014, ISBN:9781478732082 (Good/easy reading but not a Safari book)
- 3G Americas, http://www.3gamericas.org
- 3G Americas," The mobile broadband revolution: 3GPP Release 8 and beyond, HSPA+, SAE/LTE and LTE-Advanced," White paper, February 2009.

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Acronyms

3GPP	3rd Generation Partnership Project
AMPS	Advanced Mobile Phone System
AuC	Authentication Center
BS	Base Station
BSC	Base Station Controller
BTS	Base transceiver station
CDMA	Code Division Multiple Access
CoW	Cell on Wheels
CS	Circuit Switched
DC	District of Columbia
DO	Data-Only
DV	Data+Voice
EDGE	Enhanced Data rate for GSM evolution
EIR	Equipment Identity Register
eNB	eNodeB
EPC	Evolved Packet Core

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Acronyms (Cont)

- EPS Evolved Packet System
- ETSI European Telecommunications Standards Institute
- EVDO Evolution to Data only
- EVDV Evolution to Data and voice
- FACCH Fast Associated Control Channel
- FDD Frequency Division Duplexing
- FDMA Frequency Division Multiple Access
- FEC Forward Error Correction
- GERAN GSM Enhanced Radio Access Network
- GGSN Gateway GPRS Support
- GMSK Gaussian Minimum Shift Keying
- GP GPRS user slot
- GPRS General Packet Radio Service
- GSM Global System for Mobile Communications
- GW Gateway
- HLR Home Location Register

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Acronyms (Cont)

- HS High Speed
- HSDPA High-speed Downlink Packet Access
- HSPA High-speed Packet Access
- HSPA+ Evolved High-speed Packet Access
- HSUPA High-Speed Uplink Packet Access
- IEEE Institution of Electrical and Electronic Engineers
- IMEI International Mobile Equipment Identity
- IMT-2000 International Mobile Communications 2000
- IMT-Advanced International Mobile Communications Advanced
- IP Internet Protocol
- IS International Standard
- kHz Kilo Hertz
- LTE Long-Term Evolution
- MGW Media Gateway
- MHz Mega Hertz
- MIMO Multiple Input Multiple Output
- MME Mobility Management Utility

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Acronyms (Cont)

MS	Mobile Station
MSA	Metropolitan Service Areas
MSC	Mobile Switching Center
NA-TDMA	North America Time Division Multiple Access
NA	North America
NIMBY	Not in my backyard
NodeB	Base Station
OFDMA	Orthogonal Frequency Division Multiple Access
PIN	Personal Identification Number
PS	Packet Switched
PSK	Phase Shift Keying
PSTN	Public Switched Telephone Network
QAM	Quadrature Amplitude Modulation
RNC	Radio Network Control
SACCH	Slow Associated Control Channel

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Acronyms (Cont)

- SCDMA Synchronous CDMA
- SGSN Service GPRS Support Node
- SGW Service Gateway
- SIM Subscriber Identify Module
- SMS Short Message Service
- SS7 Signaling System 7
- TACS Total Access Communications System
- TD-SCDMA Time Duplexed Synchronous Code Division Multiple Access
- TDMA Time Division Multiple Access
- UE User Element
- UMB Ultra Mobile Broadband
- UMTS Universal Mobile Telecommunications System
- UTRA UMTS Terrestrial Radio Access
- UTRAN UMTS Terrestrial Radio Access Network
- VLR Visitor Location Register
- VOIP Voice over IP

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Acronyms (Cont)

- WCDMA Wideband Code Division Multiple Access
- WiMAX Worldwide Interoperability for Microwave Access

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http://rajjain.com

http://www.cse.wustl.edu/~jain/cse574-22/j_16cel.htm

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Related Modules

CSE567M: Computer Systems Analysis (Spring 2013),
https://www.youtube.com/playlist?list=PLjGG94etKypJEKjNAa1n_1X0bWWNyZcof

CSE473S: Introduction to Computer Networks (Fall 2011),
https://www.youtube.com/playlist?list=PLjGG94etKypJWOSPMh8Azcgy5e_10TiDw

Recent Advances in Networking (Spring 2013),
https://www.youtube.com/playlist?list=PLjGG94etKypLHyBN8mOgwJLHD2FFIMGq5

CSE571S: Network Security (Fall 2011),
https://www.youtube.com/playlist?list=PLjGG94etKypKvzfVtutHcPFJXumyyg93u

Video Podcasts of Prof. Raj Jain's Lectures,
https://www.youtube.com/channel/UCN4-5wzNP9-ruOzQMs-8NUw

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