Wireless and Mobile Networks

Raj Jain
Washington University in Saint Louis
Saint Louis, MO 63130
Jain@wustl.edu

Audio/Video recordings of this lecture are available on-line at:
http://www.cse.wustl.edu/~jain/cse473-16/

Overview

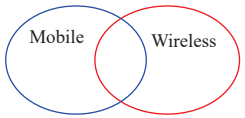
1. Wireless Link Characteristics
2. Wireless LANs and PANs
3. Cellular Networks
4. Mobility Management
5. Impact on Higher Layers

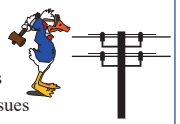
Note: This class lecture is based on Chapter 7 of the textbook (Kurose and Ross) and the figures provided by the authors.

Wireless Link Characteristics

- Mobile vs. Wireless
- Wireless Networking Challenges
- Peer-to-Peer or Base Stations?
- Code Division Multiple Access (CDMA)
  - Direct-Sequence Spread Spectrum
  - Frequency Hopping Spread Spectrum

Mobile vs Wireless

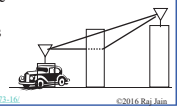




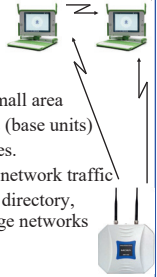
- Mobile vs Stationary
- Wireless vs Wired
- Wireless ⇒ media sharing issues
- Mobile ⇒ routing, addressing issues

Wireless Networking Challenges

1. Propagation Issues: Shadows, Multipath
2. Interference ⇒ High loss rate, Variable Channel
   ⇒ Retransmissions and Cross-layer optimizations
3. Transmitters and receivers moving at high speed
   ⇒ Doppler Shift
4. Low power transmission ⇒ Limited reach
   100mW in WiFi base station vs. 100 kW TV tower
5. License-Exempt spectrum ⇒ Media Access Control
6. Limited spectrum ⇒ Limited data rate
   Original WiFi (1997) was 2 Mbps.
   New standards allow up to 200 Mbps
7. No physical boundary ⇒ Security
8. Mobility ⇒ Seamless handover

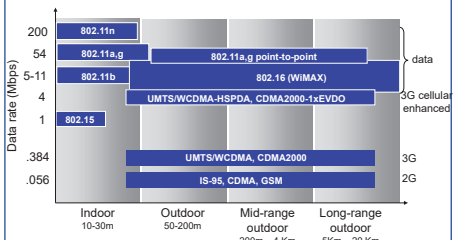


Peer-to-Peer or Base Stations?



- Ad-hoc (Autonomous) Group:
  - Two stations can communicate
  - All stations have the same logic
  - No infrastructure, Suitable for small area
- Infrastructure Based: Access points (base units)
  - Stations can be simpler than bases.
  - Base provide connection for off-network traffic
  - Base provides location tracking, directory, authentication ⇒ Scalable to large networks
- IEEE 802.11 provides both.

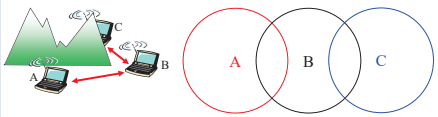
Characteristics of Selected Wireless Link Standards



Wireless Network Taxonomy

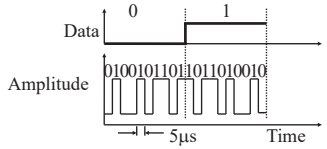
	Single hop	Multiple hops
Infrastructure (Access Points, Towers)	Host connects to base station (WiFi, WiMAX, cellular) which connects to larger Internet	Host may have to relay through several wireless nodes to connect to larger Internet: *Mesh net*
No Infrastructure	No base station (Bluetooth, ad hoc nets)	Relay to reach other a given wireless node. Mobile Ad-hoc Network (MANET), Vehicular Ad-hoc Network (VANET)

Hidden Node Problem



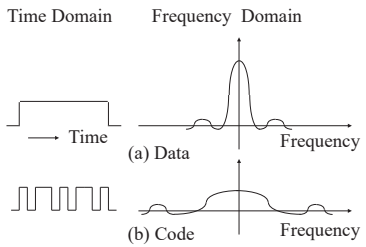
- B and A can hear each other
  B and C can hear each other
  A and C cannot hear each other
  ⇒ C is hidden for A and vice versa
- C may start transmitting while A is also transmitting
  A and C can't detect collision.
- Only the receiver can help avoid collisions

Direct-Sequence Spread Spectrum CDMA

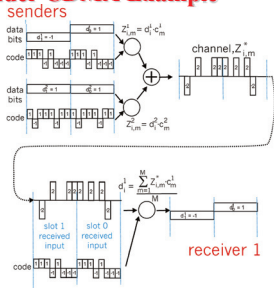


- Spreading factor = Code bits/data bit, 10-100 commercial (Min 10 by FCC), 10,000 for military
- Signal bandwidth >10 × data bandwidth
- Code sequence synchronization
- Correlation between codes ⇒Interference⇒ Orthogonal

DS Spectrum



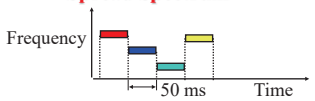
Two Sender CDMA Example



Homework 7A

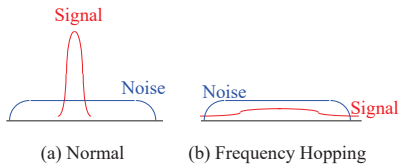
- Two CDMA sender use the codes of (1, -1, 1, -1) and (-1, 1, -1, 1). First sender transmits data bit 1 while the 2nd transmits –1 at the same time. What is the combined signal waveform seen by a receiver? Draw the waveform.

Frequency Hopping Spread Spectrum



- Pseudo-random frequency hopping
- Spreads the power over a wide spectrum
  ⇒ Spread Spectrum
- Developed initially for military
- Patented by actress Hedy Lamarr (1942)
- Narrowband interference can't jam

Spectrum



Review: Wireless Link Characteristics

1. Wireless is not the same as mobile.
   However, most mobile nodes are wireless.
2. Wireless signal is affected by shadows, multipath, interference, Doppler shift
3. A wireless network can be ad-hoc or infrastructure based.
4. Multi-hop ad-hoc networks are called MANET
5. It is not possible to do collision detection in wireless
6. Code division multiple access is commonly used in wireless

Ref: Section 7.2, Review Exercises R3-R4

Wireless LANs and PANs

- IEEE 802.11 Wireless LAN PHYs
- 4-Way Handshake
- IEEE 802.11 MAC
- 802.11 Frame Format
- 802.11 Frame Addressing
- 802.11 Rate Adaptation
- Power Management
- IEEE 802.15.4
- IEEE 802.15.4 MAC
- ZigBee Overview

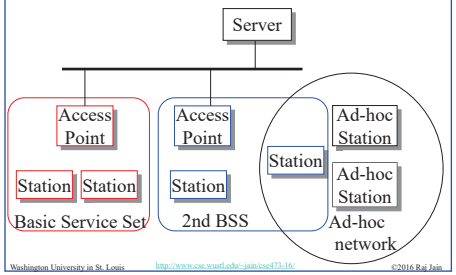
IEEE 802.11 Wireless LAN PHYs

- **802.11**: 2.4 GHz, 1-2 Mbps
- **802.11b**: 2.4 GHz, 11 Mbps nominal
  - Direct sequence spread spectrum (DSSS) in physical layer
  - All hosts use the same chipping code
- **802.11a**: 5.8 GHz band, 54 Mbps nominal
- **802.11g**: 2.4 GHz band, 54 Mbps nominal
- **802.11n**: 2.4 or 5.8 GHz, Multiple antennae, up to 200 Mbps
- These are different PHY layers. All have the same MAC layer.
- All use CSMA/CA for multiple access
- All have base-station and ad-hoc network versions
- Supports multiple priorities
- Supports time-critical and data traffic
- Power management allows a node to doze off

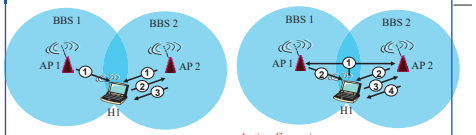
IEEE 802.11 MAC

- Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA)
- Listen before you talk. If the medium is busy, the transmitter backs off for a random period.
- Avoids collision by sending a short message: Ready to send (RTS)
  RTS contains dest. address and duration of message.
  Tells everyone to backoff for the duration.
- Destination sends: Clear to send (CTS)
- Can not detect collision ⇒ Each packet is acked.
- MAC level retransmission if not acked.

IEEE 802.11 Architecture



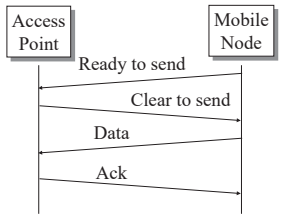
802.11: Passive/Active Scanning



Passive Scanning:
(1) Beacon frames sent from APs
(2) Association Request frame sent: H1 to selected AP
(3) Association Response frame sent: selected AP to H1

Active Scanning:
(1) **Probe Request** frame broadcast from H1
(2) Probes response frame sent from APs
(3) Association Request frame sent: H1 to selected AP
(4) Association Response frame sent: selected AP to H1

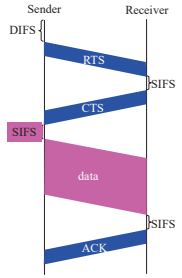
4-Way Handshake



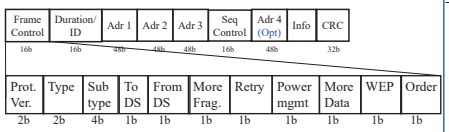
Architecture (Cont.)

- Basic Service Area (BSA) = Cell
- Each BSA may have several wireless LANs
- Extended Service Area (ESA) = Multiple BSAs interconnected via Access Points (AP)
- Basic Service Set (BSS)
  = Set of stations associated with an AP
- Extended Service Set (ESS)
  = Set of stations in an ESA
- Ad-hoc networks coexist and interoperate with infrastructure-based networks.

Transmission Example



Frame Format 16b



- Type: Control, management, or data
- Sub-Type: Association, disassociation, re-association, probe, authentication, de-authentication, CTS, RTS, Ack, …
- Retry/retransmission
- Going to Power Save mode
- More buffered data at AP for a station in power save mode
- Wireless Equivalent Privacy (Security) info in this frame
- Strict ordering

MAC Frame Fields

- **Duration/Connection ID**:
  - If used as duration field, indicates time (in µs) channel will be allocated for successful transmission of MAC frame. Includes time until the end of Ack
  - In some control frames, contains association or connection identifier
- **Sequence Control**:
  - 4-bit fragment number subfield
    - For fragmentation and reassembly
  - 12-bit sequence number
  - Number frames between given transmitter and receiver

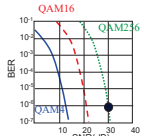
Lab 7

Download the Wireshark traces from
http://gaia.cs.umass.edu/wireshark-labs/wireshark-traces.zip

Open *Wireshark_802_11.pcap* in Wireshark. Select **View → Expand All**. Answer the following questions. There is no need to attach screen captures.

1. Frame 1 is a beacon frame. Ignore the first 24 bytes. (The frame control field is 80:00.) What is the SSID of the access point that is issuing this beacon frame?
2. What (in hexadecimal notation) is the source MAC address on Frame 1.
3. What (in hexadecimal notation) is the destination MAC address on the Frame 1?
4. What (in hexadecimal notation) is the MAC BSS ID in Frame 1?
5. Frame 50 is a Probe Request and Frame 51 is a Probe response. What are the sender, receiver and BSS ID MAC addresses in these frames? What is the purpose of these two types of frames?

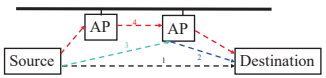
802.11 Rate Adaptation



- Base station and mobile dynamically change transmission rate (physical layer modulation technique) as mobile moves, SNR varies
- SNR decreases ⇒BER increase as node moves away from base station
- When BER becomes too high, switch to lower transmission rate but with lower BER

802.11 Frame Address Fields

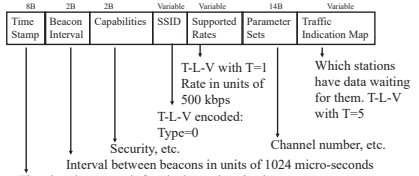
- All stations filter on "Address 1"



	To Distribution System	From Distribution System	Address 1	Address 2	Address 3	Address 4
1	0	0	Destination Address	Source Address	BSS ID	-
2	0	1	Destination Address	BSS ID	Source Address	-
3	1	0	BSS ID	Source Address	Destination Address	-
4	1	1	Receiver Address	Transmitter Address	Destination Address	Source Address

Beacon Frame Format

- Info field in the 802.11 frame (after Address 4)



Ref: Nayarasi, "802.11 Mgmt: Beacon Frame," https://mrncciew.com/2014/10/08/802-11-mgmt-beacon-frame/

Power Management

- A station can be in one of three states:
  - Transmitter on
  - Receiver only on
  - Dozing: Both transmitter and receivers off.
- Access point (AP) buffers traffic for dozing stations.
- AP announces which stations have frames buffered. Traffic indication map included in each beacon. All multicasts/broadcasts are buffered.
- Dozing stations wake up to listen to the beacon. If there is data waiting for it, the station sends a poll frame to get the data.

Bluetooth

- Started with Ericsson's Bluetooth Project in 1994
- Named after Danish king Herald Blatand (AD 940-981) who was fond of blueberries
- Radio-frequency communication between cell phones over short distances
- IEEE 802.15.1 approved in early 2002 is based on Bluetooth
- Key Features:
  - Lower Power: 10 µA in standby, 50 mA while transmitting
  - Cheap: $5 per device
- A piconet consists of a master and several slaves. Master determines the timing and polls slaves for transmission.
- Frequency hopping spread spectrum

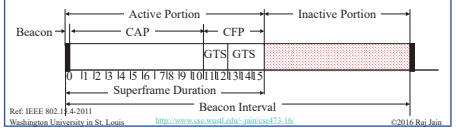
IEEE 802.15.4

- Low Rate Wireless Personal Area Network (LR-WPAN)
- Used by several "Internet of Things" protocols: ZigBee, 6LowPAN, Wireless HART, MiWi, and ISA 100.11a
- Lower rate, short distance ⇒ Lower power ⇒ Low energy

IEEE 802.15.4 MAC

Beacon-Enabled CSMA/CA

- Coordinator sends out beacons periodically
- Part of the beacon interval is inactive ⇒ Everyone sleeps
- Active interval consists of 16 slots
- Contention Access Period (CAP). Slotted CSMA.
- Contention Free Period (CFP)
  - Guaranteed Transmission Services (GTS): For real-time services. Periodic reserved slots.

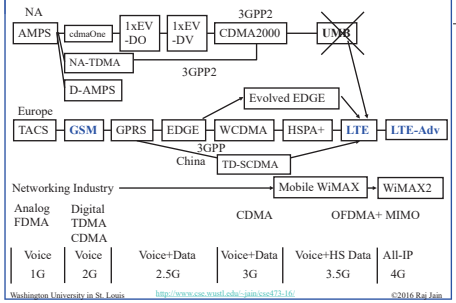


Ref: IEEE 802.15.4-2011

Cellular Networks

- Evolution of Cellular Technologies
- GSM Cellular Architecture
- Evolved Packet System (EPS)

Cellular Telephony Generations



ZigBee Overview

- Industrial monitoring and control applications requiring small amounts of data, turned off most of the time (<1% duty cycle), e.g., wireless light switches, meter reading
- Ultra-low power, low-data rate, multi-year battery life
- **Range**: 1 to 100 m, up to 65000 nodes.
- IEEE 802.15.4 MAC and PHY. Higher layer, interoperability by ZigBee Alliance
- Named after zigzag dance of the honeybees Direction of the dance indicates location of food
- Multi-hop ad-hoc mesh network

Multi-Hop Routing: message to non-adjacent nodes
Ad-hoc Topology: No fixed topology. Nodes discover each other
Mesh Routing: End-nodes help route messages for others
Mesh Topology: Loops possible

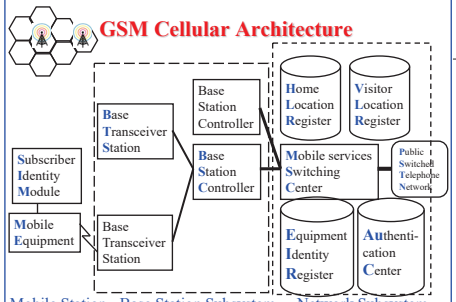
Ref: ZigBee Alliance, http://www.ZigBee.org

Review: Wireless LANs and PANs

1. IEEE 802.11 PHYs: 11, 11b, 11g, 11a, 11n, …
2. IEEE 802.11 MAC uses CSMA/CA with a 4-way handshake: RTS, CTS, data, and ack
3. IEEE 802.11 network consists of ESS consisting of multiple BSSs each with an AP.
4. 802.11 Frame Format may have up to 4 addresses and includes final destination's MAC which may not be wireless
5. Power management allows stations to sleep.
6. Bluetooth uses frequency hopping spread spectrum
7. IEEE 802.15.4 PHY layer allows coordinators to schedule transmissions of other nodes
8. ZigBee uses IEEE 802.15.4

Ref: Section 7.3, Review Exercises R5-R13

GSM Cellular Architecture



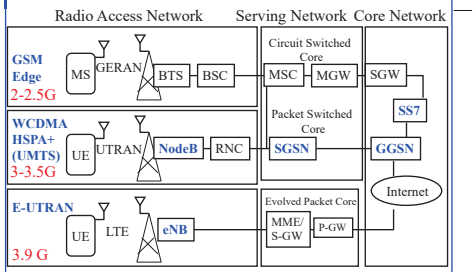
Cellular Architecture (Cont.)

- Base station controller (BSC) and Base transceiver station (BTS)
- One BTS per cell.
- One 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, authentication. Contains Equipment Identity Register.

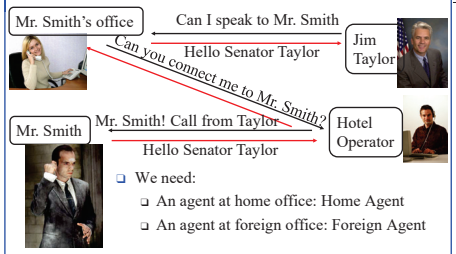
Cellular Architecture (Cont.)

- Home Location Register (HLR) and Visitor Location Register (VLR) provide 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 a International Mobile Equipment Identity (IMEI) number.

Evolved Packet System (EPS)

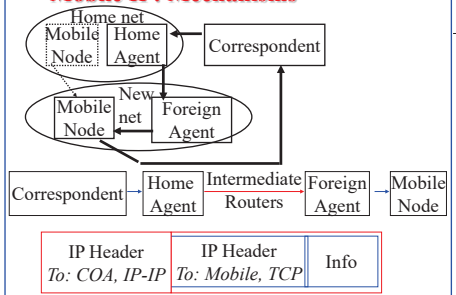


Mobility: Mr. Smith Goes to Washington



- We need:
  - An agent at home office: Home Agent
  - An agent at foreign office: Foreign Agent

Mobile IP: Mechanisms



Review: Cellular Networks

1. 1G was Analog voice, 2G was Digital voice, 3G was CDMA with voice and high-speed data, 4G is high-speed data
2. A cellular system has a RAN with BTS, BSC and a network subsystem with HLR, VLR, MSC, EIR, and AuC
3. 3G replaced RAN with GERAN and BTS with NodeB. 4G uses eNB.

Ref: Section 7.4, Review Exercises R14-R17

Mobility Management

- Mobile IP
- GSM: Routing to Mobile
- GSM Handoff
- Mobility: GSM versus Mobile IP

Mechanism (Cont.)

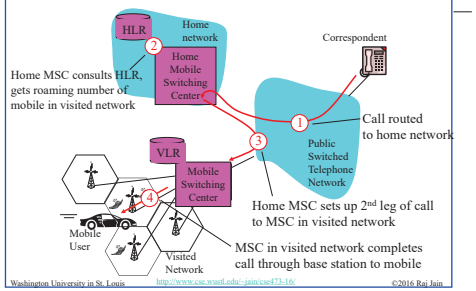
- Mobile node finds foreign agents via solicitation or advertising
- Mobile registers with the foreign agents and informs the home agent
- Home agent intercepts mobile node's datagrams and forwards them to the care-of-address
- Care-of-address (COA): Address of the end-of-tunnel towards the mobile node. May or may not be foreign agent
- At COA, datagram is extracted and sent to mobile

Homework 7B

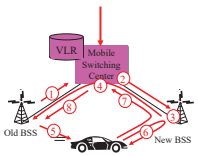
- Suppose an 802.11b station is configured to always reserve the channel with the RTS/CTS sequence. Suppose this station suddenly wants to transmit 1,000 bytes of data, and all other stations are idle at this time. Using SIFS of 10us and DIFS of 50us, and ignoring propagation delay and assuming no bit errors, calculate the time required to transmit the frame and receive the acknowledgment. Assume a frame without data (RTS/CTS/Ack) is 32 bytes long and the transmission rate is 11 Mbps.

Ref: Problem P7

GSM: Routing to Mobile



GSM: Handoff with Common MSC



1. Old BSS informs MSC of impending handoff, provides list of 1^+ new BSSs
2. MSC sets up path (allocates resources) to new BSS
3. New BSS allocates radio channel for use by mobile
4. New BSS signals MSC, old BSS: ready
5. Old BSS tells mobile: perform handoff to new BSS
6. Mobile, new BSS signal to activate new channel
7. Mobile signals via new BSS to MSC: handoff complete. MSC reroutes call
8 MSC-old-BSS resources released

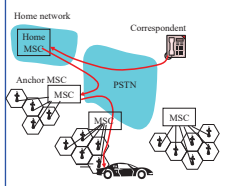
Impact on Higher Layer Protocols

- Layered Architecture ⇒ Upper layers are independent of lower layers
- Wireless ⇒ High error rate ⇒ Frequent packet losses ⇒ Triggers TCP congestion control even if no overload
- TCP modifications:
  - Local Recovery: Link level retransmissions and error correction
  - Wireless-aware TCP Sender: Distinguish overload (sustained) and random errors
  - Split-Connection: Host1-to-AP + AP-to-Host2

Summary

1. Code division multiple access "was" commonly used in wireless networks
2. IEEE 802.11 uses CSMA/CA with RTS, CTS, data, and ack. A frame may have up to 4 addresses.
3. Bluetooth and ZigBee are PANs that use very little energy
4. Cellular networks have evolved from analog voice to digital voice and finally to high-speed data.
5. Mobile IP uses home agents as anchors.
6. Cellular networks use MSCs to manage mobility.
7. Frequency packet losses due to error may confuse TCP as network congestion.

GSM: Handoff between MSCs



- *Anchor MSC:* first MSC visited during call
  - Call remains routed through anchor MSC
- New MSCs add on to end of MSC chain as mobile moves to new MSC
- IS-41 allows optional path minimization step to shorten multi-MSC chain

Review: Mobility Management

- Mobile IP uses Home Agent as an Anchor Packets are tunneled from Home Agent to Care-of-Address
- GSM uses HLR and VLR for mobility. All packets are routed through home network
- Handoff between towers in a single network is done through MSC

Ref: Sections 7.6 and 7.7, Review Exercises R18-R20

Acronyms

1xEV-DO	1 times Evolution to Data Only
1xEV-DV	1 times Evolution to Data and Voice
3GPP1	3rd Generation Partnership Project
6LowPAN	IPv6 over Low Power Personal Area Networks
ACK	Acknowledgement
AMPS	Advanced Mobile Phone System
AP	Access Point
BER	Bit Error Rate
BSA	Basic Service Area
BSC	Base station controller
BSS	ID Basic Service Set Identifier
BTS	Base transceiver station
CA	Collision Avoidance
CAP	Contention Access Period
CDMA	Code Division Multiple Access
CEPT	Committee of European Posts and Telecom

Acronyms (Cont)

CFP	Contention Free Period
COA	Care-Of-Address
CRC	Cyclic Redundancy Check
CSMA	Carrier Sense Multiple Access
CTS	Clear to Transmit
D-AMPS	Digital Advanced Mobile Phone System
dB	Deci-Bel
DCN	Data Communication Network
DHCP	Dynamic Host Control Protocol
DIFS	Distributed Inter-Frame Spacing
DSSS	Direct Sequence Spread Spectrum
E-UTRAN	Evolved UTRAN
EDGE	Enhanced Data rate for GSM evolution
EGPRS	Enhanced GPRS
EIA	Electronic Industry Association
EIR	Equipment Identity Register

Acronyms (Cont)

eNB	evolved Node B
ESA	Extended Service Area
ESS	Extended Service Set
FCC	Federal Communications Commission
FDMA	Frequency Division Multiple Access
GERAN	GSM Enhanced Radio Access Network
GGSN	Gateway GPRS Support Node
GHz	Giga-Hertz
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
GTS	Guaranteed Transmission Service
GW	Gateway
HART	Highway Addressable Remote Transducer Protocol
HLR	Home Location Register
HSPA	High Speed Packet Access
HSPDA	High Speed Packet Download Access

Acronyms (Cont)

ID	Identifier
IEEE	Institution of Electrical and Electronics Engineers
IFS	Inter-frame space
IMEI	International Mobile Equipment Identity
IP	Internet Protocol
IS	International Standard
ISA	International Society of Automation
ISDN	Integrated Switched Digital Network
kW	Kilo-Watt
LAN	Local Area Network
LR	Long-Range
LTE	Long-Term Evolution
mA	Milli-Ampere
MAC	Media Access Control
MANET	Mobile Ad-hoc Network
MGW	Media Gateway

Acronyms (Cont)

TIA	Telecom Industry Association
TV	Television
UE	User Element
UK	United Kingdom
UMB	Ultra Mobile Broadband
UMTS	Universal Mobile Telecommunications System
UTRAN	UMTS Terrestrial Radio Access Network
VANET	Vehicular Ad-hoc Network
VLR	Visitor Location Register
WCDMA	Wide-band CDMA
WEP	Wired Equivalend Privacy
WiFi	Wireless Fidelity
WPAN	Wireless Personal Area Network

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Acronyms (Cont)

MHz	Mega Hertz
MIMO	Multiple Input Multiple Output
MME	Mobility Management Entity
MS	Mobile Subscriber
MSC	Mobile Switching Center
mW	Milli-Watt
NA	North America
NAT	Network Address Translator
NodeB	Node B (Base Station)
PAN	Personal Area Network
PC	Personal Computer
PHY	Physical Layer
PIFS	Point-Coordination Inter-Frame Spacing
PSTN	Public Switched Telephone Network
QAM	Quadrature Amplitude Modulation

Acronyms (Cont)

RAN	Radio Access Network
RNC	Radio Network Controller
RTS	Ready to send
SCDMA	Synchronous CDMA
SGSN	Service GPRS Support Node
SGW	Serving Gateway
SIFS	Short Inter-Frame Spacing
SIM	Subscriber Identification Module
SNR	Signal to Noise Ratio
SS7	Signaling System 7
SSID	Service Set Identifier
SYN	Synchronizing Frame
TACS	Total Access Communications System
TCP	Transmission Control Protocol
TD-SCDMA	Time Duplexed Synchronous Code Division Multiple Access
TDMA	Time Division Multiple Access

Related Modules

CSE 473s: Introduction to Computer Networks (Course Overview), http://www.cse.wustl.edu/~jain/cse473-16/ftp/i_0int.pdf

CSE473S: Introduction to Computer Networks (Fall 2016), http://www.cse.wustl.edu/~jain/cse473-16/index.html

Wireless and Mobile Networking (Spring 2016), http://www.cse.wustl.edu/~jain/cse574-16/index.html

CSE571S: Network Security (Fall 2014), http://www.cse.wustl.edu/~jain/cse571-14/index.html

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