Evolution of Cellular Wireless Systems

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 world-wide
  » 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

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

- 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
**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

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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</th>
<th>Resource Type</th>
<th>Priority</th>
<th>Packet Delay Budget</th>
<th>Packet Error Loss Rate</th>
<th>Example Services</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>GBR</td>
<td>2</td>
<td>100 ms</td>
<td>10^(-3)</td>
<td>Conversational Voice</td>
</tr>
<tr>
<td>2</td>
<td>GBR</td>
<td>4</td>
<td>150 ms</td>
<td>10^(-3)</td>
<td>Conversational Video (live streaming)</td>
</tr>
<tr>
<td>3</td>
<td>GBR</td>
<td>3</td>
<td>50 ms</td>
<td>10^(-3)</td>
<td>Real-Time Gaming</td>
</tr>
<tr>
<td>4</td>
<td>Non-GBR</td>
<td>5</td>
<td>300 ms</td>
<td>10^(-3)</td>
<td>Non-Conversational Video (buffered streaming)</td>
</tr>
<tr>
<td>5</td>
<td>Non-GBR</td>
<td>1</td>
<td>100 ms</td>
<td>10^(-4)</td>
<td>IMS Signalling</td>
</tr>
<tr>
<td>6</td>
<td>Non-GBR</td>
<td>6</td>
<td>300 ms</td>
<td>10^(-4)</td>
<td>Video (buffered streaming)</td>
</tr>
<tr>
<td>7</td>
<td>Non-GBR</td>
<td>7</td>
<td>100 ms</td>
<td>10^(-3)</td>
<td>Voice, Video (live streaming)</td>
</tr>
<tr>
<td>8</td>
<td>Non-GBR</td>
<td>8</td>
<td></td>
<td></td>
<td>Video (buffered streaming)</td>
</tr>
<tr>
<td>9</td>
<td>Non-GBR</td>
<td>9</td>
<td>300 ms</td>
<td>10^(-4)</td>
<td>Video (buffered streaming)</td>
</tr>
</tbody>
</table>

* QCI value typically used for the default bearer

Guaranteed (minimum) Bit Rate

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

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

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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

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Different Solution for Up and Downlink

- The downlink uses OFDM with Multiple Access (OFDMA)
  - Multiplexes multiple mobiles on the same subcarrier
  - Improved flexibility in bandwidth management, e.g., multiple low bandwidth users can share subcarriers
  - Enables per-user frequency hopping to mitigate effects of narrowband fading
- The uplink uses Single Carrier OFDM (SC-OFDM)
  - OFDM but using a single carrier
  - Provides better energy and cost efficiency for battery-operated mobiles
  - Large number of subcarriers leads to high peak-to-average Power ratio (PAPR), which is energy-inefficient

LTE Radio Access Network

- LTE uses both TDD and FDD
  - Both have been widely deployed
- Time Division Duplexing (TDD)
  - Uplink and downlink transmit in the same frequency band, but alternating in the time domain
- Frequency Division Duplexing (FDD)
  - Different frequency bands for uplink and downlink
- LTE uses two cyclic prefixes (CPs)
  - Extended CP is for worse environments

Spectrum Allocation for FDD and TDD

- TDD
- FDD

Resource Blocks

- A time-frequency grid is used to illustrate allocation of physical resources
- Each column is 6 or 7 OFDM symbols per slot
- Each row corresponds to a subcarrier of 15 kHz
  - Some subcarriers are used for guard bands
  - 10% of bandwidth is used for guard bands for channel bandwidths of 3 MHz and above

FDD Frame Structure

- Resource Block
  - 12 subcarriers, 6 or 7 OFDM symbols
  - Results in 72 or 84 resource elements in a resource block
- MIMO: 4×4 in LTE, 8×8 in LTE-Advanced
  - Separate resource grids per antenna port
- eNodeB assigns RBs with channel-dependent scheduling
  - Multiuser diversity can be exploited
    - To increase bandwidth usage efficiency
    - Assign resource blocks for UEs with favorable qualities on certain time slots and subcarriers
    - Can also consider fairness, QoS priorities, typical channel conditions, ..

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**LTE-Advanced**

- Carrier aggregation – up to 100 MHz
- MIMO enhancements to support higher dimensional MIMO – up to 8 x 8
- Relay nodes
- Heterogeneous networks involving small cells such as femtocells, picocells, and relays
- Cooperative multipoint transmission and enhanced intercell interference coordination
- Voice over LTE

**Comparison LTE and LTE-Advanced**

<table>
<thead>
<tr>
<th>System Performance</th>
<th>LTE</th>
<th>LTE-Advanced</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Peak rate</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Downlink</td>
<td>100 Mbps @20 MHz</td>
<td>1 Gbps @100 MHz</td>
</tr>
<tr>
<td>Uplink</td>
<td>50 Mbps @20 MHz</td>
<td>500 Mbps @100 MHz</td>
</tr>
<tr>
<td><strong>Control plane delay</strong></td>
<td>Idle to connected</td>
<td>&lt;100 ms</td>
</tr>
<tr>
<td></td>
<td>Dormant to active</td>
<td>&lt;50 ms</td>
</tr>
<tr>
<td><strong>User plane delay</strong></td>
<td>&lt; 5ms</td>
<td>Lower than LTE</td>
</tr>
<tr>
<td><strong>Spectral efficiency (peak)</strong></td>
<td>Downlink</td>
<td>5 bps/Hz @2x2</td>
</tr>
<tr>
<td></td>
<td>Uplink</td>
<td>2.5 bps/Hz @1x2</td>
</tr>
<tr>
<td><strong>Mobility</strong></td>
<td>Up to 350 km/h</td>
<td>Up to 350—500 km/h</td>
</tr>
</tbody>
</table>

**Relaying**

- Relay nodes (RNs) extend the coverage area of an eNodeB
  - Receive, demodulate and decode the data from a UE
  - Apply error correction as needed
  - Transmit a new signal to the base station
- An RN functions as a new base station with smaller cell radius
- RNs can use out-of-band or inband frequencies

**Heterogeneous Networks**

- It is increasingly difficult to meet data transmission demands in densely populated areas
- **Small cells** provide low-powered access nodes
  - Operate in licensed or unlicensed spectrum
  - Range of 10 m to several hundred meters indoors or outdoors
  - Best for low speed or stationary users
- **Macro cells** provide typical cellular coverage
  - Range of several kilometers
  - Best for highly mobile users
Heterogeneous Network Examples

- Femtocell
  - Low-power, short-range self-contained base station
  - In residential homes, easily deployed and use the home’s broadband for backhaul
  - Also in enterprise or metropolitan locations
- Network densification is the process of using small cells
  - Issues: Handovers, frequency reuse, QoS, security
- A network of large and small cells is called a heterogeneous network (HetNet)

Trends

- Cloud RAN optimizes spectrum use
  - Goal is to reuse frequencies very aggressively
  - Leverage cloud technology to centralize the processing for many cells
- Standards are complex and rigid and need to support several generations
  - E.g., switch seamlessly from 4G to 3G
  - Still need to support 2G (legacy phones, voice)
- Scalability of infrastructure wrt signaling traffic is a growing concern
  - Hardware cannot keep up with changes in usage
- Wide-spread use of custom hardware
  - Move to commodity, programmable equipment

5G Vision

Faster 4G

Growing application domains

Performance Goals ITU

https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.2083-0-201509-I!!PDF-E.pdf
5G technology

- Goal is 10+ fold increase in bandwidth over 4G
  - Combination of more spectrum and more aggressive use of 4G technologies
- Very aggressive use of MIMO
  - Tens to hundred antennas
  - Very fine grain beamforming and MU-MIMO
- More spectrum: use of millimeter bands
  - Challenging but a lot of spectrum available
  - Bands between 26 and 60 GHz
  - Beamforming extends range
- Also new lower frequency bands
  - Low-band and mid-band 5G: 600 MHz to 6 GHz