Introduction to LTE

Raj Jain
Washington University in Saint Louis
Saint Louis, MO 63130
Jain@cse.wustl.edu

Audio/Video recordings of this class lecture are available at:
http://www.cse.wustl.edu/~jain/cse574-18/
Overview

1. LTE: Key Features
2. OFDMA and SC-FDMA
3. Evolved Packet Core (EPC)
4. LTE Frame Structure
5. Resource Allocation
LTE: Key Features

Long Term Evolution. 3GPP Release 8, 2009.

1. **3.9G** (Pre-4G) cellular technology
   Sold as 4G by some providers.
   4G=International Mobile Telecommunication (IMT) Advanced Requirements in ITU M.2134-2008

2. **Many different bands**: 700/1500/1700/2100/2600 MHz

3. **Flexible Bandwidth**: 1.4/3/5/10/15/20 MHz

4. Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD)
   ⇒ Both *paired* and *unpaired* spectrum

5. 4x4 MIMO, Multi-user collaborative MIMO

6. Beamforming in the downlink

Safari book.
Washington University in St. Louis  [http://www.cse.wustl.edu/~jain/cse574-18/](http://www.cse.wustl.edu/~jain/cse574-18/)
LTE: Key Features (Cont)

8. Data Rate: 326 Mbps/down 86 Mbps up (4x4 MIMO 20 MHz)
9. Modulation: OFDM with QPSK, 16 QAM, 64 QAM
10. **OFDMA** downlink, Single Carrier Frequency Division Multiple Access (**SC-FDMA**) uplink
11. **Hybrid ARQ** Transmission
12. Short **Frame Sizes** of 10ms and 1ms $\Rightarrow$ faster feedback and better efficiency at high speed
13. **Persistent scheduling** to reduce control channel overhead for low bit rate voice transmission.
14. **IP based** flat network architecture
OFDMA Downlink

- Transmitter at Base Station: IFFT converts frequency to time

- Receiver at User Terminal: FFT converts time to frequency

Washington University in St. Louis http://www.cse.wustl.edu/~jain/cse574-18/ ©2018 Raj Jain
Peak-to-Average Power Ratio (PAPR)

- OFDM
  - Each carrier modulated according to specific channel condition
  - High variation of power levels
  - Higher Peak-to-Average Power Ratio (PAPR)
  - Higher cost of amplifiers

- Amplifiers are linear only over a restricted region
  - Costly amplifier or reduce average signal power significantly
  - Can afford such amplifiers in Base stations but not in mobiles

![PAPR Diagram](V_{out} \text{ Linear} \rightarrow \text{ Non-Linear} \rightarrow V_{in})

V_{avg} \rightarrow V_{peak}
SC-FDMA

- Single-Carrier Frequency Division Multiple Access
- Each user gets a contiguous part of the channel
  
<table>
<thead>
<tr>
<th>User 1</th>
<th>User 2</th>
<th>User 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Uses single carrier modulation and adds a cyclic prefix
- Single carrier $\Rightarrow$ Not much variation in amplitude
  $\Rightarrow$ Lower PAPR
- Better for uplink because slight mis-synchronization among users does not affect the decoding significantly
- With OFDMA each user’s subcarriers are spread all over the band and may affect other users subcarriers all over the band

Washington University in St. Louis  
http://www.cse.wustl.edu/~jain/cse574-18/  
©2018 Raj Jain
SC-FDMA (Cont)

- In practice, SC-FDMA is implemented as if the user is allocated a contiguous subset of subcarriers.

- Transmitter at the User Terminal:

- Receiver at the Base Station:

- SC-FDMA = Discrete Fourier Transform Pre-coded OFDMA


Washington University in St. Louis  http://www.cse.wustl.edu/~jain/cse574-18/  ©2018 Raj Jain
Space Time Block Codes (STBC)

- Invented 1998 by Vahid Tarokh.
- Transmit multiple redundant copies from multiple antennas.
- Precisely coordinate distribution of symbols in space and time.
- Receiver combines multiple copies of the received signals optimally to overcome multipath.
- Example: Two antennas: Two symbols in two slots ⇒ Rate 1

\[ S = x + iy \]
\[ S^* = x - iy \]

S1* is complex conjugate of S1 ⇒ columns are orthogonal
Space-Frequency Block Codes

- **STBC on OFDM (Multi-carrier):** Two alternatives
- **STBC on each subcarrier:**
  - Helps if channel changes fast


Washington University in St. Louis http://www.cse.wustl.edu/~jain/cse574-18/ ©2018 Raj Jain
Puncturing

- Use large number of error correcting code (ECC) bits but send only some of them.
- Example: 1/2 code = 1 ECC bit/Original bit
- Or 4 bits for each 2-bit symbol
- \( \frac{1}{4} \) puncturing ⇒ Drop every 4\textsuperscript{th} bit
  ⇒ send 3 bits for each 2-bit symbol = 2/3 code
- Receiver puts random bits in the punctured positions and decodes ⇒ high probability of correct decoding particularly if the SINR is high
- ½ code with \( \frac{1}{4} \) puncture is not as good as 2/3 code in general but puncturing helps in some situations, such as, H-ARQ
ARQ

- Automatic Repeat reQuest (ARQ)
- Retransmit a packet if it is received in error
- Previous (bad) bits are discarded.
Hybrid ARQ

- PHY and MAC layers work together ⇒ Hybrid
- PHY layer sends some bits first (uses puncturing)
  - Sends additional bits only if necessary.
  - Additional bits are sent until the decoding is successful. (Incremental Redundancy or Type II H-ARQ)
- Another alternative is to combine the good bits of multiple transmissions (Chase Combining or Type I H-ARQ)
IP-Based Flat Network Architecture

- Flat ⇒ Less hierarchical and fewer nodes
- All services (Voice/multimedia) over IP
- For backward compatibility some non-IP protocols and services are still used in LTE network
Evolved Packet Core (EPC)

- Four new elements:
  1. **Serving Gateway**: Demarcation point between RAN and Core. Serves as mobility anchor when terminals move
  2. **Packet Data network Gateway (PGW)**: Termination of EPC towards Internet or IMS network. IP services, address allocation, deep packet inspection, policy enforcement
  3. **Mobility Management Entity (MME)**: Location tracking, paging, roaming, and handovers. All control plane functions related to subscriber and session management.
  4. **Policy and Charging Rules Function (PCRF)**: Manages QoS
Evolved Packet System (EPS)

Radio Access Network

GSM Edge
- MS
- GERAN
- BTS
- BSC

WCDMA
- UE
- UTRAN
- NodeB
- RNC

E-UTRAN
- UE
- LTE
- eNB

Serving Network

CS Core
- MSC
- MGW
- SGW

PS Core
- SGSN
- GGSN

EPC
- MME/S-GW
- P-GW

Core Network

Internet

SS7

Washington University in St. Louis
http://www.cse.wustl.edu/~jain/cse574-18/
©2018 Raj Jain
Evolved Packet System (Cont)

- CS = Circuit Switched
- EPC = Evolved Packet Core
- EPS = Evolved Packet System
- GERAN = GSM Enhanced Radio Access Network
- GGSN = Gateway GPRS Support Node
- LTE = Long Term Evolution
- MME = Mobility Management Utility
- MSC = Mobile Switching Center
- P-GW = Packet Gateway
- PS = Packet Switched
- RNC = Radio Network Control
- S-GW = Serving Gateway
- SGSN = Service GPRS Support Node
- SS7 = System 7
- eNB = Evolved NodeB
**LTE Frame Structure**

Superframes (10 ms)  
SU0  SU1  SU2

Subframes (1 ms)  
SF0  SF1  SF2  SF3  SF4  SF5  SF6  SF9

- Subframe = 2 slots of 0.5 ms each
- Slot = 6 or 7 symbols of 0.667 ms each
- Normal Cyclic Prefix: 5.2 us for 1st symbol, 4.7 us for others
- Extended Cyclic Prefix: for larger networks. 16.7 us

Ref: Rhode and Schwarz, “UMTS Long Term Evolution (LTE) Technology Introduction,”  
http://www.rohde-schwarz.de/file/1MA111_4E_LTE_technology_introduction.pdf

Washington University in St. Louis  
http://www.cse.wustl.edu/~jain/cse574-18/ 
©2018 Raj Jain
Resource Allocation

- **Time slot**: 0.5 ms
  - 6 or 7 OFDM symbols
- **Subcarriers**: 15 kHz
- **Physical Resource Block**:
  - 12 subcarriers (180 kHz)
  - over 1 time slot
- **Minimum Allocation**: 2 PRBs per subframe

WiMAX vs. LTE

- Similar with very minor differences
- Net Head vs. Bell Head
- Enterprise Networking vs. Carrier Networking
- Academic vs. Telecom
- Intel/Google vs. Ericsson/QUALCOMM
- Both use OFDMA. Both are incompatible with 2G and 3G (CDMA) radios.
- Quad-band $\Rightarrow$ Penta-band
Summary

1. WiMAX and LTE are pre-4G technologies.
2. WiMAX and LTE have numerous common features: Many bands, flexible bandwidth, FDD/TDD. MIMO/Beamforming H-ARQ, IP-Based, OFDMA. The key differentiator is SC-FDMA for uplink in LTE to reduce PAPR.
3. STBC requires transmitting redundant symbols from multiple antenna. SFBC require that these redundant symbols be sent on different subcarriers.
4. Puncturing allows some ECC bits to be not transmitting. This is used in H-ARQ to send extra bits only if necessary.
5. LTE uses a super-frame of 10 subframes of 1 ms each. Each subframe has one slot for uplink and downlink each.
Reading List

- 3GPP, “LTE,” http://www.3gpp.org/technologies/keywords-acronyms/98-lte
- 3GPP, “The Evolved Packet Core,” http://www.3gpp.org/technologies/keywords-acronyms/100-the-evolved-packet-core
Wikipedia Links

- https://en.wikipedia.org/wiki/Space%E2%80%93time_block_code
- https://en.wikipedia.org/wiki/Space%E2%80%93time_code
- https://en.wikipedia.org/wiki/Multi-user_MIMO
- https://en.wikipedia.org/wiki/Transmit_diversity
- https://en.wikipedia.org/wiki/Mobility_management
- https://en.wikipedia.org/wiki/Multi-user_MIMO
- https://en.wikipedia.org/wiki/Precoding
Wikipedia Links (Cont)

- https://en.wikipedia.org/wiki/Antenna_diversity
- https://en.wikipedia.org/wiki/Many_antennas
- https://en.wikipedia.org/wiki/Multi-user_MIMO
- https://en.wikipedia.org/wiki/Smart_antenna
- https://en.wikipedia.org/wiki/Precoding
- https://en.wikipedia.org/wiki/Puncturing
- https://en.wikipedia.org/wiki/Fading
Wikipedia Links (Cont)

- https://en.wikipedia.org/wiki/Hybrid_automatic_repeat_request
- https://en.wikipedia.org/wiki/Flat_IP
- https://en.wikipedia.org/wiki/Mobility_Management_Entity
- https://en.wikipedia.org/wiki/Packet_data_serving_node
- https://en.wikipedia.org/wiki/Automatic_repeat_request
- https://en.wikipedia.org/wiki/Multimedia_Broadcast_Multicast_Service
- https://en.wikipedia.org/wiki/Broadcast/Multicast_Control
- https://en.wikipedia.org/wiki/Multicast-broadcast_single-frequency_network
Wikipedia Links (Cont)

- https://en.wikipedia.org/wiki/Orthogonal_frequency-division_multiple_access
- https://en.wikipedia.org/wiki/Orthogonal_frequency-division_multiple_access
- https://en.wikipedia.org/wiki/Cyclic_prefix
LTE References

- 3GPP TS 36.104, “Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) radio transmission and reception (Release 8) ”
- 3GPP TR 25.913., “Requirements for Evolved UTRA (E-UTRA) and Evolved UTRAN (E-UTRAN),” v8.0.0, December 2008.
### Acronyms

- **3GPP**: 3rd Generation Partnership Project
- **ARQ**: Automatic Repeat Request
- **BPSK**: Binary Phase Shift Keying
- **BSC**: Base Station Controller
- **BTS**: Base Transceiver Station
- **CDMA**: Code Division Multiple Access
- **CS**: Circuit Switched
- **ECC**: Error Correcting Code
- **eNB**: Enhanced Node B
- **eNode-B**: Enhanced Node B
- **EPC**: Evolved Packet Core
- **EPS**: Evolved Packet System
- **FDD**: Frequency Division Duplexing
- **FDMA**: Frequency Division Multiple Access
- **FEQ**: Frequency Domain Equalizer
- **FFT**: Fast Fourier Transform
Acronyms (Cont)

- FSTD: Frequency-Shift Transmit Diversity
- GERAN: GSM/EDGE Radio Access Network
- GGSN: Gateway GPRS Support
- GPRS: General Packet Radio Service
- GSM: Global System for Mobile Communications
- GW: Gateway
- HSPA: High-Speed Packet Access
- IEEE: Institution of Electrical and Electronic Engineers
- IMS: Internet Multimedia System
- IMT-Advanced: International Mobile Telecommunications Advanced
- IP: Internet Protocol
- ITU: International Telecommunications Union
- kHz: Kilo Hertz
- LTE: Long Term Evolution
- MAC: Message Authentication Code
- MBMS: Multicast-Broadcast Mobile Services
Acronyms (Cont)

- MGW  Media Gateway
- MHz  Mega Hertz
- MIMO Multiple Input Multiple Output
- MME  Mobility Management Entity
- MS   Mobile Station
- MSC  Mobile Switching Center
- OFDM Orthogonal Frequency Division Modulation
- OFDMA Orthogonal Frequency Division Multiple Access
- PAPR Peak-to-Average Power Ratio
- PCRF Policy and Charging Rules Function
- PDFICH Physical Control Format Indicator Channel
- PDN Packet Data Network
- PGW Packet Data network Gateway
- PHY Physical Layer
- PS   Packet Switched
- QAM  Quadrature Amplitude Modulation
Acronyms (Cont)

- QoS Quality of Service
- QPSK Quadrature Phase Shift Keying
- RAN Radio Access Network
- RNC Radio Network Control
- SAE Service Access Gateway
- SC-FDMA Single Carrier Frequency Division Multiple Access
- SC Single Carrier
- SF Subframe
- SFBC Space Frequency Block Code
- SGSN Service GPRS Support
- SGW Serving Gateway
- SINR Signal to Interference and Noise Ratio
- SN Sequence Number
- SNR Signal-to-noise ratio
- SOstart Begining of Segment
Acronyms (Cont)

- STBC  Space Time Block Code
- SU    Superframe
- TD-SCDMA  Time Division Synchronous Code Division Multiple Access
- TDD   Time Division Duplexing
- TDMA  Time Division Multiple Access
- UE    User Element
- UMTS  Universal Mobile Telecommunications System
- UTRAN UMTS Terrestrial Radio Access Network
- VTC   Vehicular Technology Conference
- WCDMA Wideband Code Division Multiple Access
- WiMAX Worldwide Interoperability for Microwave Access
Scan This to Download These Slides

Raj Jain
http://raj Jain.com
Related Modules

CSE567M: Computer Systems Analysis (Spring 2013),
https://www.youtube.com/playlist?list=PLjGG94etKypJEKjNAa1n_IX0bWWNyZcQf

CSE473S: Introduction to Computer Networks (Fall 2011),
https://www.youtube.com/playlist?list=PLjGG94etKypJWOSPMh8Azcg5e_10TiDw

Recent Advances in Networking (Spring 2013),
https://www.youtube.com/playlist?list=PLjGG94etKypLHyBN8mOgwJLHD2FFIMGq5

CSE571S: Network Security (Fall 2011),
https://www.youtube.com/playlist?list=PLjGG94etKypKvzfVtutHcPFJXumyyg93u

Video Podcasts of Prof. Raj Jain's Lectures,
https://www.youtube.com/channel/UCN4-5wzNP9-ruOzQMs-8NUw