Millimeter Wave Wireless Communications: The Renaissance of Computing and Communications

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Growing Traffic and Devices

Exabyte $= 10^{18}$ Bytes
Pedabyte $= 10^{15}$ Bytes
Terabyte $= 10^{12}$ Bytes

Source: Cisco VNI Mobile, 2014

For 2018, Cisco is now forecasting that bandwidth consumption will reach 1.6 zettabytes. In its 2013 VNI forecast, Cisco had predicted that bandwidth consumption in 2017 would reach 1.4 zettabytes. A zettabyte is equal to 1000 exabytes, which is one sextillion bytes.

Even though the VNI forecast is a five-year projection for traffic, it isn't just a shot in the dark. Cisco has a sophisticated model for collecting data from multiple sources to obtain a high degree of forecast accuracy. Cisco had originally forecast traffic in 2013 to be 50 exabytes, while the actual number came in at 51 exabytes.
Mobile Data Traffic Growth

- **System Capacity Requirements**
  - Network traffic load increasing by **65-100% CAGR**
  - Requires up to **2x increase** in network capacity per annum
  - Relative to 2013 – assuming exponential growth\(^1\) maintained
    - 2025 = \(\sim 1600\) x 2013 load
    - 2040 = \(16M\) x 2013 load

Note 1: Assumes 85% CAGR in traffic.

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**Ericsson: 100%+ CAGR**

Ericsson Mobility Report, June 2013
Excludes WiFi, VoIP, MTC

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**Cisco: 66% CAGR**

Cisco Visual Networking Index, Feb. 2013

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**More “Realistic” Models**

- New Users Less “Power User”
- Modified Rate Plans
- Innovation Bursts

Source: Intel, Sept. 2013
Traffic Growth – Video Dominance
Total Network Traffic - Video vs. MTC vs. Data

Conclusion: Optimize future wireless networks for video traffic regardless of RAT – but seek to retain high performance for MTC, HTTP, etc.

Source: Intel, Sept. 2013
Subscriber Growth – Smartphone Dominance

Global Mobile and Fixed Wireless 2010-2030

Mobile and Fixed Subscriptions vs. Year

Projection to 2030 - Excludes MTC

**Conclusion:** Smartphone dominance continues, hence optimize future wide-area systems for smartphone base – but device innovation is disruptive....

**Notes:**
1. Excludes machine-machine (M2M) traffic.
2. H2H – human to human
Wearable and LP Devices by Connectivity*

*NFC not included (only one device with NFC + BT connectivity)

<table>
<thead>
<tr>
<th>Connectivity</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wi-Fi only</td>
<td>2</td>
</tr>
<tr>
<td>BT only</td>
<td>7</td>
</tr>
<tr>
<td>BLE only</td>
<td>6</td>
</tr>
<tr>
<td>Wi-Fi + BLE</td>
<td>1</td>
</tr>
<tr>
<td>BT + BLE</td>
<td>4</td>
</tr>
<tr>
<td>Wi-Fi + BT + BLE</td>
<td>2</td>
</tr>
<tr>
<td>Wi-Fi + BT + GNSS</td>
<td>1</td>
</tr>
<tr>
<td>Wi-Fi + BLE + GNSS</td>
<td>1</td>
</tr>
<tr>
<td>Wi-Fi + BT + BLE + GNSS</td>
<td>2</td>
</tr>
<tr>
<td>Total Devices</td>
<td>26</td>
</tr>
</tbody>
</table>

Majority today connect using BT/BLE to a companion device

Source: Intel, Sept. 2013
• Key Trends – 2013-2025

– “Exponential” Traffic Growth Continues
  – 100x+ by 2025 unless network capacity limits traffic

– Wireless Traffic Dominated by Video Multimedia
  – Initially H.264, then H.265, delivered via A-HTTP/DASH protocols

– Expectation of Ubiquitous Broadband Access Strengthens
  – Users expect and need wireless broadband everywhere

– Expectation of Gbps, Low Latency Access Strengthens
  – Critically in dense traffic areas: enterprise, transport centers, stadia

– New Class of Internet of Things Devices Emerges
  – Disparate class of devices – ranging from {very low-power, intermediately, very low rate} to {high power, direct, high rate}

30 More Years of Innovation, Growth and Revenue

Source: Intel, Sept. 2013
5G Requirements and Targets

DOCOMO 5G mobile communication

- Higher data rate
  - 10-100x bit rates (Even for high mobility)

- Massive device connectivity
  - 100x connected devices (Even in crowded areas)

- Higher system capacity

- Reduced latency
  - Reduced latency: < 1ms

- Energy saving & cost reduction
  - Energy saving for NW & terminals
  - Reduced NW cost incl. backhaul
5G and 10,000x the bps/Hz/km²: where will the gains come from?

**Bandwidth (20x more Hz)**

Only one place to go: mmWave
(Also LTE-U as stopgap)

**mmWave + HetNets**
- very complementary
- densifying mmWave cells yields huge gains (SNR plus cell splitting)
- Can possibly do self-backhauling!

**Effective Density (50x More Loaded BSs/km²):**

Efficient HetNets, small cell and WiFi offloading, maybe D2D

**Spectral efficiency (10x more bps/Hz)**

More dimensions (massive MIMO)
Interference suppression?

**HetNets + massive MIMO**
- HetNets may not be able to utilize massive MIMO
- Cost a key challenge here

mmWave + massive MIMO
- Some competition here
- Improved SINR via mmWave with high gain antennas, interference goes to zero?

M2M-biased view on 5G

R1: today’s systems
R2: high-speed versions of today’s systems
R3: massive access for sensors and machines
R4: ultra-reliable low rate connectivity
R5: physically impossible?

To prepare for 1000-fold increase in data traffic in next 10 years.

5G Radio Access Technology (RAT)

- **Rel-10/11**
- **Pico/Femto LTE**
- **LTE-Advanced**
- **Rel-12/13**
- **Macro-assisted small cell (Phantom cell)**
- **Rel-14/15, ...**
- **Further LTE enhancements**
- **Backward compatible enhancements**
- **5G Radio Access**
- **Potential New RAT**
- **Big gain**

- **WRC-15**
- **~2015**
- **WRC-18/19**
- **~2020**

CA/eICIC/CoMP for HetNet

TU3F-2

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IMS2014, Tampa, 1-6 June, 2014
Phantom Cell Concept for 5G

- Split of C/U-plane
- Macro cell
- Small cell using higher freq. band

Lower freq. bands
- (Existing cellular freq. = UHF)
- Ex. 800 MHz
- Ex. 2 GHz

Higher freq. bands
- Low SHF: 3~6 GHz
- High SHF: 6~30 GHz / over 30 GHz

Phantom Cell concept can easily exploit higher freq. bands!
Wireless Data Rates per Generation

Plot of generational data rates for 3G, 4G, and 5G networks. Millimeter Wave spectrum is needed to meet 5G demand.
Spectrum = real estate

Shaded Areas = Equivalent Spectrum!

60GHz Spectrum

77GHz Vehicular Radar

AM Radio

TV Broadcast

FM Radio

Cellular

Wi-Fi

Active CMOS IC Research

T. S. Rappaport, et. al., Millimeter Wave Wireless Communications, Pearson/Prentice Hall, c. 2015
• 60 GHz Spectrum allocation is worldwide
• 5 GHz common bandwidth among several countries

**Figure 1** International unlicensed spectrum around 60 GHz.

• G. L. Baldwin, “Background on Development of 60 GHz for Commercial Use,” SiBEAM, inc. white paper, May 2007,
• Additional path loss @ 60 GHz due to Atmospheric Oxygen

• Atmosphere attenuates: 20 dB per kilometer

• Many future sub-THz bands available for both cellular/outdoor and WPAN “whisper radio”

Rain attenuation at 70 GHz band:
• Heavy rain (25mm/hr): 10 dB/km

Cell size: 200 meters

Heavy Rainfall @ 73 GHz
2 dB attenuation @ 200m

Heavy Rainfall @ 28 GHz
1.2 dB attenuation @ 200m

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mmWave Wavelength Visualization – 60GHz

- 5 millimeters
- 16 antennas
- Integrated Circuit
Overview of spatial channel models for antenna array communication systems

Smart Antennas for Wireless Communications (book by Prentice-Hall)
J. C. Liberti, T.S. Rapapport, c. 1999

Application of narrow-beam antennas and fractional loading factor in cellular communication systems
Cardieri, et. al., IEEE TRANS. ON VHEICULAR TECHNOLOGY, Vol. 50, No. 3, March 2001

Spatial and temporal characteristics of 60-GHz indoor channels
Xu, et. al., IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, VOL. 20, NO. 3, April 2002

Wideband Measurement of Angle and Delay Dispersion for Outdoor/Indoor/ Peer-to-Peer Channels @ 1920 MHz
Durgin, et. al., IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 51, NO. 5, May 2003

1) Multipath Shape Factor Theory found new parameters to describe directional channels

2) RMS delay spreads, interference, and Doppler effects all shrink dramatically for small cell directional antennas.

3) Multipath power is arriving from several discrete directions in azimuth instead of across a smooth continuum of azimuthal angles in NLOS channels.
Key Challenge: Range

• Friis’ Law: \( \frac{P_r}{P_t} = G_t G_r \left( \frac{\lambda}{4\pi r} \right)^2 \)
  - Free-space channel gain \( \propto \lambda^2 \), but antenna gains \( \propto 1/\lambda^2 \)
  - For fixed physical size antennas in free space, frequency does not matter!
  - Path loss can be overcome with beamforming, independent of frequency!

• Shadowing: Significant transmission losses possible:
  - Brick, concrete > 35 dB
  - Human body: Up to 35 dB
  - But channel is rich in scattering and reflection, even from people

• It works! NLOS propagation uses reflections and scattering
  Rappaport, et. al, “Millimeter wave mobile communications for 5G cellular: It will work!” IEEE Access, 2013
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.

T. S. Rappaport, et. al., Millimeter Wave Wireless Communications, Pearson/Prentice Hall
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

T. S. Rappaport, et. al., *Millimeter Wave Wireless Communications*, Pearson / Prentice Hall, 2014

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Future Applications

Information Showers

- The future: Showering of information
- Mounted on ceilings, walls, doorways, roadside
- Massive data streaming while walking or driving

Roadside markers can provide safety information, navigation, or even advertisements

Future Applications

Decentralized Computing

- Replace interconnect with wireless
- Applications in warehouse data centers
- Cooling servers is paramount problem
- Decentralize and focus cooling on heat-intensive components
- Increase efficiency

Cellular Spectrum above 6 GHz
Will it happen, and will it work?
A look at past research
• Attenuation due to foliage increases at mmWave frequencies.
• However, the spatial variation in shadowing is greater than lower frequencies.
• mmWave frequencies have very small wavelengths, hence smaller Fresnel zone
• Wind may modify link quality

Seidel measured signal strength up to 5 km for wireless backhaul at 28 GHz

Coverage area increases with receiver antenna height

Receiver antenna scanned only in azimuth direction

Our study showed elevation angle scanning increases coverage significantly

Table 1. Percentage of locations where sufficient signal strength was NOT received for different antenna heights and ranges of distances from the transmitter.

<table>
<thead>
<tr>
<th>Antenna Height</th>
<th>All Measurement Locations</th>
<th>&lt; 3 km From Transmitter</th>
<th>&lt; 2 km From Transmitter</th>
<th>&lt; 1 km From Transmitter</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.3 m</td>
<td>32%</td>
<td>32%</td>
<td>28%</td>
<td>14%</td>
</tr>
<tr>
<td>7.3 m</td>
<td>54%</td>
<td>55%</td>
<td>50%</td>
<td>29%</td>
</tr>
<tr>
<td>3.4, 4.0 m</td>
<td>74%</td>
<td>73%</td>
<td>70%</td>
<td>52%</td>
</tr>
</tbody>
</table>

Path loss (PL) is important: SNR (coverage) and CIR (interference) – determines cell size.

Log-normal shadowing model is most commonly used.

\[ PL_0 \]

\[ PL_0 \] is path loss measured at close-in distance \( d_0 \).

Shadowing is log-Gaussian with standard deviation \( \sigma \) in dB about distant-dependent mean PL.


Propagation Path Loss Exponent (PLE)

Maximum Coverage Distance VS Combined TX-RX Antenna Gain

- $n = 3$
- $n = 4$
- $n = 5$

Two 15 dBi Antennas
Two 24.5 dBi Antennas

$\text{Combined TX-RX Antenna Gain (dBi)}$

$\text{Maximum Coverage Distance (m)}$


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The World’s first radio channel measurements for 5G cellular

P2P (D2D), cellular, indoor
28, 38, 60, 73 GHz
In Texas and New York City
Pseudorandom Noise (PN) Generator

- Chip Rate up to 830MHz
- Size 2” X 2.6”
- 11 bit Sequence
- Custom design

Upconverter and Downconverter assemblies at 38 and 60 GHz, newer ones built at 28 GHz, 72 GHz
Transmitter
- PN sequence Generator PCB
- IF frequency of 5.4 GHz
- Changeable RF upconverter for 28, 38, 60, 72 GHz

Receiver
- Changeable RF downconverter
- IQ demodulation from IF to baseband using quadrature hybrid LO phase shifting
- Correlation circuit for multiplying and filtering PN signals
- Data Acquisition using NI USB-5133 with LabVIEW control
2011 Measurements at University of Texas

- **Peer-to-Peer 38 and 60 GHz**
  - Antennas 1.5m above ground
  - Ten RX locations (18-126m TR separation)
  - Both LOS and NLOS links measured using 8° BW 25dBi gain antennas
- **Cellular (rooftop-to-ground) at 38 GHz**
  - Four TX locations at various heights (8-36m above ground) with TR separation of 29 to 930m.
  - 8° BW TX antenna and 8° or 49°(13.3dBi gain) RX antenna. ~half of locations measured with 49° ant.
  - LOS, partially-obstructed LOS, and NLOS links
  - Outage Study – likelihood of outage
    - Two TX locations of 18 and 36m height.
    - 8° BW antennas
    - 53 random RX locations
• **Observation**: Links exist at only few angles

• Thus, full AOA is not needed to characterize channel

• Only angles that have a signal are measured

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Transmitter Locations

WRW-A          ENS-A

ECJ            ENS-B

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38 GHz 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 23m above ground
38 GHz Cellular Path Loss

- Measurements performed using 13.3 and 25dBi horn antennas
- Similar propagation was seen for clear LOS links ($n = 1.9$)
- Wider beam antenna captured more scattered paths in the case of obstructed LOS
- Large variation in NLOS links

### Summary of Path Loss Measurements

<table>
<thead>
<tr>
<th></th>
<th>25dBi RX Ant.</th>
<th>13.3dBi RX Ant.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LOS</td>
<td>NLOS</td>
</tr>
<tr>
<td><strong>Path Loss Exponent</strong></td>
<td>2.30 (clear 1.90)</td>
<td>3.86 (best: 3.20)</td>
</tr>
<tr>
<td><strong>Path Loss std. dev. (dB)</strong></td>
<td>11.6 (clear 4.6)</td>
<td>13.4 (best 11.7)</td>
</tr>
</tbody>
</table>

38 GHz Outage Study

- 2 adjacent TX locations
  - **ENS**: Western side of an **8-story** building (36 m high)
  - **WRW**: Western side of a **4-story** building (18 m high)
- 53 randomly selected outdoor RX locations (indoor excluded)
- 460x740 meter region examined
- Contour lines on map show a 55 feet elevation increase from the TX locations to the edge of the investigated area

### 38 GHz 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 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.
- Shorter WRW cellsite results in a tighter cell (i.e. less interference), yet its range is significantly smaller in distance.


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28 GHz Measurements in 2012
Dense Urban NYC

- 4 TX sites
- 33 RX sites (35 w/ LOS)

- Pedestrian and vehicular traffic
- High rise-buildings, trees, shrubs

- TX sites:
  - TX-COL1 – 7 m
  - TX-COL2 – 7 m
  - TX-KAU – 17 m
  - TX-ROG – 40 m

- RX sites:
  - Randomly selected near AC outlets
  - Located outdoors in walkways
Millimeter Wave Measurements in NYC

RX location: RX9 (Othmer Residence Hall NYU-Poly, Brooklyn, New York)

TX location: ROG1 (Rogers Hall NYU-Poly, Brooklyn, New York)
73 GHz Channel Sounder 2013

TX Hardware

RX Hardware
### Summary of Measurement Locations in NYC

**28 GHz Campaign in Manhattan for 200 m cell (2012)**

<table>
<thead>
<tr>
<th>TX Location</th>
<th>TX Height (meters)</th>
<th>Number of RX Locations</th>
<th>RX Height (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>COL1</td>
<td>7</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>COL2</td>
<td>7</td>
<td>10</td>
<td>1.5</td>
</tr>
<tr>
<td>KAU</td>
<td>17</td>
<td>15</td>
<td></td>
</tr>
</tbody>
</table>

**73 GHz Campaign in Manhattan for 200 m cell (2013)**

<table>
<thead>
<tr>
<th>TX Location</th>
<th>TX Height (meters)</th>
<th>Number of RX Locations (Cellular)</th>
<th>RX Height (Cellular) (meters)</th>
<th>Number of RX Locations (Backhaul)</th>
<th>RX Height (backhaul) (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>COL1</td>
<td>7</td>
<td>11</td>
<td>2</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>COL2</td>
<td>7</td>
<td>9</td>
<td></td>
<td>14</td>
<td>11</td>
</tr>
<tr>
<td>KAU</td>
<td>17</td>
<td>11</td>
<td>2</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>KIM1</td>
<td>7</td>
<td>3</td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>KIM2</td>
<td>7</td>
<td>2</td>
<td></td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>
75 TX-RX separation distances range from 19 m to 425 m

Signal acquired up to 200 m TX-RX separation

14% of 35 TX-RX location combinations within 200 m are found to be outage

For outage, path loss > 178 dB (5 dB SNR per multipath sample) for all unique pointing angles


• 74 TX-RX separation distance range from 27 m to 216 m

• 17% of 36 TX-RX location combinations were outage in mobile scenario; 16% of 38 TX-RX location combinations found to be outages in backhaul scenario

• For outage, path loss > 181 dB (5 dB SNR per multipath sample) for all unique pointing angles

• Receiver locations chosen based on previous 28 GHz campaign


* Only a limited amount of RX selected for KIM1 and KIM2
At 28 GHz in cellular measurements the estimated outage probability is 14% for all RX locations within 200 meters;

At 73 GHz the outage probabilities are 16% and 17% within 216 meters cell size for backhaul and cellular access scenarios, respectively;

Site-specific propagation planning easily predicts outage.

*Published ICC ‘14 paper erroneously stated 20% and 50% for distances up to 425 m– corrected here.

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Signals were received at 23 out of 36 RX azimuth angles (10 degree increments)
No. of Multipath Components at 28 GHz for Unique Directional Angle Combinations

Average number of multipath components (MPCs) per distance:
First increases and then decreases with the increasing distance

Average number of MPCs per PDP:
Nearly identical for both the narrow-beam (10.9-degree HPBW) and wide-beam (28.8-degree HPBW) antenna measured cases

Measured RMS delay spread vs. T-R separation distance:
Smaller RMS delay spreads at larger distances (near 200 m) due to large path loss.

CDF of RMS delay spread:
Average and maximum RMS delay spreads are slightly smaller for wide-beam antenna case due to lower antenna gain thus smaller detectable path loss range.

Average RMS delay spread values are only slightly larger than those for 38 GHz in suburban environments.

Each point on scatter plot represents a unique pointing angle for TX and RX horn antennas.
RX (UE) Beam combining results using 1 m free space reference distance for the 7-m high TX antenna “PLE” is path loss exponent, “STD” is shadowing std. dev., “NC” is noncoherent combining, “C” denotes coherent combining.

Coherent combining of 2 beams (n=3.41) < Noncoherent combining of 4 beams (n=3.44)
Coherent combining of 4 beams (n=3.15) < single best beam (n=3.68)

Path gain: 13.2 dB/decade in distance w/ 4 strongest beams coherently combined at different pointing angles compared to randomly pointed single beam.
Path gain: 5.3 dB/decade w/4 beams over single best beam (1.4X range increase)

28 GHz NLOS Omnidirectional Path Loss Models


Channel gain $\propto \lambda^2$, antenna gains $\propto 1/\lambda^2$

Frequency does not matter!

Path loss can be overcome with beamforming, independent of frequency!


Isotropic Path Loss Comparison

• Isotropic NLOS path loss measured in NYC
  • ~ 20 - 30 dB worse than 3GPP urban micro model for fc=2.5 GHz

• Beamforming will more than offset this loss.

• Bottom line:
  mmW omni channels do not experience much path loss beyond the simple free space frequency dependence in urban New York City


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Hybrid LOS-NLOS-Outage Model

- mmW signals susceptible to severe shadowing.
  - Not incorporated in standard 3GPP models, but needed for 5G

- New three state link model:
  LOS-NLOS-outage
  - Other Outage modeling efforts (Bai, Vaze, Heath ‘13)

- Outages significant only at $d > 150m$
  - Will help smaller cells by reducing interference


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Simulations: SNR Distribution

• Simulation assumptions:
  • 200m ISD
  • 3-sector hex BS
  • 20 / 30 dBm DL / UL power
  • 8x8 antenna at BS
  • 4x4 (28 GHz), 8x8 (73 GHz) at UE

• A new regime:
  • High SNR on many links
  • Better than current macro-cellular
  • Interference is non dominant

Comparison to Current LTE

- Initial results show significant gain over LTE
- Further gains with spatial mux, subband scheduling and wider bandwidths

<table>
<thead>
<tr>
<th>System antenna</th>
<th>Duplex BW</th>
<th>fc (GHz)</th>
<th>Antenna</th>
<th>Cell throughput (Mbps/cell)</th>
<th>Cell edge rate (Mbps/user, 5%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>mmW</td>
<td>1 GHz TDD</td>
<td>28</td>
<td>4x4 UE 8x8 eNB</td>
<td>DL: 1514, UL: 1468</td>
<td>DL: 28.5, UL: 19.9</td>
</tr>
<tr>
<td>mmW</td>
<td>73</td>
<td></td>
<td>8x8 UE 8x8 eNB</td>
<td>DL: 1435, UL: 1465</td>
<td>DL: 24.8, UL: 19.8</td>
</tr>
<tr>
<td>Current LTE</td>
<td>20+20 MHz FDD</td>
<td>2.5</td>
<td>(2x2 DL, 2x4 UL)</td>
<td>DL: 53.8, UL: 47.2</td>
<td>DL: 1.80, UL: 1.94</td>
</tr>
</tbody>
</table>

10 UEs per cell, ISD=200m, hex cell layout
LTE capacity estimates from 36.814

~ 25x gain  ~ 10x gain


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Recent Results by Nokia for 73 GHz

* Assumes RF BW of 2.0 GHz, NCP-SC Modulation
* Symbol Rate 1.536 Gigasymbols/sec (50 X LTE)
* Access Point Array: 4 sectors, dual 4X4 polarization
* Ideal Channel State estimator and Fair Scheduler
* Beamforming using uplink signal

Simulation Results:
4X4 array: 3.2 Gbps (15.7 Gbps peak), 19.7% outage
8X8 array: 4.86 Gbps (15.7 Gbps peak), 11.5% outage

Outage can be reduced by denser cells, smart repeaters/relays

Multi-Cell Analysis (1/2)

Ray-Tracing Simulation in Real City Modeling with Different Antenna Heights

Real City (Ottawa)

Antenna Height Scenario

- **Scenario 1**
  - 30m above Rooftop

- **Scenario 2**
  - 5m above Rooftop

- **Scenario 3**
  - 10m above Ground

Ray-Tracing
Ray-Tracing based Channel Models and System Level Simulations

Scenario 3 (Higher Path-loss Exponent) gives better system performances in small cell deployment
Samsung's Vision
Mobile Device Feasibility – Antenna Implementation

32 Elements Implemented on Mobile Device with “Zero Area” and 360° Coverage

“Zero Area” Design

Negligible Area for Antennas In Edges

< 0.2 mm

Measurement Results

Normalized Gain (dBi)

Angle (deg)

Mobile Device Feasibility – Antenna Implementation

© 2014 Samsung DMC R&D Communications Research Team
Multihop Relaying for mmW

- Significant work in multi-hop transmissions for cellular
- Gains have been minimal
- Why?
  - Current cellular systems are bandwidth-limited
  - mmWave is noise-limited
- Millimeter wave are different
  - Overcome outage via macrodiversity
  - Many degrees of freedom
  - Spatial processing / beamforming are key
Welcome Address by

Hossein Moiin
Chief Technology Officer (CTO) of NSN
John Stankey
Group President and Chief Strategy Officer, AT&T

Keynote: Better, Stronger, Faster: Unleashing the Next Generation of Innovation
US Spectrum Status for Higher Speed
Michael Ha, FCC
For now, the field is still in what Rappaport cheerfully calls a "pre-competitive" stage, where the industry is sharing support for research institutions around the world and putting its heads together around standards. Once the first product rolls off the production line, though, it's game on.
Industry and academia is paying attention

MILLIMETER WAVE PAPER AMONG IEEE’S MOST RESEARCHED

"Millimeter Wave Mobile Communications for 5G Cellular: It Will Work," a recent journal paper co-authored by NYU WIRELESS Director Theodore (Ted) Rappaport and his students, was among the top 50 papers downloaded from the entire library of IEEE in the month of June. Ranked as the 36th most popular paper throughout the world in IEEE’s global collection of publications, the paper promotes a vision of a new millimeter-wave mobile communication standard that could permit thousands of times greater data throughput to cellphones, and presents pioneering radio channel measurements made in New York City and Austin, Texas. The work points the way for futuristic adaptive antennas in cellphones that would use the millimeter wave spectrum.
The Renaissance is before us

Technical.ly

Do we have a shortage of bandwidth or imagination?: Dr. Andrea Goldsmith

‘The Internet of Things’ movement aimed at connecting anything with a plug to the web will define 5G. We’ll see something like 50 billion sharing information through the cloud by 2020.

Checking out technology exhibits at the Brooklyn 5G Summit.

Do we really have a shortage of bandwidth? Or do network providers need to simply deploy more of the technology we already have available? That was the
mmW systems offer orders of magnitude capacity gains

Experimental confirmation in NYC

- 200 m cell radius very doable
- Greater range extension through beam combining
- Orders of magnitude capacity gains from increased bandwidth
- Early days for channel modeling and adaptive arrays – a new frontier
- NYU WIRELESS has created a Statistical Spatial Channel Model for 28 GHz – complete simulator

Systems enter new regime:

- Links are directionally isolated, high SNR, noise-limited channel
- Links rely heavily on beamforming
- Cooperation and base station diversity should offer big improvements

What is old is new again!

- Revisit old concepts, relays, channels, narrow beams -- mature concepts but now noise-limited
• There is a lack of measurements and models at millimeter wave frequencies for outdoor cellular

• We found no outages for cells smaller than 200 m, with 25 dB gain antennas and typical power levels in Texas

• We continue to investigate New York City, for indoor and outdoor mmWave channels

• On-chip and integrated package antennas at millimeter wave frequencies will enable massive data rates, far greater than today’s 4G LTE

• Massive investments will soon be made

• This an exciting frontier for the future of wireless,
In the *massively broadband* ® era, wireless will obviate print, magnetic media and wired connections, in revolutionary ways!

It took 30 years to go one decade in wireless carrier frequency (450 MHz to 5.8 GHz), yet we will advance another decade in the next year (5.8 to 60 GHz). By 2020, we will have devices well above 100 GHz and 20 Gbps in 5G and 6G cellular networks.

Millimeter Wave Wireless Communications offers a rich research field for low power electronics, integrated antennas, space-time processing, communication theory, simulation, networking, and applications – a new frontier.

The Renaissance of wireless is before us. Massive bandwidths and low power electronics will bring wireless communications into new areas never before imagined, including vehicles, medicine, and the home of the future.
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To Zettabytes…and beyond