9/4/2012: Introduction to Cellular Networks
Cellular Networks Impact our Lives

More Mobile Connection

More Mobile Users

More Infrastructure Deployment

More Mobile Information Sharing
Mobile Data Tsunami Challenges
Current Cellular Technologies

• Global growth 18 times from 2011 to 2016

• AT&T network:
  – wireless data traffic has grown 20,000%
  – At least doubling every year since 2007

• Existing cellular technologies are inadequate
  – Fundamental redesign of cellular networks is needed

Outline

Goal of this lecture: understand the basics of current networks

• Basic Architecture of LTE
• Access Procedure
  – Why no carrier sensing
• Connection Setup
  – Unlike WiFi, need to keep the same IP address at different attachment points
• Mobility Management
• Power Management and Mobile Apps
• Differences between 3G and LTE
• Conclusion
LTE Infrastructure

- **UE**: user equipment
- **eNodeB**: base station
- **S-GW**: serving gateway
- **P-GW**: packet data network gateway
- **MME**: mobility management entity
- **HSS**: home subscriber server
- **PCRF**: policy charging and rule function

Diagram:
- **Cellular Core Network**
- **MME/PCRF/HSS**
- **S-GW 1**
- **S-GW 2**
- **P-GW**
- **eNodeB 1**
- **eNodeB 2**
- **eNodeB 3**
- **UE 1**
- **UE 2**
- **GTP Tunnels**

**Internet and Other IP Networks**
LTE Architecture (Cont’d)

- eNodeB, S-GW and P-GW are involved in session setup, handoff, routing.

- User Equipment (UE)
- Control Plane
- Data Plane
- Home Subscriber Server (HSS)
- Mobility Management Entity (MME)
- Policy Control and Charging Rules Function (PCRF)
- Base Station (eNodeB)
- Serving Gateway (S-GW)
- Packet Data Gateway (P-GW)
Access Procedure

• Cell Search
  – Base station broadcasts synchronization signals and cell system information (similar to WiFi)
  – UE obtains physical layer information
    • UE acquires frequency and synchronizes to a cell
    • Determine the start of the downlink frame
    • Determine the cell identity

• Random access to establish a radio link
Random Access

Step 1: random access request (pick one of 64 preambles)

Step 2: random access response

Adjust uplink timing

Step 3: transmission of mobile ID

Step 4: contention resolution msg

Only if UE is not known in Base station

If ID in msg matches UE ID, succeed.
If collision, ID will not match!
Random Access (Cont’d)

Why not carrier sensing like WiFi?

• Base station coverage is much larger than WiFi AP
  – UEs most likely cannot hear each other

• How come base station can hear UEs’ transmissions?
  – Base station receivers are much more sensitive and expensive
Connection Setup

• Session Requests
  – UE to base station
  – Base station to MME
    • MME obtains subscriber info from HSS, selects S-GW and P-GW
  – S-GW sends to P-GW
    • P-GW obtains policy from PCRF
Connection Setup (Cont’d)

- **Session Response**
  - Establishes GPRS Tunnels (GTP) between S-GW and P-GW, between S-GW and UE
  - Base station allocates radio resources to UE
Mobility Management

Handoff

• Handoff without change of S-GW
  – No change at P-GW

• Handoff with change of S-GW or MME

• Inter-technology handoff (LTE to 3G)
Mobility Management (Cont’d)

Paging

• If S-GW receives a packet to a UE in IDLE state, inform MME

• MME pages UE through base station
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Power Management: LTE

- UE runs radio resource control (RRC) state machine
- Two states: IDLE, CONNECTED
- Discontinuous reception (DRX): monitor one subframe per DRX cycle; receiver sleeps in other subframes
Power Management: UMTS

- State promotions have promotion delay
- State demotions incur tail times

<table>
<thead>
<tr>
<th>Channel</th>
<th>Radio Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>IDLE</td>
<td>Not allocated</td>
</tr>
<tr>
<td>CELL_FACH</td>
<td>Shared, Low Speed</td>
</tr>
<tr>
<td>CELL_DCH</td>
<td>Dedicated, High Speed</td>
</tr>
</tbody>
</table>
Example in Detail: RRC State Machine for a Large Commercial 3G Network

DCH: High Power State (high throughput and power consumption)
FACH: Low Power State (low throughput and power consumption)
IDLE: No radio resource allocated

Promo Delay: 2 Sec  FACH Tail: 12 sec

Waiting inactivity timers to expire

Courtesy: Feng Qian
**Example in Detail: Pandora Music**

**Problem:** High resource overhead of periodic audience measurements (every 1 min)

**Recommendation:**
- Delay transfers and batch them with delay-sensitive transfers

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### Pandora profiling results (Trace len: 1.45 hours)

<table>
<thead>
<tr>
<th>Burst type</th>
<th>Payloads</th>
<th>Energy</th>
<th>DCH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>LB</td>
<td>UB</td>
</tr>
<tr>
<td>LARGE_BURST</td>
<td>96.4%</td>
<td>35.6%</td>
<td>35.9%</td>
</tr>
<tr>
<td>APP_PERIOD</td>
<td>0.2%</td>
<td>45.9%</td>
<td>46.7%</td>
</tr>
<tr>
<td>APP</td>
<td>3.2%</td>
<td>12.8%</td>
<td>13.4%</td>
</tr>
<tr>
<td>TCP_CONTROL</td>
<td>0.0%</td>
<td>1.2%</td>
<td>1.6%</td>
</tr>
<tr>
<td>TCP LOSS RECOVER</td>
<td>0.2%</td>
<td>0.2%</td>
<td>0.6%</td>
</tr>
<tr>
<td>NON_TARGET</td>
<td>0.0%</td>
<td>1.8%</td>
<td>1.8%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>23.6 MB</td>
<td>846 J</td>
<td>895 sec</td>
</tr>
</tbody>
</table>

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*Courtesy: Feng Qian*
Why Power Consumptions of RRC States so different?

• IDLE: procedures based on reception rather than transmission
  – Reception of System Information messages
  – Cell selection registration (requires RRC connection establishment)
  – Reception of paging messages with a DRX cycle (may trigger RRC connection establishment)
  – Location and routing area updates (requires RRC connection establishment)
UMTS RRC State Machine (Cont’d)

• CELL_FACH: need to continuously receive (search for UE identity in messages on FACH), data can be sent by RNC any time
  – Can transfer small data
  – UE and network resource required low
  – Cell re-selections when a UE moves
  – Inter-system and inter-frequency handoff possible
  – Can receive paging messages without a DRX cycle
UMTS RRC State Machine (Cont’d)

• CELL_DCH: need to continuously receive, and sent whenever there is data
  – Possible to transfer large quantities of uplink and downlink data
  – UE and network resource requirement is relatively high
  – Soft handover possible for dedicated channels and Inter-system and inter-frequency handover possible
  – Paging messages without a DRX cycle are used for paging purposes
LTE vs UMTS (3G): Architecture

- Functional changes compared to the current UMTS Architecture
  - RNC functions moved to eNodeB.
    - No central radio controller node
    - OFDM radio, no soft handover
    - Operator demand to simplify
  - Control plane/user plane split for better scalability
    - MME control plane only
    - Typically centralized and pooled
  - Mobility Management Entity
  - PDN Gateway
  - Serving Gateway
  - PGW/SGW
    - Deployed according to traffic demand
    - Only 2 user plane nodes (non-roaming case)
  - Operator demand to simplify
Physical Layer: UMTS

Simultaneous meetings in different rooms (FDMA)

Simultaneous meetings in the same room at different times (TDMA)

Multiple meetings in the same room at the same time (CDMA)

Courtesy: Harish Vishwanath
Physical Layer: UMTS (Cont’d)

Code Division Multiple Access (CDMA)

• Use of orthogonal codes to separate different transmissions

• Each symbol or bit is transmitted as a larger number of bits using the user specific code – Spreading

• Spread spectrum technology
  – The bandwidth occupied by the signal is much larger than the information transmission rate
  – Example: 9.6 Kbps voice is transmitted over 1.25 MHz of bandwidth, a bandwidth expansion of \(~100\)
Orthogonal Frequency Division Multiple Access (OFDM)

- Closely spaced sub-carriers without guard band
- Each sub-carrier undergoes (narrow band) flat fading
  - Simplified receiver processing
- Frequency or multi-user diversity through coding or scheduling across sub-carriers
- Dynamic power allocation across sub-carriers allows for interference mitigation across cells
- Orthogonal multiple access

Sub-carriers remain orthogonal under multipath propagation
Physical Layer: LTE (Reverse link OFDM)

- Users are carrier synchronized to the base
- Differential delay between users’ signals at the base need to be small compared to symbol duration
- Efficient use of spectrum by multiple users
- Sub-carriers transmitted by different users are orthogonal at the receiver
  - No intra-cell interference
- CDMA uplink is non-orthogonal since synchronization requirement is \( \sim 1/W \) and so difficult to achieve

Courtesy: Harish Vishwanath
Typical Multiplexing in OFDMA

Each color represents a user. Each user is assigned a frequency-time tile which consists of pilot sub-carriers and data sub-carriers. Block hopping of each user’s tile for frequency diversity.

Typical pilot ratio: 4.8% (1/21) for LTE for 1 Tx antenna and 9.5% for 2 Tx antennas.
LTE vs UMTS (3G): Physical Layer

- **UMTS has CELL_FACH**
  - Uplink un-synchronized
    - Base station separates random access transmissions and scheduled transmissions using CDMA codes

- **LTE does not have CELL_FACH**
  - Uplink needs synchronization
    - Random access transmissions will interfere with scheduled transmissions
Conclusions

• LTE promises hundreds of Mbps and 10s msec latency

• Mobile apps need to be cellular friendly, e.g. avoid periodic small packets, use push notification services

• Roaming and inter-technology handoff not covered

• Challenges
  – P-GW central point of control, bad for content distribution, and scalable policy enforcement
  – Mobile video will be more than half of the traffic
  – Needs lots of spectrum (spectrum crunch)