5G Millimeter Wave Wireless: Trials, Testimonies, and Target Rollouts

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Outline

- 4G LTE and 5G: Practical Base Station Deployment Issues
- How 4G is evolving to 5G and small cells: myth-busting at mmW
- Recent testimonies and results of 5G Trials in the USA
- Key Regulatory Needs: Inputs for Regulatory Focus at FCC
- Conclusion

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4G LTE Base Stations and Antennas [1,2]

Cellular antennas on a lattice tower (Katherin USA).

Bass drum in the sky, courtesy of CommScope [3].

A example of 8×2 antenna array architecture [4].

Streetlight small cells (CommScope).

Cell sites on rooftops.

Typical and Relative Multi-column Antenna Size for [4]:

- 850 MHz, 1900 MHz, 2500 MHz
- 4-column planar arrays with 0.5 wavelength spacing

Why *hybrid* beamforming for mmWave?

- Large numbers of antennas at TX/RX
- Reduced number of RF chains, reduced hardware complexity & cost
- Comparable spectral efficiency with digital beamforming


3GPP LTE-Advanced (4G) Downlink Schemes

[1,2]

Single-user MIMO (SU-MIMO)

Single-layer beamforming (Single-layer BF)

Multi-user MIMO (MU-MIMO)

Joint processing CoMP (JP-CoMP)

Coordinated scheduling/beamforming-CoMP (CS/CB-CoMP)


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5G Motivation & mmWave Measurements

- **Spectrum shortage** in microwave band motivates use of **millimeter wave (mmWave)** for 5G cellular
- **Channel measurements** and **channel model** needed for mmWave communications

Pioneering mmWave propagation measurements in New York City by NYU WIRELESS
28 GHz & 73 GHz urban microcell (UMi), urban macrocell (UMa), small-scale fading, indoor office measurements, and 73 GHz rural macrocell (RMa) measurements from 2012 to 2017

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier Freq.</td>
<td>28 GHz</td>
</tr>
<tr>
<td>RF Bandwidth</td>
<td>800 MHz</td>
</tr>
<tr>
<td>TX &amp; RX Antenna Type</td>
<td>Rotatable Horn Antenna</td>
</tr>
<tr>
<td>TX &amp; RX Ant. Gain</td>
<td>24.5 dBi; 15 dBi</td>
</tr>
<tr>
<td>TX &amp; RX AZ Ant. HPBW</td>
<td>10.9°; 28.8°</td>
</tr>
<tr>
<td>TX &amp; RX EL Ant. HPBW</td>
<td>8.6°; 30°</td>
</tr>
<tr>
<td>TX &amp; RX Ant. Sweep</td>
<td>Yes</td>
</tr>
<tr>
<td>TX Height</td>
<td>7 m, 17 m</td>
</tr>
<tr>
<td>RX Height</td>
<td>1.5 m</td>
</tr>
<tr>
<td>Max. TX Power</td>
<td>30.1 dBm</td>
</tr>
<tr>
<td>Max. Measurable Path Loss</td>
<td>178 dB</td>
</tr>
</tbody>
</table>


T. S. Rappaport *et al.*, "Wideband millimeter-wave propagation measurements and channel models for future wireless communication system design," *IEEE Transactions on Communications*, vol. 63, no. 9, pp. 3029-3056, Sep. 2015.

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Myth-busting at MmWave

- Atmospheric absorption too high? NO
  - 0.06 dB/km at 28 GHz; 0.08 dB/km at 38 GHz

- Rain attenuation too high?
  - At 200 m 28 GHz: 1.2 dB; 73 GHz: 2.0 dB

- Free Space Path Loss too high? NO
  - Friis’ FSPL: \( \frac{P_r}{P_t} = G_t G_r \left( \frac{\lambda}{4\pi d} \right)^2 \)
  - Antenna gain: \( G = \frac{A_e 4\pi}{\lambda^2} \)
  - As \( f \) increases with constant \( A_e \), gain of each antenna increases as a function of the square of the frequency ratio: \( G_{\text{increase}} = \left( \frac{f_2}{f_1} \right)^2 \)
  - TX \( A_e \) constant, Rx order of \( \lambda \), \( P_r \) is identical
  - TX/RX \( A_e \) constant, \( P_r \) is greater than lower \( f \)!!!

Path Loss (PL) Models at MmWave

- Identified inaccuracies with floating-intercept (FI) model compared with close-in (CI) path loss model [1]

\[
\text{PL}^{\text{CI}}(f_c, d)[\text{dB}] = \text{FSPL}(f_c, d_0) + 10n \log_{10} \left( \frac{d}{d_0} \right) + \chi \sigma; \text{ for } d_0 = 1 \text{ m}
\]

\[
\text{PL}^{\text{FI}}(d)[\text{dB}] = 10 \cdot \alpha \log_{10}(d) + \beta + X^{\text{FI}}_\sigma
\]

- Use a 1 m universal FSPL reference distance [2, 3]

- Stressed importance of directional PL models [1, 2]

- Path loss at mmWaves attenuate with distance similarly to UHF bands [2]. The first meter is the key!


Major Differences Between 3GPP/ITU and NYUSIM Channel Models

Number of clusters – Relates to Channel Rank

<table>
<thead>
<tr>
<th>Parameter Name and Reference Source</th>
<th>LOS</th>
<th>NLOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>3GPP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of clusters [3]</td>
<td>12</td>
<td>19</td>
</tr>
<tr>
<td>Number of rays per cluster [3]</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Number of time clusters [6]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Discrete Uniform [1, 6]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NYUSIM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of subpaths per time cluster [6]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poisson(1.9)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poisson(1.5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of spatial lobes (departure) [6]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poisson(1.8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of spatial lobes (arrival) [6]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poisson(2.1)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

LOS probability model

Path loss model

- Not PLE
- Floating intercept, no physical basis

NYUSIM & 3GPP Optional Path Loss Model: Close-in Free Space Reference Distance (CI) Model

$$PL^{CI}(f, d)[dB] = FSPL(f, 1 \, m)[dB] + 10n \log_{10} \left( \frac{d}{1 \, m} \right) + \chi^{CI}$$

where

- PLABG is defined as $$PL^{ABG}(f, d)[dB] = 10 \log_{10} \left( \frac{d}{1 \, m} \right) + \beta + 10n \log_{10} \left( \frac{f}{1 \, GHz} \right) + \chi^{ABG}$$
- d ≥ 1 m
- FSPL is the Free Space Path Loss
- n is the path loss exponent
- χ is the path loss parameter

PLE holds physical meaning, virtually independent of frequency

Free space path loss at 1 m & 1 GHz

Channel models impact predicted spectral efficiency

### Table: NYUSIM & 3GPP Optional Path Loss Models Comparison

<table>
<thead>
<tr>
<th>Model</th>
<th>ABG</th>
<th>CI</th>
</tr>
</thead>
<tbody>
<tr>
<td># Parameters</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Physical Basis</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Computation Complexity</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Prediction Accuracy</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Parameter Stability</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

3GPP, “Study on channel model for frequencies from 0.5 to 100 GHz,” 3rd Generation Partnership Project (3GPP), TR 38.901 V14.2.0, Sep. 2017.


Cluster Definitions: 3GPP v NYUSIM

Base station

Reflection and scattering

Line of sight

Diffraction

Scattering

Joint spatial and temporal **cluster** in 3GPP/**Spatial lobe** in NYUSIM

Subpath/Ray in a cluster (3GPP) or spatial lobe (NYUSIM)

User

In NYUSIM, rays from different spatial lobes may belong to the same **time cluster**, and vice versa

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3GPP, “Study on channel model for frequencies from 0.5 to 100 GHz,” 3rd Generation Partnership Project (3GPP), TR 38.901 V14.2.0, Sep. 2017.


NYUSIM Cluster Definition Based on mmWave Field Measurements

Time Cluster 1
Duration: 77.9 ns
8 subpaths

Time Cluster 2
Duration: 31.6 ns
6 subpaths

Void 1:
Duration: 92.5 ns

All data provided to users in “OmniPDPInfo.txt”, “OmniPDPInfo.mat”, “DirPDPInfo.txt”, and “DirPDPInfo.mat” [1][2]


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Channel eigenvalues represent power gains of parallel sub-channels, directly related to spectral efficiency. Eigenvalues of $\mathbf{HH}^H$ are squares of singular values of $\mathbf{H}$.

3GPP: Yields more eigen-channels but with weaker powers in dominant eigen-channels.

NYUSIM: Produces few but strong dominant eigen-channels.

$\eta_i = \frac{\eta'_i}{\sum_{i=1}^{N_R} \eta'_i}$

$\eta'_i$: $i$-th largest eigenvalue of $\mathbf{HH}^H$

$N_R$: minimum of numbers of TX and RX antennas.

---

[1] 3GPP, “Study on channel model for frequencies from 0.5 to 100 GHz,” 3rd Generation Partnership Project (3GPP), TR 38.901 V14.2.0, Sep. 2017.


4G LTE Advanced Pro [1,2]:

• \( \leq 64 \) antenna elements
• 1-2 Gbps data rate
• \(~10\) ms latency
• Digital beamforming

5G NR [3, 4]:

• \( \geq 256 \) antenna elements (same size)
• BS Placement: site-specific sensitivity
• > 10 Gbps data rate
• < 1 ms latency
• Hybrid beamforming [4] (most possible)

# A Simple Comparison Between LTE and 5G New Radio (NR)

<table>
<thead>
<tr>
<th></th>
<th>LTE</th>
<th>5G NR (eMBB)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of Streams</strong></td>
<td>SISO</td>
<td>SISO</td>
</tr>
<tr>
<td><strong>BW</strong></td>
<td>20 MHz</td>
<td>800 MHz</td>
</tr>
<tr>
<td><strong>Subcarrier spacing</strong></td>
<td>15KHz</td>
<td>240KHz</td>
</tr>
<tr>
<td><strong>FFT size</strong></td>
<td>2048</td>
<td>2048</td>
</tr>
<tr>
<td><strong>Number of Occupied Subcarrier</strong></td>
<td>1200</td>
<td>~1600</td>
</tr>
<tr>
<td><strong>Spectral Occupancy</strong></td>
<td>90%</td>
<td>98%</td>
</tr>
<tr>
<td><strong>Slot Duration</strong></td>
<td>0.5 ms [7symbols]</td>
<td>65us [14 symbols]</td>
</tr>
<tr>
<td><strong>Antenna</strong></td>
<td>Omni</td>
<td>64 Beams</td>
</tr>
</tbody>
</table>
5G Multi-tier network [1]

5G base stations (Nokia 5G AirScale Base Station [2]).

The directionality of 5G base stations.

5G Massive MIMO, here ten user terminals and one hundred BS antennas. The antenna array is scalable.

Heterogeneous 5G networks, Small cells and WiFi [3]

Example illustrations showing the difference between non-CoMP and CoMP (coordinated scheduling/beamforming)

**Non-CoMP**
- TP
- Each TP serves UEs in its own cell
- 2 UEs per cell

**CoMP**
(coordinated scheduling/beamforming) [1]
- TPs exchange CSI
- Each TP serves UEs in its own cell

---
Measurement Goals:
- 7 combinations of 3 TXs to 1 RX
- 7 combinations of 3 RXs from 1 TX
- Transmit across large azimuth TX sector
- Measure impulse responses at RX across azimuth and elevation planes
- Measure various LOS and NLOS environments

<table>
<thead>
<tr>
<th>RX Location</th>
<th>TX Location</th>
<th>T-R Dist (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>L3, L4, L7, L11, L13</td>
<td>80 ≤ d ≤ 140</td>
</tr>
<tr>
<td>L2</td>
<td>L3, L9, L12</td>
<td>61 ≤ d ≤ 78</td>
</tr>
<tr>
<td>L3</td>
<td>L2</td>
<td>77</td>
</tr>
<tr>
<td>L4</td>
<td>L1, L3, L7, L10, L13</td>
<td>80 ≤ d ≤ 170</td>
</tr>
<tr>
<td>L7</td>
<td>L1, L2, L4, L10</td>
<td>72 ≤ d ≤ 72</td>
</tr>
<tr>
<td>L8</td>
<td>L1, L7, L9</td>
<td>21 ≤ d ≤ 133</td>
</tr>
<tr>
<td>L9</td>
<td>L1, L2, L4, L11</td>
<td>63 ≤ d ≤ 78</td>
</tr>
<tr>
<td>L10</td>
<td>L4, L7, L13</td>
<td>50 ≤ d ≤ 123</td>
</tr>
<tr>
<td>L12</td>
<td>L1, L2, L4, L7, L11</td>
<td>61 ≤ d ≤ 140</td>
</tr>
<tr>
<td>L13</td>
<td>L1, L4, L10</td>
<td>59 ≤ d ≤ 107</td>
</tr>
</tbody>
</table>

Nearest Neighbor TX Distance Stats over all RX Locations

<table>
<thead>
<tr>
<th>Nearest Neighbor</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean [m]: d / Median [m]: d</td>
<td>62/61</td>
<td>74/78</td>
<td>93/87</td>
</tr>
<tr>
<td>STD [m]: σ</td>
<td>18</td>
<td>14</td>
<td>20</td>
</tr>
<tr>
<td>Range [m]: d ∈ [min, max]</td>
<td>[21,80]</td>
<td>[41,87]</td>
<td>[78,140]</td>
</tr>
</tbody>
</table>

NYU Tandon Brooklyn Campus - UMi Open Square – CoMP at 73 GHz

11 Locations over 200 m x 200 m

TX height: 4 m
RX height: 1.4 m

MmWave CoMP Downlink: Conclusions

- Assuming blockages from pedestrian users (4-state markov)
- Full-Interference Results (22% of NYU dual BS CoMP links):
  - 81% of network realizations have SE gain (MMSE)
  - 16% of network realizations have SE gain (MMSE) ≥ 2
- Partial-Interference Results (35% of NYU dual BS CoMP):
  - 81% of network realizations w/ MMSE have gain
  - 7% of network realizations w/ MMSE have gain ≥ 2
- Almost half (~43%) of network realizations have no need for coordination; lack interference at mmW!
- CoMP for interference suppression is perhaps not worth CU processing resources and overhead, similar to LTE.
  - CSI inaccuracies (errors and outdated), synchronization, resource overhead, etc.


### 28 GHz Millimeter Wave Cellular Communication

Measurements for Penetration Loss in and around Buildings in New York City

<table>
<thead>
<tr>
<th>Environment</th>
<th>Location</th>
<th>Material</th>
<th>Thickness (cm)</th>
<th>Received Power - Free Space (dBm)</th>
<th>Received Power - Material (dBm)</th>
<th>Penetration Loss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outdoor</td>
<td>ORH</td>
<td>Tinted Glass</td>
<td>3.8</td>
<td>-34.9</td>
<td>-75.0</td>
<td>40.1</td>
</tr>
<tr>
<td></td>
<td>WWH</td>
<td>Brick</td>
<td>185.4</td>
<td>-34.7</td>
<td>-63.1</td>
<td>28.3</td>
</tr>
<tr>
<td></td>
<td>MTC</td>
<td>Clear Glass</td>
<td>&lt;1.3</td>
<td>-35.0</td>
<td>-38.9</td>
<td>3.9</td>
</tr>
<tr>
<td>Indoor</td>
<td>WWH</td>
<td>Tinted Glass</td>
<td>&lt;1.3</td>
<td>-34.7</td>
<td>-59.2</td>
<td>24.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Clear Glass</td>
<td>&lt;1.3</td>
<td>-34.7</td>
<td>-38.3</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wall</td>
<td>38.1</td>
<td>-34.0</td>
<td>-40.9</td>
<td>6.8</td>
</tr>
</tbody>
</table>

**TABLE II**

COMPARISON OF PENETRATION LOSSES FOR DIFFERENT ENVIRONMENTS AT 28 GHZ. THICKNESSES OF DIFFERENT COMMON BUILDING MATERIALS ARE LISTED. BOTH OF THE HORN ANTENNAS HAVE 24.5 DBI GAINS WITH 10° HALF POWER BEAMWIDTH.

NYU WIRELESS, Rappaport, et. al. “Millimeter Wave Mobile Communications for 5G Cellular, it will work!” IEEE ACCESS Vol. 1, 2013
AT&T launched its largest 5G fixed wireless trial in Waco, Texas, at the Silos [1].

- 5G trial service is distributed through a number of WiFi access points to serve 5,000 people who shop at the Silos[1]. Attenuation by tinted glass is major issue.

- AT&T launched fixed wireless 5G trials to business and residential customers in Austin, Texas; Kalamazoo, Michigan; and South Bend, Indiana [2].

- More than1 Gbps download rate and less than 10 ms latency (15 and 28 GHz) [2] using the first release of 3GPP (before 5GNR).

- First commercial roll-outs likely to focus on stand alone “pucks”, fixed devices that serve as relays/hotspots for WiFi in fixed/indoor use

- First cellphones with 5GNR mmW not expected until late 2018/early 2019

Verizon Wireless has been trialing fixed 5G in **eleven** cities [1].


- First commercial service available in Sacramento, Calif., during the second half of 2018 [1].

- Trials of fixed 5G service are progressing better than expected (28 and 39 GHz) [2]. Well over 1 Gbps, less than 10 ms

- These systems use first 3GPP implementation (prior to 5GNR)

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[3] https://technewstt.com/pr-ericsson-verizon-5g/
Examples of FWA deployment alternatives
Excerpt from Ericsson Technology review, 5G & Fixed Wireless Access 10-2016

- Typical FWA deployment
- CPE is on rooftop or Wall mounted
- Windows/Wall penetration is difficult
- Wifi distribution is used inside premise
- Multi Gbps networking is limited to WiFi speed
Intel: MGbps In-Home/office Wireless Networking

External Window

Internal Wall

5G / LTE

Up to 3 Gbps

WRRH

WiFi Router
March 22, 2018—FCC voted to streamline the national approval process for deploying small cells.

Removes unnecessary regulatory barriers (NEPA/NHPA) to wireless broadband deployment.

Between 2018-2026, the order would save $1.56 billion.

The cost savings alone would allow providers to build in excess of 57,000 extra small cells and create 17,000 jobs.

Projected NHPA/NEPA Costs (2018 to 2026) [2]

<table>
<thead>
<tr>
<th>Year</th>
<th>Cumulative Small Cells Deployed by Year End ('000s)</th>
<th>Total In-Year NHPA/NEPA costs ($mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018(F)</td>
<td>138</td>
<td>$241</td>
</tr>
<tr>
<td>2019(F)</td>
<td>200</td>
<td>$176</td>
</tr>
<tr>
<td>2020(F)</td>
<td>273</td>
<td>$218</td>
</tr>
<tr>
<td>2021(F)</td>
<td>363</td>
<td>$275</td>
</tr>
<tr>
<td>2022(F)</td>
<td>468</td>
<td>$328</td>
</tr>
<tr>
<td>2023(F)</td>
<td>550</td>
<td>$263</td>
</tr>
<tr>
<td>2024(F)</td>
<td>635</td>
<td>$285</td>
</tr>
<tr>
<td>2025(F)</td>
<td>722</td>
<td>$297</td>
</tr>
<tr>
<td>2026(F)</td>
<td>821</td>
<td>$349</td>
</tr>
</tbody>
</table>

Acknowledgement to our NYU WIRELESS Industrial Affiliates and NSF
Great technology must be deployed rapidly and efficiently (time/$)

FCC small-cell Order is excellent first step, but must aggressively auction more prime (< 6 GHz) and mmW spectrum: want 39 GHz w/24 & 28 GHz 2018

Efforts needed to streamline deployment shot clock and reduce fees for deployment of 5G technology in the Right of Way (ROW), on poles, lamps.

Avoid zoning if infrastructure falls within a specific physical size or within a prescribed acceptable aesthetic footprint on lamp posts, ROW.

Create new interference and radiation rules for directional antennas, since OOBE and similar interference regs. are based on EIRP/omni antennas.
February 22, 2018—FCC initiated a proceeding to expand access to spectrum above 95 GHz.

Seeks comment on making a total 102.2 GHz of spectrum available for licensed point-to-point services, 15.2 GHz of spectrum available for use by unlicensed devices.

Seeks comment on creating a new category of experimental licenses available in spectrum between 95 GHz and 3 THz.
4G LTE morphing into 5G; MU-MIMO and CoMP offer 5 bps/Hz > UC

Interference much less of concern w/directional arrays – CoMP for IC?

Myth-busting at mmW shows greater data rates, greater coverage!

Recent testimonies, results of 5G Trials in the USA – it’s real!

Key Regulatory Needs: Small Cells and Auctions for Spectrum

mmW is “tip of the iceberg” as FCC, other countries move to THz
Acknowledgement to our NYU WIRELESS Industrial Affiliates and NSF
Thank You!
Selected References

- 3GPP, “Technical specification group radio access network; study on channel model for frequencies from 0.5 to 100 GHz (Release 14),” 3rd Generation Partnership Project (3GPP), TR 38.901 V14.2.0, Sept. 2017.
- ——, “Human body blockage - guidelines for TGad MAC development,” doc.: IEEE 802.11-09/1169r0, Nov. 2009.


• D. Kurita et al., “Field experiments on 5G radio access using multi-point transmission,” in 2015 IEEE Global Telecommunications Conference Workshops (Globecom Workshops), Dec. 2015, pp. 1-6.
