18-452/18-750
Wireless Networks and Applications
Lecture 17: LTE

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http://www.cs.cmu.edu/~prs/wirelessS18/

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"

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

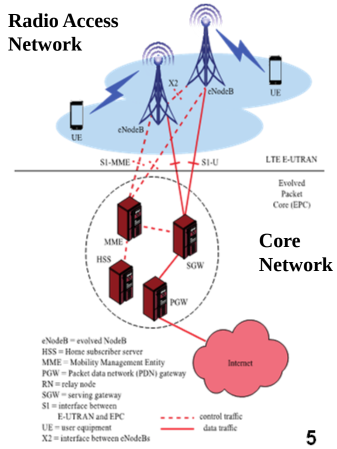
High Level Features

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

Technology	1G	2G	2.5G	3G	4G
Design began	1970	1980	1985	1990	2000
Implementation	1984	1991	1999	2002	2012
Services	Analog voice	Digital voice	Higher capacity packetized data	Higher capacity, broadband	Completely IP based
Data rate	1.9. kbps	14.4 kbps	384 kbps	2 Mbps	200 Mbps
Multiplexing	FDMA	TDMA, CDMA	TDMA, CDMA	CDMA	OFDMA, SC-FDMA
Core network	PSTN	PSTN	PSTN, packet network	Packet network	IP backbone

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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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)

QCI	Resource Type	Priority	Packet Delay Budget	Packet Error Loss Rate	Example Services
1	GBR	2	100 ms	10^{-2}	Conversational Voice
2		4	150 ms	10^{-3}	Conversational Video (live streaming)
3		3	50 ms	10^{-3}	Real Time Gaming
4		5	300 ms	10^{-6}	Non-Conversational Video (buffered streaming)
5	Non-GBR	1	100 ms	10^{-6}	IMS Signalling
6		6	300 ms	10^{-6}	Video (buffered streaming) TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)
7		7	100 ms	10^{-3}	Voice, Video (live streaming) Interactive Gaming
8		8	300 ms	10^{-6}	Video (buffered streaming) TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)
9*		9			

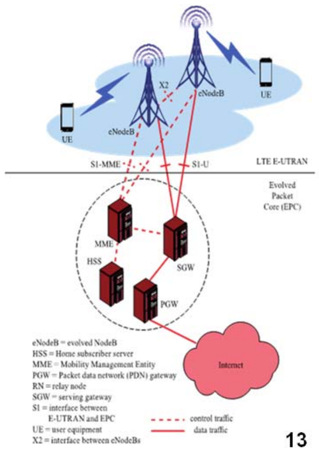
* QCI value typicaly used for the default bearer

Guaranteed (minimum) Bit Rate (QCI 1–4)

No Guarantees (QCI 5–9)

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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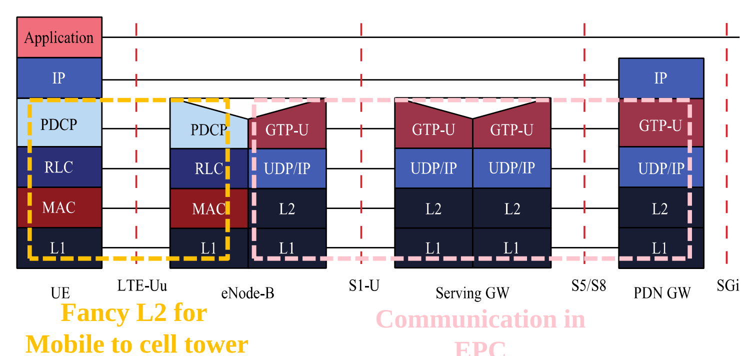
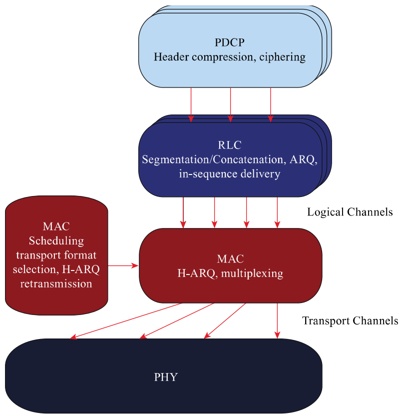
Protocol Layers End-to-End

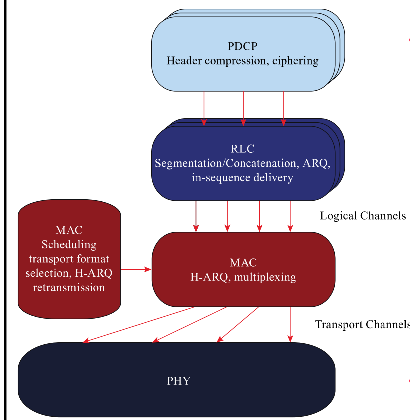


Protocol Layers PDCP and RLC



- 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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LTE Radio Access Network

- LTE uses OFDM and MIMO
- OFDM offers benefits similar to those of CDMA
  - Good 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
  - Low modulation rates 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

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

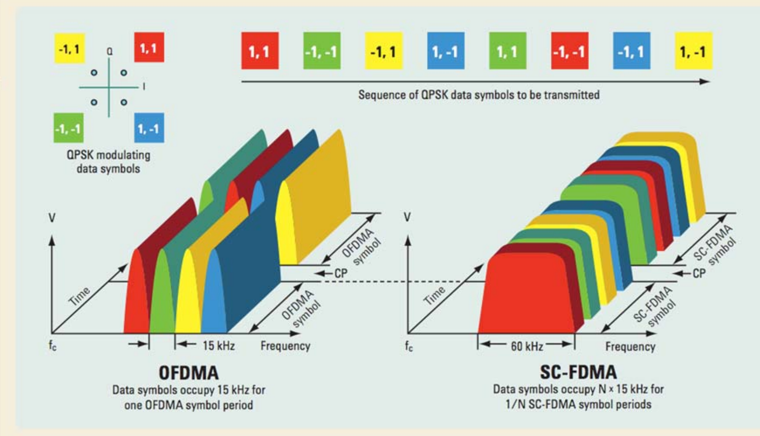
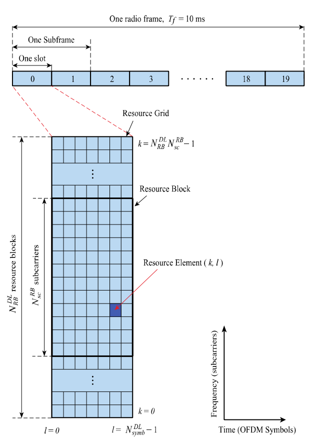


Figure 2. Comparison of how OFDMA and SC-FDMA transmit a sequence of QPSK data symbols

http://cp.literature.agilent.com/litweb/pdf/5989-7898EN.pdf

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



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LTE-Advanced

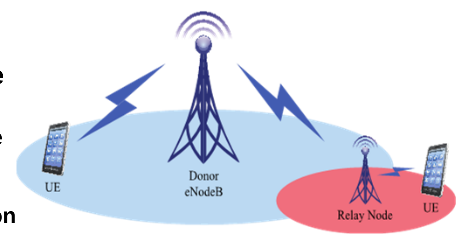
- Carrier aggregation – up to 100 MHz
- MIMO enhancements to support higher dimensional MIMO – up to 8 x 8
- Relay nodes
- Heterogeneous networks involving small cells such as femtocells, picocells, and relays
- Cooperative multipoint transmission and enhanced intercell interference coordination
- Voice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

Comparison LTE and LTE-Advanced

System Performance		LTE	LTE-Advanced
Peak rate	Downlink	100 Mbps @20 MHz	1 Gbps @100 MHz
	Uplink	50 Mbps @20 MHz	500 Mbps @100 MHz
Control plane delay	Idle to connected	<100 ms	< 50 ms
	Dormant to active	<50 ms	< 10 ms
User plane delay		< 5ms	Lower than LTE
Spectral efficiency (peak)	Downlink	5 bps/Hz @2×2	30 bps/Hz @8×8
	Uplink	2.5 bps/Hz @1×2	15 bps/Hz @4×4
Mobility		Up to 350 km/h	Up to 350—500 km/h

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



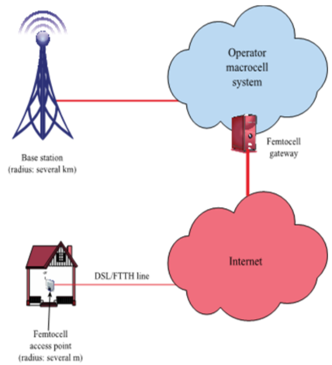
- An RN functions as a new base station with smaller cell radius
- RNs can use out-of-band or inband frequencies

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***)



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 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 a few hundred antennas
- More spectrum: use of millimeter bands
  - » Challenging but a lot of spectrum available
  - » Bands between 26 and 60 GHz
- Also new lower frequency bands
  - » Low-band and mid-band 5G: 600 MHz to 6 GHz