4G TECHNOLOGY : LTE
(LONG TERM EVOLUTION)

CS-1699 Wireless Networks
Term : Spring 2018

Instructor : Xerandy
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
PURPOSE, MOTIVATION, AND APPROACH TO 4G

• No support for circuit-switched voice
  – Instead providing Voice over LTE (VoLTE)

• Replace spread spectrum with OFDM

Table 14.1 Wireless Network Generations

<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>1.9 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>
4G TECHNOLOGY

• 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
14.1 THIRD VS. FOURTH GENERATION CELLULAR NETWORKS

(a) Third Generation (3G) Cellular Network

(b) Fourth Generation (4G) Cellular Network
LTE ARCHITECTURE

• Some features started in the 3G era for 3GPP
• Initial LTE data rates were similar to 3G
• 3GPP Release 8
  – *Clean slate* approach
  – Completely new air interface
    • OFDM, OFDMA, MIMO
• 3GPP Release 10
  – Known as *LTE-Advanced*
  – Further enhanced by Releases 11 and 12
Table 14.2 Comparison of Performance Requirements for 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></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><strong>User plane delay</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt; 5ms</td>
<td>Lower than LTE</td>
</tr>
<tr>
<td><strong>Spectral efficiency</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(peak)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Downlink</td>
<td>5 bps/Hz @2×2</td>
<td>30 bps/Hz @8×8</td>
</tr>
<tr>
<td>Uplink</td>
<td>2.5 bps/Hz @1×2</td>
<td>15 bps/Hz @4×4</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>
14.2 OVERVIEW OF THE EPC/LTE ARCHITECTURE

eNodeB = evolved NodeB
HSS = Home subscriber server
MME = Mobility Management Entity
PGW = Packet data network (PDN) gateway
RN = relay node
SGW = serving gateway
S1 = interface between E-UTRAN and EPC
S1-MME = S1 interface to MME
S1-U = S1 interface to User Equipment (UE)
S5/S8 = S5 and S8 interface
S6a = S6a interface
X2 = interface between eNodeBs

Internet

UE

eNodeB

MME

HSS

SGW

PGW

LTE E-UTRAN

Evolved Packet Core (EPC)

data traffic

control traffic
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
EVOLVED PACKET SYSTEM

- Evolved Packet Core (EPC)
  - Operator or carrier core network
  - It is important to understand the EPC to know the full functionality of the architecture

- Some of the design principles of the EPS
  - Clean slate design
  - Packet-switched transport for traffic belonging to all QoS classes including conversational, streaming, real-time, non-real-time, and background
  - Radio resource management for the following: end-to-end QoS, transport for higher layers, load sharing/balancing, policy management/enforcement 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
FUNCTIONS OF THE EPS

- Network access control, including network selection, authentication, authorization, admission control, policy and charging enforcement, 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 to support operation and maintenance
- IP networking functions, connections of eNodeBs, E-UTRAN sharing, emergency session support, among others
LTE ARCHITECTURE

• evolved NodeB (eNodeB)
  – Most devices connect into the network through the eNodeB

• Evolution of the previous 3GPP NodeB
  – Now based on OFDMA instead of CDMA
  – Has its own control functionality, rather than using the Radio Network Controller (RNC)
    • eNodeB supports radio resource control, admission control, and mobility management
    • Originally the responsibility of the RNC
**EVOLVED PACKET CORE**

- Traditionally circuit switched but now entirely packet switched
  - Based on IP
  - Voice supported using voice over IP (VoIP)
- Core network was first called the *System Architecture Evolution (SAE)*
EPC COMPONENTS

- Mobility Management Entity (MME)
  - Supports user equipment context, identity, authentication, and authorization
  - Mainly perform Non Access Stratum procedures, which consist of two main groups
    - Functions related to bearer management (EPS Session Management)
      - Bearer can be seen as a logical communication tunnel
    - Functions related to connection management (EPS Mobility Management)
- Serving Gateway (SGW)
  - Receives and sends packets between the eNodeB and the core network
  - Perform packet routing and forwarding within EPC
  - Anchor point for intra LTE-mobility
  - Lawful intercept
- Packet Data Network Gateway (PGW)
  - Connects the EPC with external networks
  - A router that performs UE IP assignment, per user packet filtering
  - Anchor point for mobility with non 3GPP access network
  - Lawful intercept
EPC COMPONENTS

• Home Subscriber Server (HSS)
  – Database of user-related and subscriber-related information
  – Similar to HLR in GSM architecture

• Interfaces
  – S1 interface between the E-UTRAN and the EPC
    • For both control purposes (connect MME to eNodeB) and for user plane data traffic (connect SGW to eNodeB)
  – S5/S8 connects MME with PGW
  – S11 connects SGW with MME
E-UTRAN : ACCESS NETWORK

• Mainly consist of eNodeB
• Runs protocol known as Access Stratum Protocol (AS)
• An interface X2 interconnects between eNodeB
  – Consist of two type : X2 control and X2 user
• Main functions
  – Radio resource management : related to the radio bearer such as radio bearer control, radio mobility control, scheduling and dynamic allocation of radio resource at uplink and downlink
  – Header compression
  – Security
  – Connectivity to EPC
LTE RESOURCE MANAGEMENT

• LTE uses *bearers* for quality of service (QoS) control instead of circuits
  – QoS is discussed in Chapter 3
• 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
14.3 LTE QOS BEARERS
LTE RESOURCE MANAGEMENT: 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.
LTE RESOURCE MANAGEMENT: BEARER MANAGEMENT

• Each bearer is given a QoS class identifier (QCI)

Table 14.3 Standardized QCI characteristics

<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>$10^{-2}$</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>3</td>
<td>50 ms</td>
<td>$10^{-3}$</td>
<td>Real Time Gaming</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>5</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>$10^{-6}$</td>
<td>IMS Signalling</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) TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>7</td>
<td>100 ms</td>
<td>$10^{-3}$</td>
<td>Voice, Video (live streaming) Interactive Gaming</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>8</td>
<td></td>
<td></td>
<td>Video (buffered streaming) TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>9</td>
<td>300 ms</td>
<td>$10^{-6}$</td>
<td></td>
</tr>
</tbody>
</table>

* QCI value typically used for the default bearer
LTE RESOURCE MANAGEMENT: 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
LTE RESOURCE MANAGEMENT:
BEARER MANAGEMENT

• 3GPP additionally defines groups of bearers
  – UE-Aggregate Maximum Bit Rate (UE-AMBR): upper limit on the aggregate bit rate across all non GBR bearers for a UE, enforced by eNodeB
  – APN-Aggregate Maximum Bit Rate( APN-AMBR): Upper limit on the aggregate bit rate across all non GBR bearers over all packet data network connections in the same network

• When UE connect to the EPS, a persistent, default bearer connection is established through the life time of the connection

• User plane transports IP packets between PGW and UE
  – In EPC, it is tunneled using GPRS tunneling protocol (GTP)
  – From eNodeB to UE, it is tunneled by Packet Data Convergence Protocol (PDCP)
LTE RESOURCE MANAGEMENT: ICIC

• Inter-cell interference coordination (ICIC)
  – Reduces interference when the same frequency is used in a neighboring cell
  – Goal is universal frequency reuse ($N = 1$ from Chapter 13)
    • 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
MOBILITY MANAGEMENT

- LTE Release 8, hand-overs are hard handover
- Interface S1 and X2 can be used for mobility management
- S1 mobility
  - Preparation:
    - Decision has been made for handover and the destination MME and eNodeB have been identified
    - MME sends handover request to destination eNodeB
    - MME sends handover command to UE
  - Execution:
    - UE performs RAN procedures for the handover
    - Involving eNodeB’s exchange relevant data for handover.
  - Completion:
    - Target eNodeB notifies MME
    - MME direct source eNodeB to release the resources that has been used by the UE
MOBILITY MANAGEMENT

- **X2 mobility**
  - **Preparation:**
    - Source eNodeB sends handover request to destination eNodeB
    - Destination eNodeB works with MME and SGW to establish resources for the UE
  - **Execution:**
    - Source eNodeB signals the UE
    - The UE performs RAN procedures for handover
    - Data exchanges between involving eNodeB
  - **Completion:**
    - UE sends handoff complete message to MME and SGW.
    - SGW switch GTP tunnel to the destination eNodeB
    - Destination eNodeB asks source eNodeB to release the resource for the UE
To determine handover decisions, the following information might be included:

- Radio link quality, UE capability, call type, QoS requirements, and policy-related aspects.
  - The Reference Signal Received Power (RSCP) indicates radio link quality for a connection in an LTE cell.
  - UE prepares a measurement report that contains the RSCP for the neighboring eNodeBs.
  - The serving eNodeB provides the list of eNodeBs as requested by the UE.
RADIO ACCESS NETWORK PROCEDURE FOR MOBILITY

– Handover between eNodeBs in the same EPC can be triggered by 5 events:
  • Event A1: Serving cell radio link quality goes above an absolute threshold
  • Event A2: Serving cell radio link quality goes below an absolute threshold
  • Event A3: A neighbor cell radio link quality becomes better by an amount relative to the serving cell
  • Event A4: A neighbor cell radio link quality goes above an absolute threshold
  • Event A5: Serving cell radio link quality goes below an absolute threshold and a neighbor radio link quality goes above an different absolute threshold

– E-UTRAN uses a TimeToTrigger parameter which determines how these events must be satisfied
NON-ACCESS STRATUM PROTOCOLS

• For interaction between the EPC and the UE
  – Not part of the Access Stratum that carries data

• EPS Mobility Management (EMM)
  – Manage the mobility of the UE

• EPS Session Management (ESM)
  – Activate, authenticate, modify, and de-activate user-plane channels for connections between the UE, SGW, and PGW
14.2 OVERVIEW OF THE EPC/LTE ARCHITECTURE
LTE CHANNEL STRUCTURE AND PROTOCOLS

• LTE radio interface is divided
  – Control Plane
  – User Plane

• User plane protocols
  – Part of the Access Stratum
  – Transport packets between UE and PGW
  – PDCP transports packets between UE and eNodeB on the radio interface (Fig. 14.4)
  – GTP sends packets through the other interfaces (Fig. 14.5)

• Control plane protocols
  – Part of Non-Access Stratum (NAS) for communication between MME and UE
  – Deals with mobility management, call setup, security functions between UE and MME
LAYERED COMMUNICATION PROTOCOLS

• When a communication process takes place, it actually establishes several logical connection functions between sender and receiver.
14.4 LTE RADIO INTERFACE PROTOCOLS
14.6 CONTROL PLANE PROTOCOL STACK
CONTROL PLANE PROTOCOL

• NAS (Non Access Stratum)
  – Mobility management, call setup, security functions between UE and MME

• Radio Resource Control (RRC)
  – Performs control plane functions to control radio resources
  – Important aspects of RRC:
    • Connection states : RRC_IDLE and RRC_CONNECTED connection states
    • Signaling Radio Bearers (SRB): Radio bearer to transmit RRC and NAS messages
    • System Control Information : Master Information Block and System Information Block
      – MIB and SIB contains essential information that UE needs to know about a cell characteristics
14.5 USER PLANE PROTOCOL STACK
USER AND CONTROL PLANE

• 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
  – One PDCP instance per bearer

• Radio Link Control (RLC)
  – Segments or concatenates data units
  – Performs ARQ when MAC layer H-ARQ fails
  – RLC operation modes:
    • Transparent mode (TM): No header with no RLC functions for segmentation or concatenation. Used for broadcast and paging message, not for user plane data transmission
    • Unacknowledged Mode (UM): Provides in-sequence delivery of data, no retransmission
    • Acknowledged Mode (AM): Best for error sensitive application
SEGMENTATION AND CONCATENATION

- IP
  - IP
  - UDP
  - Payload
  - IP
  - UDP
  - Payload
- PDCP
  - H
  - PDCP
  - PDCP SDU
  - PDCP
  - PDCP SDU
- RLC
  - RLC SDU
  - Segmentation
  - Concatenation
  - RLC
  - RLC SDU
- MAC
  - MAC SDU
  - MAC
  - MAC SDU
**USER AND CONTROL PLANE**

- **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
LTE CHANNEL STRUCTURE

• Three types of channels
  – Channels provide services to the layers above
  – Defined at the Service Access Points between protocol layer
  – Type of channels
    • 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 use to carry information to the upper layers
  • Different types of broadcast, multicast, paging, and shared channels
14.8 RADIO INTERFACE ARCHITECTURE AND SAPS

- **PHY**
- **MAC**
  - Scheduling transport format selection, H-ARQ retransmission
- **MAC**
  - H-ARQ, multiplexing
- **RLC**
  - Segmentation/Concatenation, ARQ, in-sequence delivery
- **PDCP**
  - Header compression, ciphering

Logical Channels

Transport Channels