Currently Available Cellular bands:

- GSM 900: 35 (uplink) + 35 (downlink) = 70 MHz
- GSM 1800: 75 (uplink) + 75 (downlink) = 150 MHz
- Cellular 850: 25 (uplink) + 25 (downlink) = 50 MHz
- UMTS: 60 (uplink) + 60 (downlink) = 120 MHz
- PCS 1900: 60 (uplink) + 60 (downlink) = 120 MHz
- AWS: 45 (uplink) + 45 (downlink) = 90 MHz

<table>
<thead>
<tr>
<th>Band</th>
<th>Uplink (MHz)</th>
<th>Downlink (MHz)</th>
<th>Carrier Bandwidth (MHz)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>700 MHz</td>
<td>746-763</td>
<td>776-793</td>
<td>1.25 5 10 15 20</td>
<td>Digital Dividend. U.S. commercial spectrum is scheduled to be auctioned in January 2008. Potential future alignment with Europe</td>
</tr>
<tr>
<td>IMT Extension</td>
<td>2500-2570</td>
<td>2620-2690</td>
<td>1.25 5 10 15 20</td>
<td>Initially Western Europe. Offers a unique opportunity for the deployment of LTE in channels of up to 20 MHz.</td>
</tr>
<tr>
<td>GSM 900</td>
<td>880-915</td>
<td>925-960</td>
<td>1.25 5 10 15 20</td>
<td>Reallocate this spectrum to advanced networks, such as LTE, from 2009 onwards</td>
</tr>
<tr>
<td>UMTS Core</td>
<td>1920-1980</td>
<td>2110-2170</td>
<td>1.25 5 10 15 20</td>
<td>Europe and Asia Pac. Potential for unused WCDMA carriers</td>
</tr>
<tr>
<td>GSM 1800</td>
<td>1710-1785</td>
<td>1805-1880</td>
<td>1.25 5 10 15 20</td>
<td>Europe and Asia Pac. Reform underutilized band along with GSM 900</td>
</tr>
<tr>
<td>PCS 1900</td>
<td>1850-1910</td>
<td>1930-1990</td>
<td>1.25 5 10 15 20</td>
<td>U.S. Reform after new 700 MHz and AWS spectrum is consumed</td>
</tr>
<tr>
<td>Cellular 850</td>
<td>824-849</td>
<td>869-894</td>
<td>1.25 5 10 15 20</td>
<td>U.S. Reform after new 700 MHz and AWS spectrum is consumed</td>
</tr>
<tr>
<td>Digital Dividend</td>
<td>470-854</td>
<td></td>
<td>1.25 5 10 15 20</td>
<td>Identified at WRC-07.</td>
</tr>
</tbody>
</table>

Spectrum Allocations
The case for higher carrier frequencies

WCDMA 3G
Cellular today – 1800 MHz band (three bands provide at most 150-200 MHz duplex per op.)

LMDS – 1.3GHz
28/38 GHz bands – 3.4GHz

60 GHz unlicensed – 7GHz
60 GHz Atmospheric Absorption – Important Short-Range mmWave Application

- Additional path loss @ 60 GHz due to Atmospheric Oxygen
- Atmosphere attenuates: 20 dB per kilometer
- 60GHz Allocation Motivation: High Attenuation Reduces Interference over Long Distances

The Mobile Bandwidth Crunch

- Mobile world-wide traffic is expected to exceed $10^8$ Tb/yr by 2020 [1]
- More spectrum needed to meet data traffic & speed demands and can be found at mm-Wave [2]

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Figure reproduced with permission by Jerry Pi of Samsung from, F. Khan and J. Pi, “Millimeter-wave Mobile Broadband: Unleashing 3-300 GHz Spectrum,” *IEEE Wireless Communications & Networking Conference*, Quintana-Roo, Mexico, 2011.


Millimeter-Wave Outage Studies

- LMDS is the most similar previously studied communication system

- Ref. [1] found coverage of 60 - 80% over 2 km radius at 28 GHz, yet others claim that only clear LOS can ensure good coverage [2]

- Smaller cells can significantly improve coverage [3]

- Urban Myth: mm-Wave will not work for cellular

Cellular and Wireless Backhaul

Trends:
- Higher data usage
- Increase in base station density (femto/pico cells)
- Greater frequency reuse

Problem: Fiber optic backhaul is expensive and difficult to install.

Solution: Cheap CMOS-based wireless backhaul with beam steering capability.
Mobile & Vehicle Connectivity

Massive data rates
- Mobile-to-mobile communication
- Establish ad-hoc networks

High directionality in sensing
- Vehicular Radar and collision avoidance
- Vehicle components connected wirelessly
Beam Forming and Steering

- Antenna Size $\propto \lambda$
  - $\lambda = 5 \text{ mm} @ 60 \text{ GHz}$
  - $\lambda = 10 \text{ mm} @ 30 \text{ GHz}$
- A large antenna array can be constructed in reasonable form factor

- Beamforming has been introduced into mmWave standards$^1$.
- Beam steering can be used to create a non-LOS link by reflecting off objects in the environment.

---

Proposed mm-Wave System

- Directional antennas at both base-station and mobile devices
- Wireless Backhaul between nearby cell sites
- Fiber optic connection to data server at edges of network


Figure reproduced with permission by Jerry Pi of Samsung from, F. Khan and J. Pi, “Millimeter-wave Mobile Broadband: Unleashing 3-300 GHz Spectrum,” *IEEE Wireless Communications & Networking Conference*, Quintana-Roo, Mexico, 2011.
Noise-Limited System using Directional Antennas

- Steerable Directional antennas preferentially directed towards each other
- Co-channel interferers get rejected by antenna pattern

Peer-to-Peer 38 and 60 GHz
  • Antennas 1.5m above ground
  • Ten RX locations (18-126m TR separation)
  • Measurements in courtyard outside ENS building
  • Both LOS and NLOS links measured using 8° BW (25 dBi gain) standard horn antennas at 38 and 60 GHz

Cellular (rooftop-to-ground)
  • Four TX locations at various heights (8-36m above ground) with TR separation of 29 to 930m.
  • RX & TX antennas: 8° BW (25 dBi gain) vertically-polarized standard horns
  • LOS, partially-obstructed LOS, and NLOS links measured
### 38 GHz Channel Sounder Hardware

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sounder Type</td>
<td>Sliding Correlator with 11-bit PN Sequence</td>
</tr>
<tr>
<td>Chip Rate</td>
<td>400 MHz</td>
</tr>
<tr>
<td>RF BW</td>
<td>800 MHz</td>
</tr>
<tr>
<td>Carrier Freq.</td>
<td>37.625 GHz</td>
</tr>
<tr>
<td>Transmit Power</td>
<td>+21.2 dBm</td>
</tr>
<tr>
<td>Measurable Path Loss</td>
<td>≤160 dB</td>
</tr>
<tr>
<td>TX Ant.</td>
<td>Standard Horn: 25 dBi gain / 7.0° Beamwidth</td>
</tr>
<tr>
<td>RX Ant.</td>
<td>Standard Horn: 25 dBi gain / 7.0° Beamwidth</td>
</tr>
</tbody>
</table>


38 GHz Channel Sounder Hardware

Transmitter

Receiver

Antennas rotated in both Azimuth and Elevation to achieve NLOS links

Non-LOS link TX points away from RX
Measurement Areas at UT Austin

Peer-to-Peer Measurements

Cellular (rooftop-to-ground) Measurements
Peer-to-Peer Angle of Arrival

- Links made at large range of receiver and transmitter angles
- Many scatterers near both RX and TX when placed 1.5m above ground
- Antenna Beam-steering can help make several NLOS links
- Objects, such as brick, reflect 38 GHz better than 60 GHz due to lower diffusive scattering
60 GHz LOS path loss slightly higher than free space (n=2)

- High atmospheric absorption is likely the cause

- Best NLOS links are about the same @ 38, 60 GHz since they usually come from **metallic** objects

- Path loss exponent for all NLOS links is a bit higher due to higher TX power at 38 GHz (+22dBm) vs. 60 GHz (+5 dBm)
Peer-to-Peer RMS Delay Spread

- Higher RMS delay spreads were seen for NLOS 38 GHz propagation
- Reduced diffusive scattering (i.e. roughness) of objects at lower freq.
- 60 GHz max path loss: 36.6 ns
- 38 GHz max path loss: 122 ns
- Minimal delay spread for all LOS links
Cellular AOA

Histogram of RX angles for all links made using 25dBi antennas (10° bins)

Histogram of TX angles for all links made using 25dBi antennas (10° bins)

TX height 24m above ground
Cellular Path Loss

- Clear LOS path loss exponent near free space (n=2)
- Partially obstructed LOS links have up to 17dB loss above free space
- NLOS links range from a few dB to >30 dB below the LOS component
- However, a beam-steering allows the best NLOS path to be chosen, which reduces the path loss noticeably.
Cellular RMS Delay Spread

- RMS Delay Spread Cumulative Distribution Functions (CDFs) for LOS and NLOS links.
- LOS and partially obstructed LOS links had minimal delay spread for all measurements.
- Worst RMS delay spread link: 117 ns.
Outage: Experimental Design

- Two TX locations and 53 randomly selected RX locations
- TX Locations: ENS (36 m, 8-stories) & WRW (18 m, 4-stories high)
- Recorded whether a link was found (i.e. signal above RX noise floor) and noted if path loss was <150 dB
- Tested distances up to about 400 m
ENS TX Location Outage Results

- 18.9% of all measured locations ended in an outage.

- 52.8% were outages for a system of lower (<150dB Max. PL) sensitivity.

- However, no outages were observed within a 200 m radius from the TX.

- Reflection and/or diffraction path existed for all locations within 200 m off the TX.

- Outages tend to cluster.
WRW TX Location Outage Results

• 39.6% of all measured locations ended in an outage.

• 52.8% were outages for a system of lower (<150 dB Max. PL) sensitivity.

• Higher outage rate experienced due to the significantly lower TX height.

• However, none of the measurements within a 200 m radius resulted in an outage.
## TX Location Comparison

<table>
<thead>
<tr>
<th>Transmitter Location</th>
<th>Height</th>
<th>% Outage with &gt;160 dB PL</th>
<th>% Outage with &gt;150 dB PL</th>
</tr>
</thead>
<tbody>
<tr>
<td>TX 1 ENS</td>
<td>36 m</td>
<td>18.9% all, 0% &lt; 200 m</td>
<td>52.8% all, 27.3 % &lt; 200 m</td>
</tr>
<tr>
<td>TX 2 WRW</td>
<td>18 m</td>
<td>39.6% all, 0% &lt; 200 m</td>
<td>52.8% all, 10% &lt; 200 m</td>
</tr>
</tbody>
</table>

### Similarities:
- No outages within a 200 m were observed.
- Outage location clustering.

### Differences:
- The lower (WRW) TX location achieved better coverage for a short range.
- The higher (ENS) TX location produced links at obstructed locations over 400 m away.
- Thus, a WRW cell will result in a tighter cell (i.e. less interference), yet its reach is significantly lower.
Impact of Base Station Height

- Higher base station enables diffraction over buildings
- Lower base station enables better reception near base station through reflection off building sides and near-ground reflectors
Summary

• Measurements at 38 and 60 GHz show that NLOS links can be made with steerable antennas, with 20 – 30 dB loss compared to free space line-of-sight.

• A link was always made using steerable antennas within a 200 m cell radius.

• 38 GHz showed more NLOS links than 60 GHz

• Cellular AOA distributions show BS should be deployed site-specifically (due to shadowing of buildings)

• Worst RMS delay spread link was 122ns, similar for peer-to-peer and cellular
Related Publications


