18-452/18-750
Wireless Networks and Applications
Lecture 16: LTE

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http://www.cs.cmu.edu/~prs/wirelessS20/

Evolution of Cellular Wireless Systems

GSM Multiple Access Example

- Combination of FDMA and TDMA
  - More on this later
- 890-915 MHz for uplink
- 935-960 MHz for downlink
- Each of those 25 MHz bands is subdivided into 124 single carrier channel of 200 KHz
  - Each with a data rate of 270.833 kbps
- In each uplink/downlink band there is a 200 KHz guard band
- Each 200 KHz channel carries 8 TDMA channels

Additional GSM Features

- GSM uses GMSK modulation
  - Gaussian Minimum Shift Keying
  - Optimized version of Frequency Shift Keying (FM)
- Slow frequency hopping: successive TDMA frames are sent over a different frequency
  - Switches every 4.615 msec
  - Spreads out effect of multipath fading
  - Also helps with co-channel interference
- Delay equalization
  - Mobile stations sharing a frame can be at different distances from the base station
  - Tail bits and guard bits provide margin to avoid overlap
Generalized Packet Radio Service (GPRS)

- Packet-oriented data transport service
  - Bursty, non-periodic traffic typical for Internet access
- Uses a new architecture for data traffic
  - Allows users to open a persistent data connection
  - Sending data traffic over a voice connection would add too much setup and teardown overhead
- Uses the same frame structure as voice
  - 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
  - Enhanced Data Rates for GSM Evolution (EDGE) further increased rates using a more aggressive PHY

GPRS Architecture

- Network Subsystem includes several new entities:
  - Serving GPRS Support Node (SGSN): data transfer between Base Station and Network Subsystem
  - Gateway GPRS Support Node: connects to other GPRS networks and the packet data network (Internet)
  - New interfaces between the various entities
- Transmission plane
  - Data packets are transmitted by a tunnel mechanisms
- Control plane
  - Protocol for tunnel management: create, remove, ...
  - GPRS Tunnel Protocol
- Radio interface
  - Changes the logical channels and how they are managed

GPRS Architecture Diagram

GPRS Radio Interface Diagram
Evolution of Cellular Wireless Systems

<table>
<thead>
<tr>
<th>Generation</th>
<th>1G</th>
<th>2G</th>
<th>2.5G</th>
<th>3G</th>
<th>3.5G</th>
<th>4G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (kbps)</td>
<td>≤33.36</td>
<td>3.1–44.14</td>
<td>64–164.14</td>
<td>144 000–2 180</td>
<td>≤144 000</td>
<td>&gt;140 Mbps</td>
</tr>
</tbody>
</table>

Who is Who

- **International Telecommunications Union (ITU)** - agency of the United Nations responsible for:
  - Assisting in the development and coordination of worldwide standards
  - Coordinate shared use of the global spectrum
  - Defined the International Mobile Telecommunications 2000 (IMT-2000) project for 3G telecommunications

- **Third Generation Partnership Project (3GPP)**
  - A group of telecommunications associations that represent large markets worldwide
  - Defined a group of 3G standards as part of the IMT-2000 framework in 1999
  - Originally defined GSM, EDGE, and GPRS
  - Later defined follow-on releases and also LTE (4G)

UMTS and WCDMA

- Part of a group of 3G standards defined as part of the IMT-2000 framework by 3GPP
- **Universal Mobile Telecommunications System (UMTS)**
  - Successor of GSM
- **W-CDMA** is the air interface for UMTS
  - Wide-band CDMA
  - Originally 144 kbps to 2 Mbps, depending on mobility
- Basically same architecture as GSM
  - Many GSM functions were carried over WCDMA
  - But they changed all the names!

Reminder: CDMA - Direct Sequence Spread Spectrum

These signals will look like noise to the receiver
Later Releases Improved Performance

- High Speed Downlink Packet Access (HSDPA): 1.8 to 14.4 Mbps downlink
  » Adaptive modulation and coding, hybrid ARQ, and fast scheduling
- High Speed Uplink Packet Access (HSUPA): Uplink rates up to 5.76 Mbps
- High Speed Packet Access Plus (HSPA+):
  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
- Eventually led to the definition of LTE

Advantages of CDMA for Cellular systems

- 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

Mobile Wireless CDMA Soft Hand-off

- Soft Handoff – mobile station temporarily connected to more than one base station simultaneously
- Requires that the mobile acquire a new cell before it relinquishes the old
- More complex than hard handoff used in FDMA and TDMA schemes

Evolution of Cellular Wireless Systems
Overview LTE

- Motivation
- Architecture
- Resource management
- LTE protocols
- Radio access network
  - OFDM refresher
- LTE advanced

Purpose, motivation, and approach to 4G

- Defined by ITU directives for International Mobile Telecommunications Advanced (IMT-Advanced)
- All-IP packet switched network.
- Ultra-mobile broadband access
- Peak data rates
  - Up to 100 Mbps for high-mobility mobile access
  - Up to 1 Gbps for low-mobility access
- Dynamically share and use network resources
- Smooth handovers across heterogeneous networks
  - 2G and 3G networks, small cells such as picocells, femtocells, and relays, and WLANs
- High quality of service for multimedia applications

High Level Features

- No support for circuit-switched voice
  - Instead providing Voice over LTE (VoLTE)
- Replace spread spectrum/CDMA with OFDM

<table>
<thead>
<tr>
<th>Technology</th>
<th>1G</th>
<th>2G</th>
<th>2.5G</th>
<th>3G</th>
<th>4G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Services</td>
<td>Analog voice</td>
<td>Digital voice</td>
<td>Higher capacity packetized data</td>
<td>Higher capacity, broadband</td>
<td>Completely IP based</td>
</tr>
<tr>
<td>Data rate</td>
<td>56 kbps</td>
<td>14.4 kbps</td>
<td>384 kbps</td>
<td>2 Mbps</td>
<td>200 Mbps</td>
</tr>
<tr>
<td>Multiplexing</td>
<td>FDMA</td>
<td>TDMA, CDMA</td>
<td>TDMA, CDMA</td>
<td>CDMA</td>
<td>OFDMA, SC-FDMA</td>
</tr>
<tr>
<td>Core network</td>
<td>PSTN</td>
<td>PSTN</td>
<td>PSTN, packet network</td>
<td>Packet network</td>
<td>IP backbone</td>
</tr>
</tbody>
</table>

LTE Architecture

- evolved NodeB (eNodeB)
  - Most devices connect into the network through the eNodeB
- Evolution of the previous 3GPP NodeB (~2G BTS)
  - Uses OFDM instead of CDMA
- Has its own control functionality
  - Dropped the Radio Network Controller (RNC - ~2G BSC)
  - eNodeB supports radio resource control, admission control, and mobility management (handover)
  - Was originally the responsibility of the RNC
Evolved Packet System

- Overall architecture is called the Evolved Packet System (EPS)
- 3GPP standards divide the network into
- Radio access network (RAN): cell towers and connectives to mobile devices
- Core network (CN): management and connectivity to other networks
- Each can evolve independently
  » Driven by different technologies: optimizing spectrum use versus management and control or traffic

Evolved Packet System Components

- Long Term Evolution (LTE) is the RAN
  » Called Evolved UMTS Terrestrial Radio Access (E-UTRA)
  » Enhancement of 3GPP’s 3G RAN
  » eNodeB is the only logical node in the E-UTRAN
  » No Radio Network Controller (RNC)
- Evolved Packet Core (EPC)
  » Operator or carrier core network – core of the system
  » Traditionally circuit switched but now entirely packet switched
    » Based on IP - Voice supported using voice over IP (VoIP)

Design Principles of the EPS

- Packet-switched transport for traffic belonging to all QoS classes
  » Voice, streaming, real-time, non-real-time, background
- Comprehensive radio resource management
  » End-to-end QoS, transport for higher layers
  » Load sharing/balancing
  » Policy management across different radio access technologies
- Integration with existing 3GPP 2G and 3G networks
- Scalable bandwidth from 1.4 MHz to 20 MHz
- Carrier aggregation for overall bandwidths up to 100 MHz

Evolved Packet Core Components

- Mobility Management Entity (MME)
  » Supports user equipment context, identity, authentication, and authorization
- Serving Gateway (SGW)
  » Receives and sends packets between the eNodeB and the core network
- Packet Data Network Gateway (PGW)
  » Connects the EPC with external networks
- Home Subscriber Server (HSS)
  » Database of user-related and subscriber-related information
- Interfaces
  » S1 interface between the E-UTRAN and the EPC
    » For both control purposes and for user plane data traffic
  » X2 interface for eNodeBs to interact with each other
    » Again for both control purposes and for user plane data traffic
Overview

- Motivation
- Architecture
- Resource management
- LTE protocols
- Radio access network
  » OFDM refresher
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Some slides based on material from
"Wireless Communication Networks and Systems"

LTE Resource Management

- LTE uses bearers for quality of service (QoS) control instead of circuits
- EPS bearers
  » Between entire path between PGW and UE
  » Maps to specific QoS parameters such as data rate, delay, and packet error rate
- Service Data Flows (SDFs) differentiate traffic flowing between applications on a client and a service
  » SDFs must be mapped to EPS bearers for QoS treatment
  » SDFs allow traffic types to be given different treatment
- End-to-end service is not completely controlled by LTE

Bearer Management based on QoS Class Identifier (QCI)

<table>
<thead>
<tr>
<th>QCI Type</th>
<th>GBR</th>
<th>No GBR</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCI Value</td>
<td>Priority</td>
<td>Packet Delay Budget</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>100 ms</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>150 ms</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>50 ms</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>300 ms</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>100 ms</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>300 ms</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>100 ms</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>300 ms</td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td>300 ms</td>
</tr>
</tbody>
</table>

* QCI value typically used for the default bearer

Guaranteed (minimum) Bit Rate

- Guaranteed
- No Guarantees

EPC: Mobility Management

- X2 interface used when moving within a RAN coordinated under the same Memory Management Entity (MME)
- S1 interface used to move to another MME
- Hard handovers are used: A UE is connected to only one eNodeB at a time

Some slides based on material from
"Wireless Communication Networks and Systems"
EPC: Inter-cell Interference Coordination (ICIC)

- Reduces interference when the same frequency is used in a neighboring cell
- Goal is universal frequency reuse
  - \( N = 1 \) in “Cellular principles” lecture
  - Must avoid interference when mobile devices are near each other at cell edges
  - Interference randomization, cancellation, coordination, and avoidance are used
- eNodeBs send indicators
  - Relative Narrowband Transmit Power, High Interference, and Overload indicators
- Later releases of LTE have improved interference control
  - “Cloud RAN”: use a cloud to manage interference, spectrum

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Protocol Layers End-to-End

Fancy L2 for Mobile to cell tower Communication in EPC

Protocol Layers PDCP and RLC

- Packet Data Convergence Protocol (PDCP)
  - Delivers packets from UE to eNodeB
  - Involves header compression, ciphering, integrity protection, in-sequence delivery, buffering and forwarding of packets during handover
- Radio Link Control (RLC)
  - Segments or concatenates data units
  - Performs ARQ when MAC layer H-ARQ fails
    - ARQ: Automatic Repeat Request (retransmission)
    - H-ARQ: Hybrid ARQ – combines FEC and ARQ
Protocol Layers
MAC and PHY

• **Medium Access Control (MAC)**
  - Performs H-ARQ: combines FEC and retransmission (ARQ)
  - Prioritizes and decides which UEs and radio bearers will send or receive data on which shared physical resources
  - Decides the transmission format, i.e., the modulation format, code rate, MIMO rank, and power level

• **Physical layer actually transmits the data**