What is UMTS?

- UMTS stands for Universal Mobile Telecommunications System
- 3G cellular standard in the US, Europe, and Asia
- Outcome of several research activities in Europe
  - Assisted the standardization efforts
- Most of the standardization work was focused in 3GPP (3rd Generation Partnership Project)
  - 3GPP refers to the physical layer as UTRA – UMTS Terrestrial Radio Access
  - There are two modes – FDD and TDD

UMTS Architecture

- The UMTS System
  - Consists of many logical network elements similar to the 2G systems
  - Logical network elements have “open interfaces”
- There are three components
  - User Equipment (UE)
  - UMTS Terrestrial Radio Access Network (UTRAN)
  - Core Network (CN)
    - Heavily borrows from GSM

References

- Material Related to LTE comes from
  - IEEE Communications Magazine, February 2009
  - IEEE Communications Magazine, April 2009
**Summary of WCDMA – I**

- WCDMA is somewhat different compared to IS-95
- It is a “wideband” direct sequence spread spectrum system
  - Supports up to 2 Mbps using
    - Variable spreading
    - Multicode connections
- The chip rate is 3.84 Mcps
  - Approximate bandwidth is 5 MHz
  - Supports higher data rates/capacity

**Summary of WCDMA – II**

- Supports variable data rates or bandwidth on demand
  - Transmissions are in frames of 10 ms
  - The data rate is constant for 10 ms
  - Data rate can change from frame to frame

**Long Term Evolution (LTE)**

- It is an evolution of UMTS
- Many terms, ideas, entities, borrowed from UMTS
  - Simplified architecture compared to UMTS
- Protocol stack is similar to UMTS
LTE – Summary

- Only packet data traffic on the air (no circuit switching)
- All IP core network that can interface better with technologies such as WiFi and WiMax
- Use of OFDMA as the medium access/modulation scheme
- Flexibility to deploy it in as little spectrum as 1.4 MHz and as much as 20 MHz of spectrum
- Support for true “broadband” with improved spectrum efficiency

Expected Downlink Data Rates in LTE

<table>
<thead>
<tr>
<th>Antenna Configuration</th>
<th>SISO</th>
<th>2 × 2 MIMO</th>
<th>4 × 4 MIMO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Rate (Mbps)</td>
<td>100</td>
<td>172.8</td>
<td>326.4</td>
</tr>
</tbody>
</table>

Mossberg’s Measurements

- Average using different versions of iPhone 5S, 20 downloads per phone
- Sprint Spark in 2015

LTE Network Architecture

- Evolved Packet System (EPS) consists of two parts
  - E-UTRAN – Evolved UMTS Terrestrial Radio Access Network
  - EPC – Evolved Packet Core
- E-UTRAN
  - Consists of only one kind of node: eNode-B
- EPC
  - Fully based on IP – consists of elements
    - MME – Mobility Management Entity (like SGSN)
    - S-GW & PDN-GW: Serving and Packet Data Network Gateways
    - Home subscriber server (HSS)
  - Voice and real-time applications will make use of the IP Multimedia Subsystem (IMS)
Channel Bandwidths

- Can vary from 1.4 MHz to 20 MHz
- Resource Block (RB)
  - 180 kHz wide and 0.5ms long
  - 12 subcarriers spaced at 15 kHz (24 at 7.5 kHz possible later)
- Data rate limited by User Equipment (UE) categories

<table>
<thead>
<tr>
<th>Channel BW (MHz)</th>
<th>1.4</th>
<th>3.0</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource Blocks</td>
<td>6</td>
<td>15</td>
<td>25</td>
<td>50</td>
<td>75</td>
<td>100</td>
</tr>
</tbody>
</table>

Orthogonal Frequency Division Multiplexing

- Idea in frequency domain:
  - Coherence bandwidth limits the maximum data rate of the channel
  - Send data in several parallel sub-channels each at a lower data rate and different carrier frequency
- Idea in time domain:
  - By using several sub-channels and reducing the data rate on each channel, the symbol duration in each channel is increased
  - If the symbol duration in each channel is larger than the multipath delay spread, we have few errors
- OFDM enables
  - Spacing carriers (sub-channels) as closely as possible
  - Implementing the system completely in digital

What is OFDM?

- Modulation/Multiplexing technique
- Usual transmission
  - Transmits single high-rate data stream over a single carrier
- With OFDM
  - Multiple parallel low-rate data streams
  - Low-rate data streams transmitted on orthogonal subcarriers
  - Allows spectral overlap of sub-channels

OFDM Advantages

- Bandwidth efficiency
- Reduction of ISI
  - Needs simpler equalizers
- Robust to narrowband interference and frequency selective fading
- Possibility of improving channel capacity using adaptive bit loading over multiple channels
How can we increase data rates?

- Traditional ways
  - Reduce the symbol duration
    - Needs larger bandwidth
    - Leads to a wideband channel and frequency selectivity - irreducible error rates
  - Increase the number of bits/symbol
    - Error rates increase with $M$ for the same $E_{b}/N_0$

- MIMO systems
  - There is no need to increase the bandwidth or power
  - But what are the limitations?
  - Use multiple transmit (Tx) and receive (Rx) antennas
  - Increases spectral efficiency to several tens of bps/Hz

What is MIMO?

- So far we have considered Single Input Single Output or SISO systems
  - Both transmitter and receiver have one antenna each
  - Simplest form of transceiver architecture
- Single input multiple-output (SIMO) systems
  - Receiver has multiple antennas
- Multiple input multiple output (MIMO) systems
  - Both transmitter and receiver have multiple antennas
  - Strictly: Each antenna has its own RF chain (modulator, encoder and so on)

Performance enhancements due to MIMO

- Diversity gain
  - Ability to receive multiple copies of the signal with independent fading
- Spatial multiplexing gain
  - Send different information bits over different antennas and recover the information
- Interference reduction
  - Reduce the region of interference thereby increasing capacity

LTE Frame Structure

- One Radio Frame = 10 ms
- One sub-frame = 1 ms
- Each sub-frame has two slots of 0.5 ms each
- Time slot = 0.5 ms
- 12 carriers each with BW 15 kHz
- 17 symbols each OFDM symbol
- Cyclic prefix
Detailed Downlink Frame Structure (FDD)

Source: Agilent Application Note

Downlink Multiple Access: OFDMA

Note users don't have to be assigned resource blocks that are together

Flexible Resource Allocation in OFDMA

Multi-user Diversity with OFDMA

- Allocate subsets of carriers to users over different times
  - Preferably, allocate carriers that have good channel characteristics
Other Downlink Features

- Support for MIMO
  - Transmit diversity
  - Beamforming
  - Spatial multiplexing
  - Combos
- Link adaptation
  - Various modulation schemes and code rates
- Frequency and time selective scheduling
  - MS reports channel quality for resource blocks
- Fractional frequency reuse (FFR)
  - A fraction of frequency resources are not reused in every cell (or are used with low transmit power)

Why SC-FDMA

- Avoid high peak-to-average power ratio (PAPR) in MS

Uplink Multiple Access: Single Carrier FDMA

- Intra-cell orthogonality
  - Unlike CDMA, there is only interference from outside the cell, not within the cell
  - No need for fast power control (compare with CDMA)
    - Still has slow power control
- Frequency and time selective scheduling using wideband channel sounding signal by mobile stations
- Mobile is always “online”
  - Has idle and connected states

Source: Agilent Application Note
LTE Simplified Protocol Stack (Control Information)

- Shaded stack is called the "access stratum" - AS, upper layers are called "non-access stratum" - NAS
- RRC = Radio Resource Control
  - Includes measurements on signals
- PDCP = Packet Data Convergence Protocol
- RLC = Radio Link Control
- GTP = GPRS Tunneling Protocol

LTE Physical Signals

<table>
<thead>
<tr>
<th>DL signals</th>
<th>Full name</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-SCH*</td>
<td>Primary synchronization signal</td>
<td>Used for cell search and identification by the UE. Carries part of the cell ID (one of three orthogonal sequences)</td>
</tr>
<tr>
<td>S-SCH*</td>
<td>Secondary synchronization signal</td>
<td>Used for cell search and identification by the UE. Carries the remainder of the cell ID (one of 188 binary sequences)</td>
</tr>
<tr>
<td>RS</td>
<td>Reference signal (Pilot)</td>
<td>Used for DL channel estimation. Exact sequence derived from cell ID (one of 3 x 168 = 504 pseudo random sequences)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>UL signals</th>
<th>Full name</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS</td>
<td>Reference signal (Demodulation and sounding)</td>
<td>Used for synchronization to the UE and UL channel estimation</td>
</tr>
</tbody>
</table>

LTE Physical Channels

<table>
<thead>
<tr>
<th>DL channels</th>
<th>Full name</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>PBCH</td>
<td>Physical broadcast channel</td>
<td>Carries cell-specific information</td>
</tr>
<tr>
<td>PMCH</td>
<td>Physical multicast channel</td>
<td>Carries the MCH transport channel</td>
</tr>
<tr>
<td>PDCCH</td>
<td>Physical downlink control channel</td>
<td>Scheduling, ACK/NACK</td>
</tr>
<tr>
<td>PDSCH</td>
<td>Physical downlink shared channel</td>
<td>Payload</td>
</tr>
<tr>
<td>PCFICH</td>
<td>Physical control format indicator channel</td>
<td>Defines number of PDCCH OFDMA symbols per sub-frame (1, 2, or 3)</td>
</tr>
<tr>
<td>PHICH</td>
<td>Physical hybrid ARQ indicator channel</td>
<td>Carries HARQ ACK/NACK</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>UL channels</th>
<th>Full name</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRACH</td>
<td>Physical random access channel</td>
<td>Call setup</td>
</tr>
<tr>
<td>PUCCH</td>
<td>Physical uplink control channel</td>
<td>Scheduling, ACK/NACK</td>
</tr>
<tr>
<td>PUSCH</td>
<td>Physical uplink shared channel</td>
<td>Payload</td>
</tr>
</tbody>
</table>
Transport Channels in LTE

<table>
<thead>
<tr>
<th>Transport channel type</th>
<th>Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downlink</td>
<td></td>
</tr>
<tr>
<td>Downlink shared channel</td>
<td>DL-SCH</td>
</tr>
<tr>
<td>Pageing channel</td>
<td>PCH</td>
</tr>
<tr>
<td>Multicast channel</td>
<td>MCH</td>
</tr>
<tr>
<td>Uplink</td>
<td></td>
</tr>
<tr>
<td>Uplink shared channel</td>
<td>UL-SCH</td>
</tr>
<tr>
<td>Random access channel</td>
<td>RACH</td>
</tr>
</tbody>
</table>

Source: Agilent Application Note

Medium Access in LTE

- **Problem**
  - ARQ between mobile and RNC incurs delays
  - ACKs/NACKs are at the RLC layer

- **Solution**
  - Do the scheduling and ARQ between mobile and Node-B
  - ARQ at Layer 1
    - Hybrid ARQ to improve success rate

- **Hybrid ARQ**
  - Combines erroneous frames with retransmitted frames to achieve diversity

- **Fast scheduling**
  - Instead of signaling from the RNC, a Node-B is allowed to make decisions on the maximum data rates that a MS can use to transmit packet data
  - Uses adaptive multi-rate transmission

Similar ideas were adopted in LTE
Link Adaptation in LTE

- Uses a “channel quality indicator” or CQI
- Sent by a mobile on an uplink control channel (PUCCH or PUSCH) for periodic or aperiodic reporting of CQI
- CQI values can be for:
  - Entire system bandwidth
  - Mobile picks a subset of the bandwidth
  - eNode-B picks a subset of the bandwidth

CQI Index | Modulation Scheme | Code Rate
---|---|---
1 | QPSK | 0.076
4 | QPSK | 0.3
8 | 16-QAM | 0.48
11 | 64-QAM | 0.55
15 | 64-QAM | 0.93

Sample adaptive transmission rates in LTE and their mapping to CQI values

Mobile uses block error rate thresholds to determine the CQI

In Brief: Cell Search in LTE

- OFDMA and time/frequency resource blocks (RBs)
- Problems:
  - Different bandwidths supported in LTE (1.25, 2.5, 5, 10, 20 MHz)
  - Need smaller delay for cell search
- Sync Channel:
  - Uses “central” 1.25 MHz bandwidth
  - Comprises of 76 sub-carriers with a spacing of 15 kHz
  - Within these, a primary (P-SCH) and secondary (S-SCH) synchronization channel is transmitted
    - Each carries part of the Cell-ID
- Reference Signal (RS):
  - Used for downlink channel estimation

Cell Search in LTE

- Entire Transmission Bandwidth
  - PRB 1-PRB 11
- Central Six PRBs carry the Synchronization Signals
- Each Radio Frame = 10 ms
- Slot 1
  - Synchronization Signal
- Slot 11

Random Access

- Uplink transmissions in a cell must be orthogonal
  - They are aligned with frame timing of an e-NodeB
- When a MS powers up or after a long period of inactivity, this alignment is lost
- RA Procedure:
  - MS sends one of several preambles (shared) with a guard period
  - E-NodeB detects preamble, estimates MS’s timing, and responds with a correct timing advance and uplink resource
  - MS sends its identity in this allocated resource + some data
  - E-NodeB echos the MS identity
More on RA Procedure

- RA procedure must be repeated if the echoed identity is not correct
  - Due to a collision of the preambles
- Backoff indication from e-NodeB can be used to reduce contention
- After an inter-eNodeB handoff, an RA procedure is imminent
  - Contention free RA procedure is possible
  - Unique preamble is assigned to the MS

Obtaining Uplink Resources

- If a MS has data to send, it can send a single “scheduling request” (SR) bit using
  - The RA Procedure OR
  - Dedicated SR on the PUCCH
- In the first allocated resource, the MS sends a buffer status report that has more information about how much data it wants to send
- E-NodeB allocates resources on a per sub-frame basis (every ms!)
  - Scheduler is responsible for handling QoS

Mobility Management in LTE

- Two scenarios
- When the E-Node B’s are connected
- When the E-Node B’s are not connected
- Recall flat architecture

Simplified Handoff – BSs connected

- Current BS
  - Handoff Request
  - Allocate Resources and Acknowledge
  - Let Target BS Know
  - Execute Handoff Process and Contact Target Base Station
  - Ask UE to flush Resources
- Target BS
  - Mobility Management Entity
  - Update Databases
Simplified Handoff – BSs are not connected