18-759: Wireless Networks
Lecture 19: LTE

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Overview

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

Some slides based on material from
“Wireless Communication Networks and Systems”

4G Technology

- High-speed, universally accessible wireless service capability
- Creating a revolution
  » Networking at all locations for tablets, smartphones, computers, and other devices
  » Similar to the revolution caused by Wi-Fi
- Our focus is LTE and LTE-Advanced
  » Goals and requirements, complete system architecture, core network (Evolved Packet System), LTE channel and physical layer
  » Will first study LTE Release 8, then enhancements from Releases 9-12

Purpose, motivation, and approach to 4G

- Ultra-mobile broadband access
  » For a variety of mobile devices
- International Telecommunication Union (ITU) 4G directives for IMT-Advanced
  » All-IP packet switched network.
  » 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, including 2G and 3G networks, small cells such as picocells, femtocells, and relays, and WLANs
  » High quality of service for multimedia applications
High Level Context

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

<table>
<thead>
<tr>
<th>Technology</th>
<th>4G</th>
<th>3G</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 packet data</td>
<td>Higher capacity, (crowded)</td>
<td>Completely IP based</td>
</tr>
<tr>
<td>Data rate</td>
<td>9.6 kbps</td>
<td>14.4 kbps</td>
<td>384 kbps</td>
<td>2 Mbps</td>
<td>20 Mbps</td>
</tr>
<tr>
<td>Multiplexing</td>
<td>FDMA</td>
<td>TDMA, CDMA</td>
<td>TDMA, CDMA</td>
<td>CDMA</td>
<td>OFDMA, OFDMA</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

- Two candidates for 4G
  » IEEE 802.16 WiMax (described in Chapter 16)
    – Enhancement of previous fixed wireless standard for mobility
  » Long Term Evolution
    – Third Generation Partnership Project (3GPP)
    – Consortium of Asian, European, and North American telecommunications standards organizations
- Both are similar in use of OFDM and OFDMA
- LTE has become the universal standard for 4G
  » All major carriers in the United States
  » WiMax is now mostly for fixed backhaul, last mile in rural areas, …

3G versus 4G

WiMAX vs. LTE

Discussion

- WiMAX first to market
- WiMAX is IEEE standard – equipment cheaper
  » E.g., more emphasis on TDD, which is easier
- LTE out of GSM, with a great install base already!
- All 3GPP operators already have spectrum that can be used for LTE – not true for WiMAX
- 802.16m (in 2009) comparable speeds to 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>Peak rate</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>Control plane delay</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Idle to connected</td>
<td>&lt;100 ms</td>
<td>&lt; 50 ms</td>
</tr>
<tr>
<td>Dormant to active</td>
<td>&lt;50 ms</td>
<td>&lt; 10 ms</td>
</tr>
<tr>
<td>User plane delay</td>
<td>&lt; 5 ms</td>
<td>Lower than LTE</td>
</tr>
<tr>
<td>Spectral efficiency (peak)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Downlink</td>
<td>5 bps/Hz @ 2x2</td>
<td>30 bps/Hz @ 8x8</td>
</tr>
<tr>
<td>Uplink</td>
<td>2.5 bps/Hz @ 1x2</td>
<td>15 bps/Hz @ 4x4</td>
</tr>
<tr>
<td>Mobility</td>
<td>Up to 350 km/h</td>
<td>Up to 350...500 km/h</td>
</tr>
</tbody>
</table>

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Evolved Packet System

- Overall architecture is called the Evolved Packet System (EPS)
- 3GPP standards divide the network into
  - Radio access network (RAN)
  - Core network (CN)
- Each evolve independently.
- Long Term Evolution (LTE) is the RAN
  - Called Evolved UMTS Terrestrial Radio Access (E-UTRA)
  - Enhancement of 3GPP’s 3G RAN
    - Called the Evolved UMTS Terrestrial Radio Access Network (E-UTRAN)
  - eNodeB is the only logical node in the E-UTRAN
  - No RNC

Some slides based on material from
“Wireless Communication Networks and Systems”
Evolved Packet System

- 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)
- Some of the design principles of the EPS
  - Packet-switched transport for traffic belonging to all QoS classes including conversational, streaming, real-time, non-real-time, and background
  - 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

EPS Functions

- Network access control, including network selection, authentication, authorization, admission control, policy and charging, and lawful interception
- Packet routing and transfer
- Security, including ciphering, integrity protection, and network interface physical link protection
- Mobility management to keep track of the current location of the UE
- Radio resource management to assign, reassign, and release radio resources taking into account single and multi-cell aspects
- Network management (operation and maintenance)
- IP networking functions, connections of eNodeBs, E-UTRAN sharing, emergency session support, etc.

EPC 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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LTE Resource Management

- LTE uses **bearers** for quality of service (QoS) control instead of circuits
- **EPS bearers**
  - 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**

<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></td>
<td>4</td>
<td>150 ms</td>
<td>10^-3</td>
<td>Conversational Video (live streaming)</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>5</td>
<td>200 ms</td>
<td>10^-3</td>
<td>Real-Time Gaming</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>1</td>
<td>300 ms</td>
<td>10^-6</td>
<td>Non-Conversational Video (buffered streaming)</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>1</td>
<td>100 ms</td>
<td>10^-3</td>
<td>IMS Signaling</td>
</tr>
<tr>
<td>6</td>
<td>Non-GBR</td>
<td>6</td>
<td>300 ms</td>
<td>10^-6</td>
<td>Video (buffered streaming)</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>7</td>
<td>100 ms</td>
<td>10^-3</td>
<td>Video (live streaming)</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>8</td>
<td>300 ms</td>
<td>10^-3</td>
<td>Interactive Gaming</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>9</td>
<td>300 ms</td>
<td>10^-3</td>
<td>Video (buffered streaming)</td>
</tr>
</tbody>
</table>

- * QCI value typically used for the default bearer

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**Classes of bearers**

- **Guaranteed Bit Rate (GBR) bearers**
  - Guaranteed a minimum bit rate
  - And possibly higher bit rates if system resources are available
  - Useful for voice, interactive video, or real-time gaming
- **Non-GBR (GBR) bearers**
  - Not guaranteed a minimum bit rate
  - Performance is more dependent on the number of UEs served by the eNodeB and the system load
  - Useful for e-mail, file transfer, Web browsing, and P2P file sharing.
Bearer management

- Each QCI is given standard forwarding treatments
  - Scheduling policy, admission thresholds, rate-shaping policy, queue management thresholds, and link layer protocol configuration
- For each bearer the following information is associated
  - QoS class identifier (QCI) value
  - Allocation and Retention Priority (ARP): Used to decide if a bearer request should be accepted or rejected
- Additionally for GBR bearers
  - Guaranteed Bit Rate (GBR): minimum rate expected from the network
  - Maximum Bit Rate (MBR): bit rate not to be exceeded from the UE into the bearer

EPC: Mobility Management

- X2 interface used when moving within a RAN coordinated under the same 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 UEs 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”

LTE Radio Interface Protocols

- Control Plane
- User Plane
- RRC
- FDCP
- EIC
- MAC
- PHY
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Protocol Layers

- Radio Resource Control (RRC)
  - Performs control plane functions to control radio resources
  - Through RRC_IDLE and RRC_CONNECTED connection states

- 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

Protocol Layers

- Radio Link Control (RLC)
  - Segments or concatenates data units
  - Performs ARQ when MAC layer H-ARQ fails

- Medium Access Control (MAC)
  - Performs H-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

Protocol Layers End-to-End
**LTE Channel Structure uses Three Types of Channels**

- **Channels provide services to the layers above**
  - **Logical channels**
    - Provide services from the MAC layer to the RLC
    - Provide a logical connection for control and traffic
  - **Transport channels**
    - Provide PHY layer services to the MAC layer
    - Define modulation, coding, and antenna configurations
  - **Physical channels**
    - Define time and frequency resources to carry information to the upper layers

**Different types of broadcast, multicast, paging, and shared channels**

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**LTE Radio Access Network**

- **LTE uses MIMO and OFDM**
  - OFDMA on the downlink
  - SC-OFDM on the uplink, which provides better energy and cost efficiency for battery-operated mobiles
- **LTE uses subcarriers 15 kHz apart**
  - Maximum FFT size is 2048
  - Basic time unit is $T_s = 1/(15000\times2048) = 1/30,720,000$ seconds.
  - Downlink and uplink are organized into *radio frames*
    - Duration 10 ms., which corresponds to $307200T_s$.

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**Why OFDM?**

- **Benefits of CDMA carry over**
  - Better immunity to fading as only a small portion of the energy for any one link is typically lost due to a fade
  - Fast power control to keep the noise floor as low as possible
- **Additional advantages**
  - Highly resistant to fading and inter-symbol interference
  - Modulation is applied at a much lower rate on each of the many sub-carriers
  - Sophisticated error correction
  - Scales rates easier than CDMA
  - Allows more advanced antenna technologies, like MIMO
- **Breaks information into pieces and assigns each one to a specific set of sub-carriers**
OFDM Key Points

- OFDM signals best described in the frequency domain with information carried in the amplitude and the phase
  - Conversion to the time domain through Inverse Fast Fourier Transform (IFFT)
  - Demodulation through Fast Fourier Transform (FFT)
- Guard interval protects against inter-symbol interference caused by multi-path reception over path delays up to the length of the guard interval
  - Guard interval is a cyclic prefix (CP in LTE)
  - A copy of the end of a symbol is added at the beginning
  - Helps fight multipath

Robustness to ISI

If time-sampling of the symbol is within the useful part, equalizers can take care of the path delay and the second path can be combined with the first to increase the probability of correct reception

Other benefits

- OFDM channel equalizers are much simpler to implement than are CDMA equalizers as the OFDM signal is represented in the frequency domain rather than the time domain
- OFDM is better suited to MIMO. The frequency domain representation of the signal enables easy pre-coding to match the signal to frequency and phase characteristics of the multipath radio channel
OFDM disadvantages

- As the number of sub-carriers increases, the composite time-domain signal starts to look like Gaussian noise, which has high peak-to-average Power ratio (PAPR)
- Avoiding distortion requires increases in cost, size and power consumption
- To minimize the lost efficiency due to the cyclic prefix, desire to have long symbols, which means closely spaced subcarriers
  - Increase in processing overhead
  - Subcarriers start losing their orthogonality due to frequency errors
  - Causes problems such as leaking of energy, doppler shift

SC-FDMA and OFDMA

- High PAPR led to SC-FDMA for uplink
  - Applies linear precoding to the signal
  - Reduces PAPR, which helps the mobile terminal in terms of power efficiency and complexity
- OFDMA is the LTE OFDM elaboration
- Increases system flexibility by multiplexing multiple users onto the same subcarriers – efficient trunking of low-rate users onto a shared channel
- Enables per-user frequency hopping to mitigate effects of narrowband fading

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)
  - Normal CP = \( 144 \times T_s = 4.7 \, \mu s \).
  - Extended CP = \( 512 \times T_s = 16.7 \, \mu s \).
    - For worse environments
Spectrum Allocation for FDD and TDD

FDD Frame Structure

TDD Frame Structure

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
Resource Blocks

- **Resource Block**
  - 12 subcarriers
  - 6 or 7 OFDM symbols
  - Results in 72 or 84 resource elements in a resource block (RB)
- For the uplink, contiguous frequencies must be used for the 12 subcarriers
  - Called a physical resource block
- For the downlink, frequencies need not be contiguous
  - Called a virtual 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, ..

Physical transmission

- **Release 8 supports up to 4×4 MIMO**
- The eNodeB uses the Physical Downlink Control Channel (PDCCH) to communicate
  - Resource block allocations
  - Timing advances for synchronization
- **Two types of ⅓ rate convolutional codes**
- QPSK, 16QAM, and 64QAM modulation based on channel conditions

- UE determines a CQI index that will provide the highest throughput while maintaining at most a 10% block error rate
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LTE-Advanced

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

Carrier Aggregation

- Ultimate goal of LTE-Advanced is 100 MHz bandwidth
  - Combine up to 5 component carriers (CCs)
  - Each CC can be 1.4, 3, 5, 10, 15, or 20 MHz
  - Up to 100 MHz
- Three approaches to combine CCs
  - Intra-band Contiguous: carriers adjacent to each other
  - Intra-band noncontiguous: Multiple CCs belonging to the same band are used in a noncontiguous manner
  - Inter-band noncontiguous: Use different bands

Enhanced MIMO

- Expanded to 8 × 8 for 8 parallel layers
- Or multi-user MIMO can allow up to 4 mobiles to receive signals simultaneously
  - eNodeB can switch between single user and multi-user every subframe
- Downlink reference signals to measure channels are key to MIMO functionality
  - UEs recommend MIMO, precoding, modulation, and coding schemes
  - Reference signals sent on dynamically assigned subframes and resource blocks
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 networks

- 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)

Coordinated Multipoint Transmission and Reception

- Release 8 provides intercell interference coordination (ICIC)
  - Small cells create new interference problems
  - Release 10 provides enhanced ICIC to manage this interference
- Release 11 implemented Coordinated Multipoint Transmission and Reception (CoMP)
  - To control scheduling across distributed antennas and cells
  - Coordinated scheduling/coordinated beamforming (CS/CB) steers antenna beam nulls and mainlobes
  - Joint processing (JT) transmits data simultaneously from multiple transmission points to the same UE
  - Dynamic point selection (DPS) transmits from multiple transmission points but only one at a time
### Other Enhancements in LTE-Advanced

- Traffic offload techniques to divert traffic onto non-LTE networks
- Adjustable capacity and interference coordination
- Enhancements for machine-type communications
- Support for dynamic adaptation of TDD configuration so traffic fluctuations can be accommodated

### Voice over LTE

- The GSM Association is the cellular industry’s main trade association
  - GSM Association documents provide additional specifications for issues that 3GPP specifications left as implementation options.
- Defined profiles and services for Voice over LTE (VoLTE)
- Uses the IP Multimedia Subsystem (IMS) to control delivery of voice over IP streams
  - IMS is not part of LTE, but a separate network
  - IMS is mainly concerned with signaling.
- The GSM Association also specifies services beyond voice, such as video calls, instant messaging, chat, and file transfer in what is known as the Rich Communication Services (RCS).