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

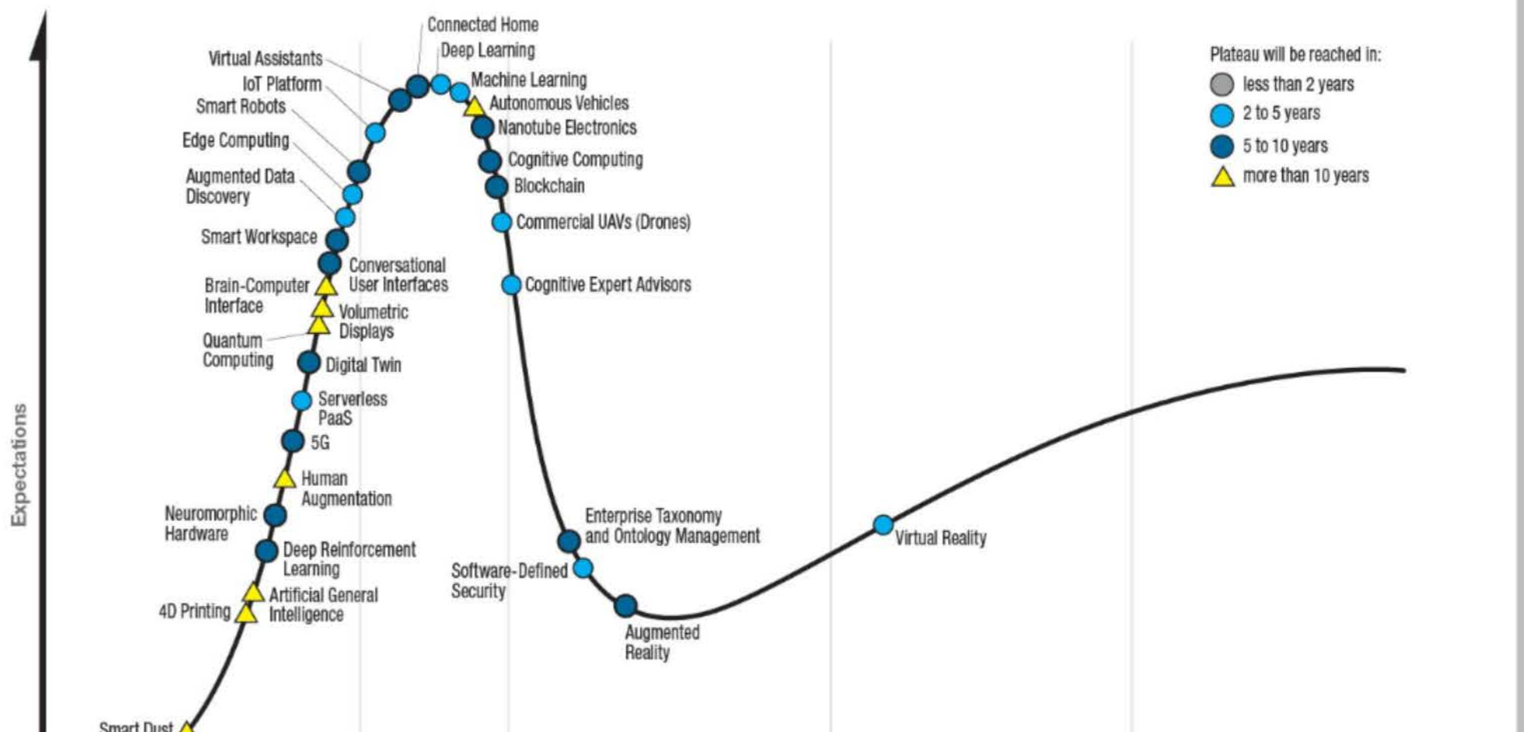
Prof. Theodore S. Rappaport
tsr@nyu.edu

Keynote Presentation
First IEEE Workshop on Millimeter-Wave Network Systems (mmSys)
IEEE Infocom
April 16, 2018
Honolulu, Hawaii

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

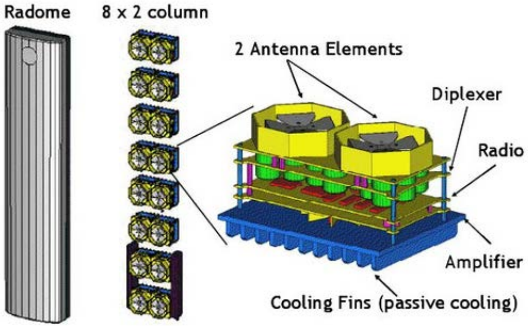
Gartner Hype Cycle for Emerging Technologies, 2017



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

Cellular antennas on a lattice tower (Katherin USA).

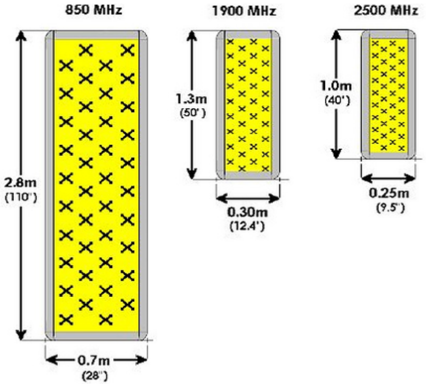
Bass drum in the sky, courtesy of CommScope [3].



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

Streetlight small cells (CommScope).

Cell sites on rooftops.



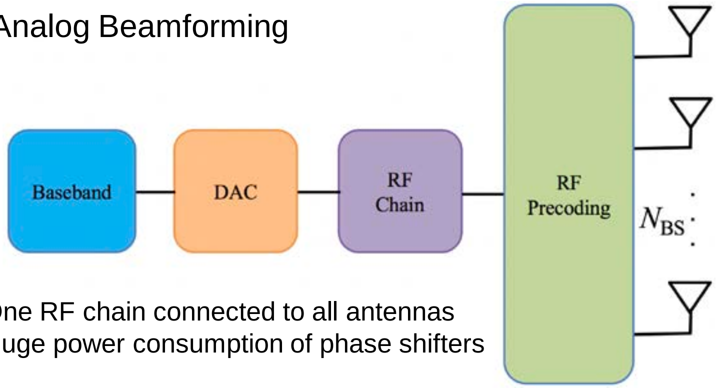
Typical and Relative Multi-column Antenna Size for [4]:

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

[1] 3GPP TR36.897 V13.0.0: "Study on elevation beamforming / full-dimension (FD) multiple input multiple output (MIMO) for LTE," Jun. 2015.
[2] 3GPP TR36.884 V13.1.0: "Performance requirements of MMSE-IRC receiver for LTE BS," Sep. 2016.
[3] https://hackaday.com/2016/04/05/a-field-guide-to-the-north-american-communications-tower/
[4] http://www.dailywireless.org/2010/05/13/mimo-the-paper-war/

Beamforming used in 4G and 5G MiMO

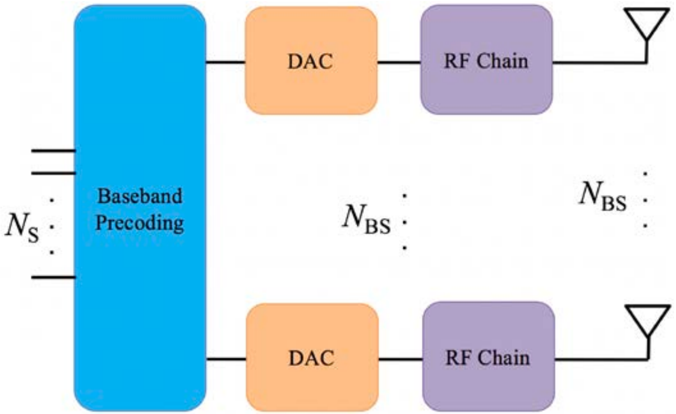
Analog Beamforming



One RF chain connected to all antennas
Huge power consumption of phase shifters

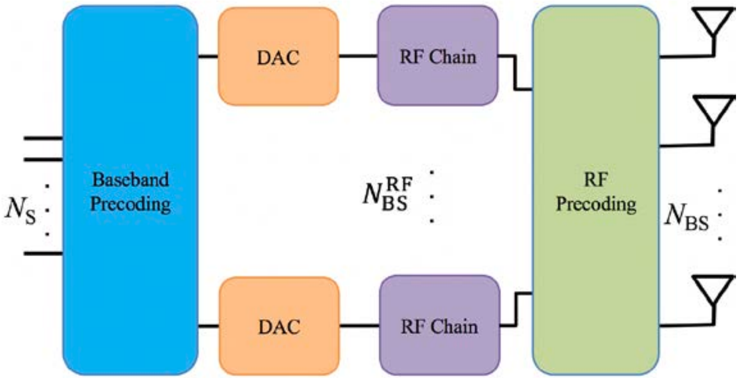
Digital Beamforming

One RF chain behind each antenna
High complexity & cost when antenna number is large



Hybrid Beamforming

Much fewer RF chains than antennas

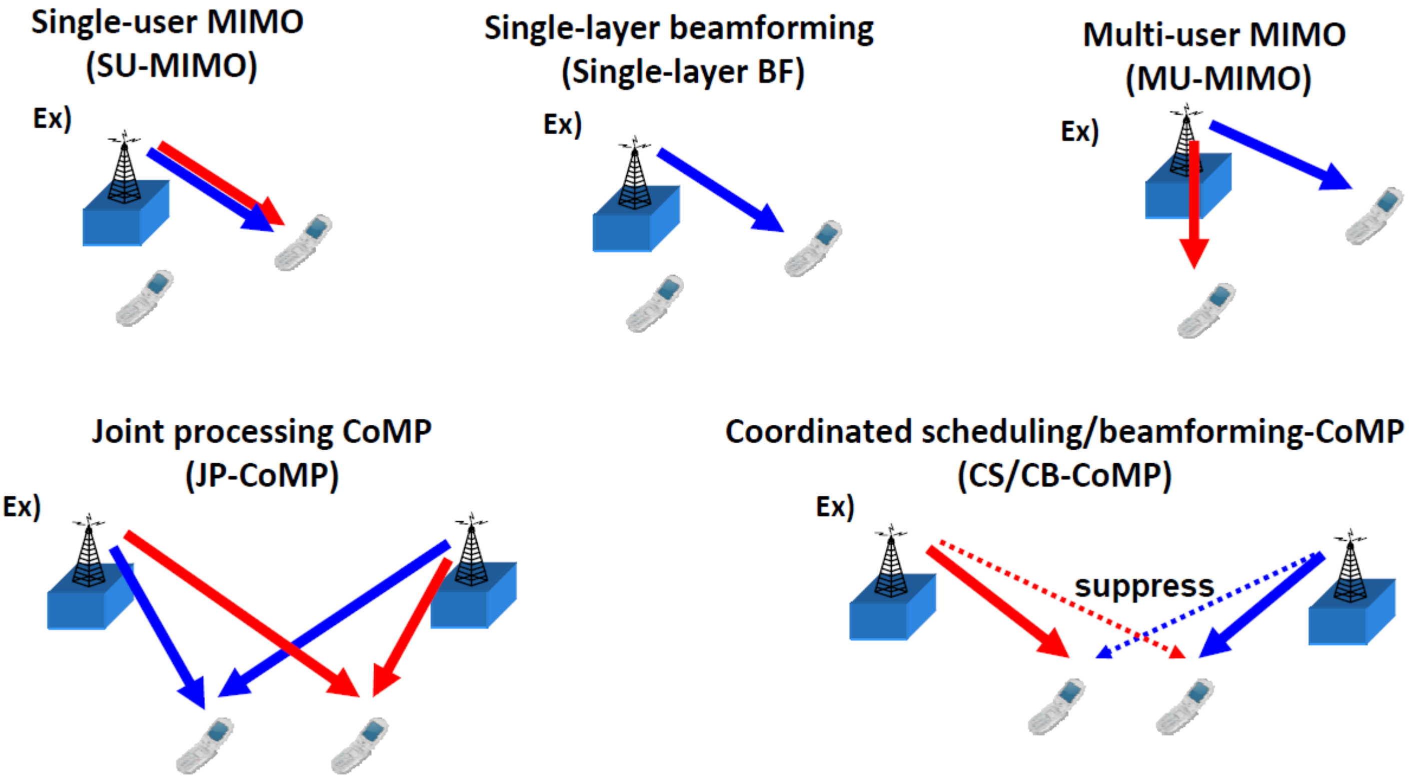


Why *hybrid* beamforming for mmWave?

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

A. Ghosh, et. al., "Millimeter-wave enhanced local area systems: A high-data-rate approach for future wireless networks," IEEE J. Sel. Areas in Communications, IEEE Journal on, vol. 32, pp. 1152-1163, June 2014. .
S. Sun, Rappaport, T. S., Heath, R. W., Nix, A., & Rangan, S. (2014) "MIMO for millimeter-wave wireless communications: Beamforming, spatial multiplexing, or both?" IEEE Communications Magazine, 52 (12), 110-121.
X. Zhang, A. F. Molisch and Sun-Yuan Kung, "Variable-phase-shift-based RF-baseband codesign for MIMO antenna selection," *IEEE Transactions on Signal Processing*, vol. 53, no. 11, pp. 4091-4103, Nov. 2005.
O. E. Ayach, S. Rajagopal, S. Abu-Surra, Z. Pi, and R. W. Heath, "Spatially sparse precoding in millimeter wave MIMO systems," *IEEE Transactions on Wireless Communications*, vol. 13, no. 3, pp. 1499–1513, Mar. 2014.

3GPP LTE-Advanced (4G) Downlink Schemes [1,2]



[1] 3GPP TR36.897 V13.0.0: "Study on elevation beamforming / full-dimension (FD) multiple input multiple output (MIMO) for LTE," Jun. 2015.
[2] 3GPP TR 36.819 V11.2.0, "Coordinated multi-point operation for LTE physical layer aspects," Sep. 2013.

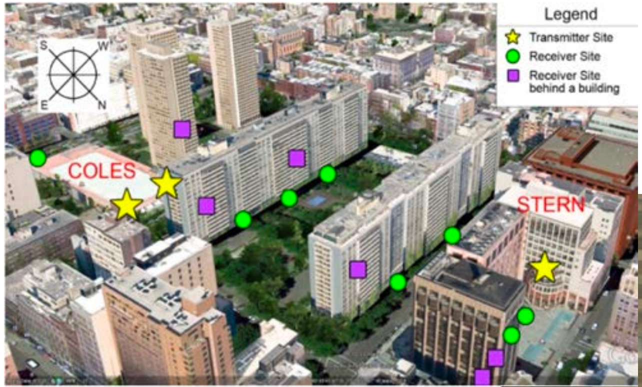
5G Motivation & mmWave Measurements

- **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

Carrier Freq.	28 GHz
RF Bandwidth	800 MHz
TX & RX Antenna Type	Rotatable Horn Antenna
TX & RX Ant. Gain	24.5 dBi; 15 dBi
TX & RX AZ Ant. HPBW	10.9^0; 28.8^0
TX & RX EL Ant. HPBW	8.6^0; 30^0
TX & RX Ant. Sweep	Yes
TX Height	7 m, 17 m
RX Height	1.5 m
Max. TX Power	30.1 dBm
Max. Measurable Path Loss	178 dB



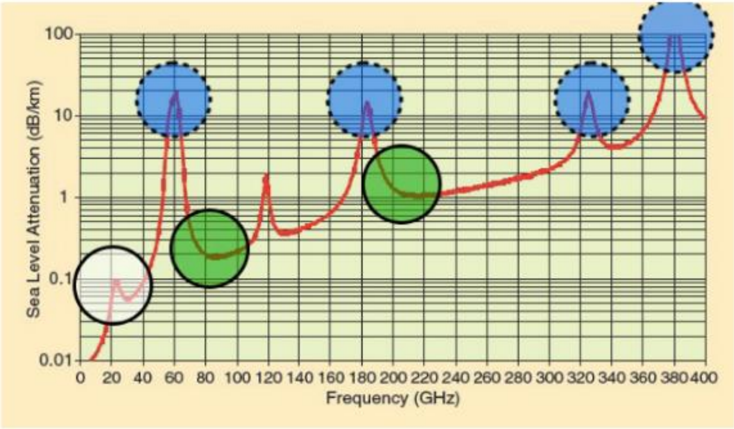
28 GHz UMi & UMa measurements in 2012

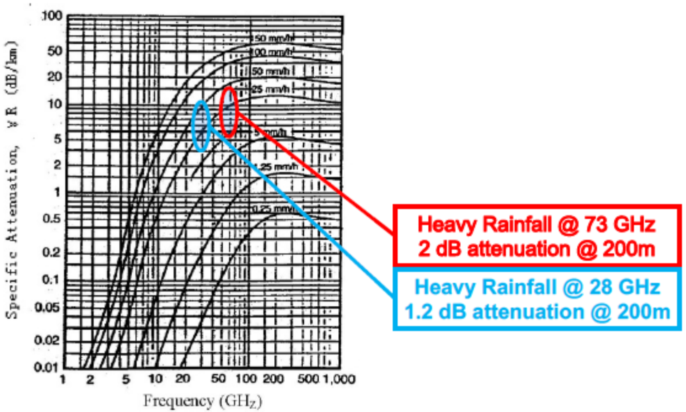
T. S. Rappaport *et al.*, "Millimeter wave mobile communications for 5G cellular: It will work!," *IEEE Access*, (1), pp. 335-349, 2013.

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.

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 frequency ratio: $G_{\text{increase}} = \left(\frac{f_2}{f_1}\right)^2$
  - TX A_e constant, Rx order of λ, P_r is identical
  - TX/RX A_e constant, P_r is greater than lower f!!!





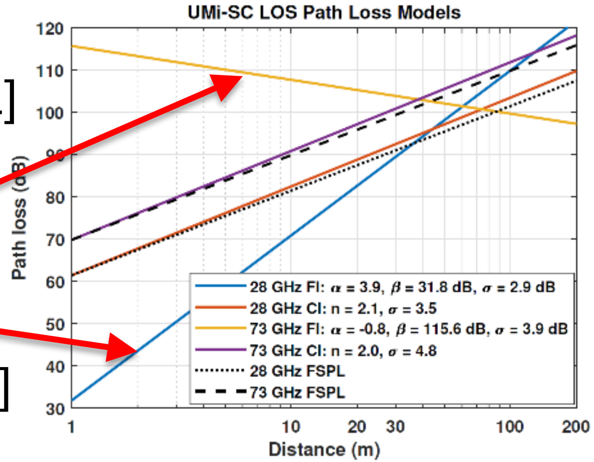
- T. S. Rappaport, et. al., "Millimeter Wave Wireless Communications," Pearson/Prentice Hall c. 2015
- T. S. Rappaport, J. N. Murdock, and F. Gutierrez, "State of the art in 60-GHz integrated circuits and systems for wireless communications," Proceedings of the IEEE, vol. 99, no. 8, pp. 1390{1436, Aug. 2011.
- T. S. Rappaport et al., "Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!" IEEE Access, vol. 1, pp. 335{349, May 2013.

Path Loss (PL) Models at MmWave

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

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

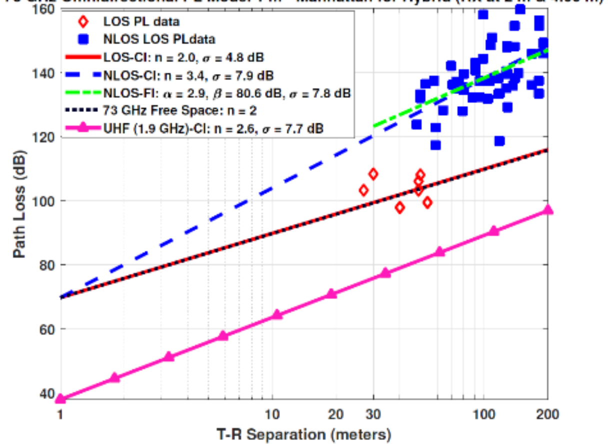
$$\mathrm{PL}^{\mathrm{FI}}(d)[\mathrm{dB}] = 10 \cdot \alpha \log_{10}(d) + \beta + X_\sigma^{\mathrm{FI}}$$



- 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!



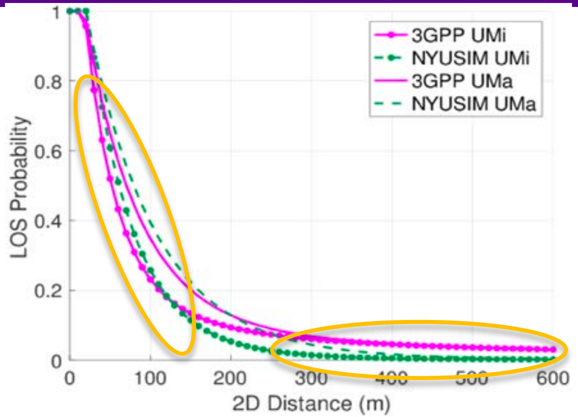
[1] G. R. MacCartney, Jr., J. Zhang, S. Nie, and T. S. Rappaport, “Path loss models for 5G millimeter wave propagation channels in urban microcells,” in 2013 IEEE Global Communications Conference (GLOBECOM), Atlanta, GA, Dec. 2013, pp. 3948-3953.
[2] T. S. Rappaport, G. R. MacCartney, Jr., M. K. Samimi, and S. Sun, “Wideband millimeter-wave propagation measurements and channel models for future wireless communication system design (Invited),” IEEE Transactions on Communications, vol. 63, no. 9, pp. 3029-3056, Sept. 2015.
[3] G. R. MacCartney, Jr., M. K. Samimi, and T. S. Rappaport, “Omnidirectional Path Loss Models in New York City at 28 GHz and 73 GHz,” in 2014 IEEE 25th Annual International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC), Washington, D.C., Sept. 2014, pp. 227-231.

Major Differences Between 3GPP/ITU and NYUSIM Channel Models

Number of clusters – Relates to Channel Rank

	Parameter Name and Reference Source	LOS	NLOS
3GPP	Number of clusters [3]	12	19
	Number of rays per cluster [3]	20	20
NYUSIM	Number of time clusters [6]	Discrete Uniform [1, 6]	
	Number of subpaths per time cluster [6]	Discrete Uniform [1, 30]	
	Number of spatial lobes (departure) [6]	Poisson(1.9)	Poisson(1.5)
	Number of spatial lobes (arrival) [6]	Poisson(1.8)	Poisson(2.1)

LOS probability model



Path loss model

Not PLE

Floating intercept, no physical basis

$$\mathrm{PL}^{\mathrm{ABG}}(f,d)[\mathrm{dB}] = 10\alpha \log_{10}\left(\frac{d}{1\ m}\right) + \beta + 10\gamma \log_{10}\left(\frac{f}{1\ \mathrm{GHz}}\right) + \chi_\sigma^{\mathrm{ABG}},\ \text{where } d \geq 1\ \mathrm{m}$$

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

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

$$= \boxed{10n \log_{10}\left(\frac{d}{1\ \mathrm{m}}\right)} + 32.4 + 20 \log_{10}\left(\frac{f}{1\ \mathrm{GHz}}\right) + \chi_\sigma^{\mathrm{CI}},\ \text{where } d \geq 1\ \mathrm{m}$$

PLE holds physical meaning, virtually independent of frequency

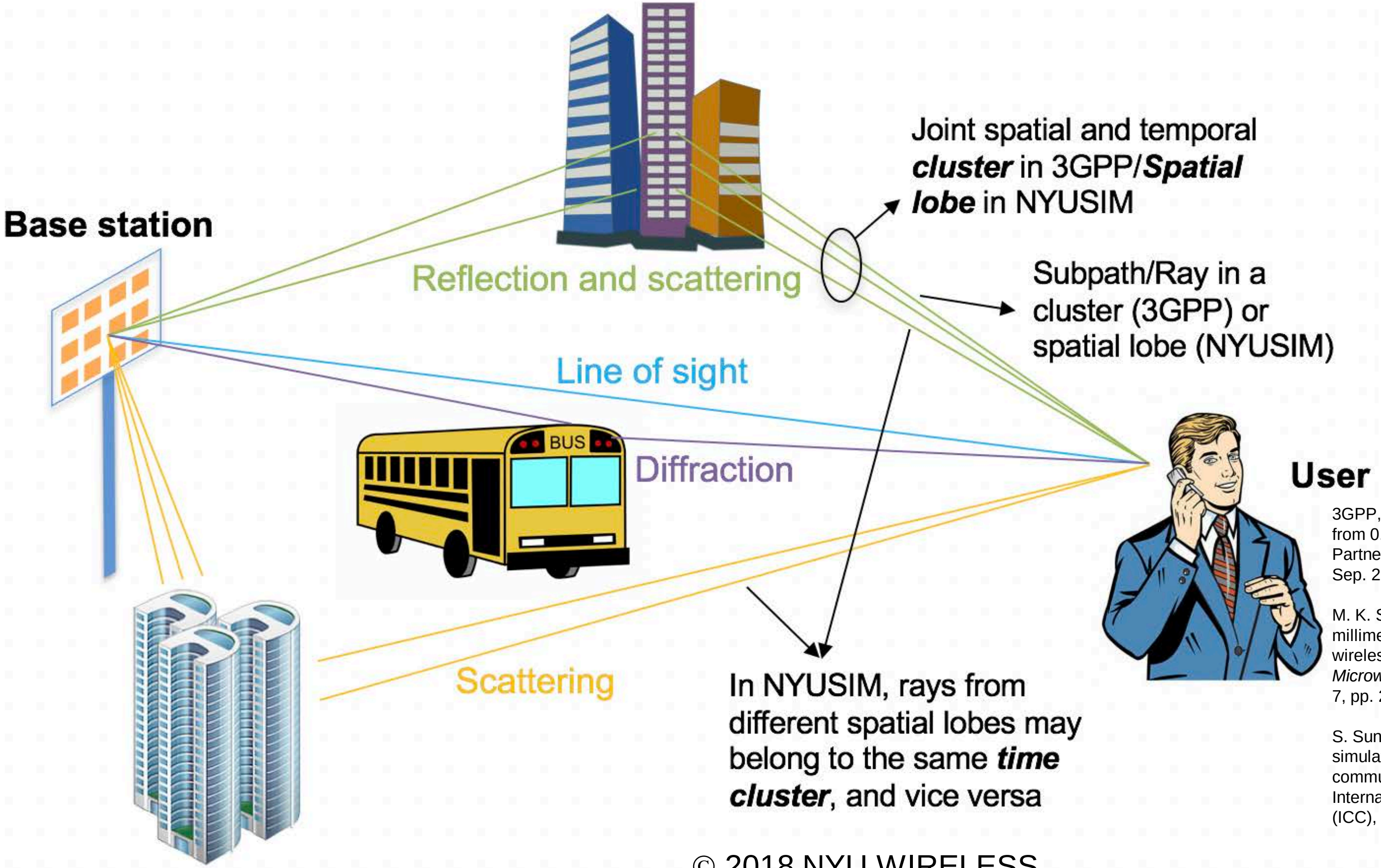
Free space path loss at 1 m & 1 GHz

Model	ABG	CI
# Parameters	3	1
Physical Basis	No	Yes
Computation Complexity	High	Low
Prediction Accuracy	Low	High
Parameter Stability	Low	High

Channel models impact predicted spectral efficiency

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.
S. Sun *et al.*, "Investigation of prediction accuracy, sensitivity, and parameter stability of large-scale propagation path loss models for 5G wireless communications," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 5, pp. 2843-2860, May 2016.
M. K. Samimi and T. S. Rappaport, "3-D millimeter-wave statistical channel model for 5G wireless system design," *IEEE Transactions on Microwave Theory and Techniques*, vol. 64, no. 7, pp. 2207–2225, Jul. 2016.
S. Sun *et al.*, "A novel millimeter-wave channel simulator and applications for 5G wireless communications," in *Proceedings of the IEEE International Conference on Communications (ICC)*, Paris, France, 2017, pp. 1-7.

Cluster Definitions: 3GPP v NYUSIM

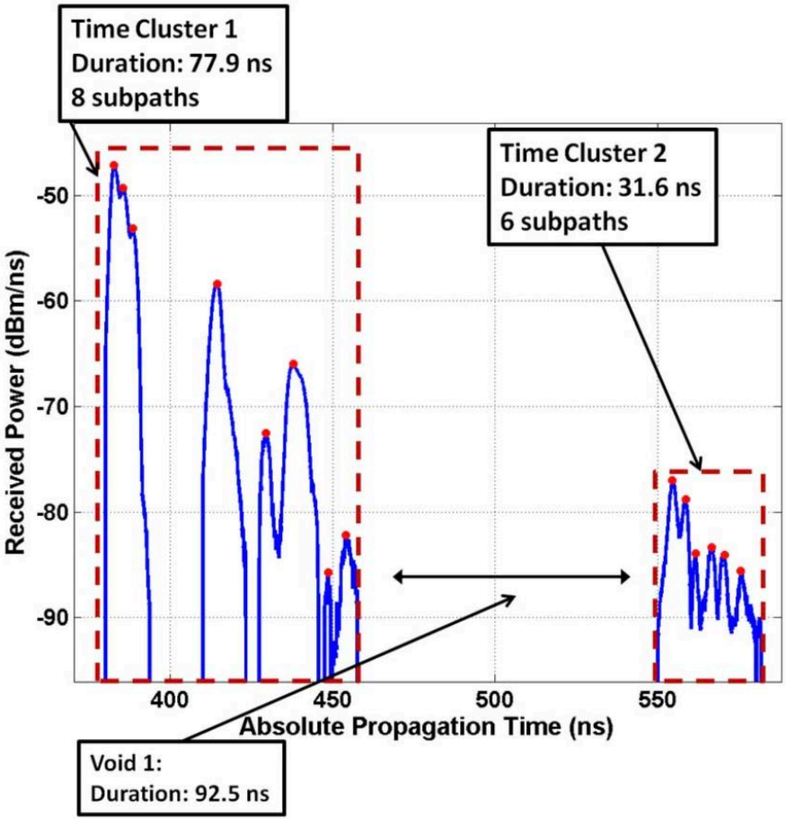


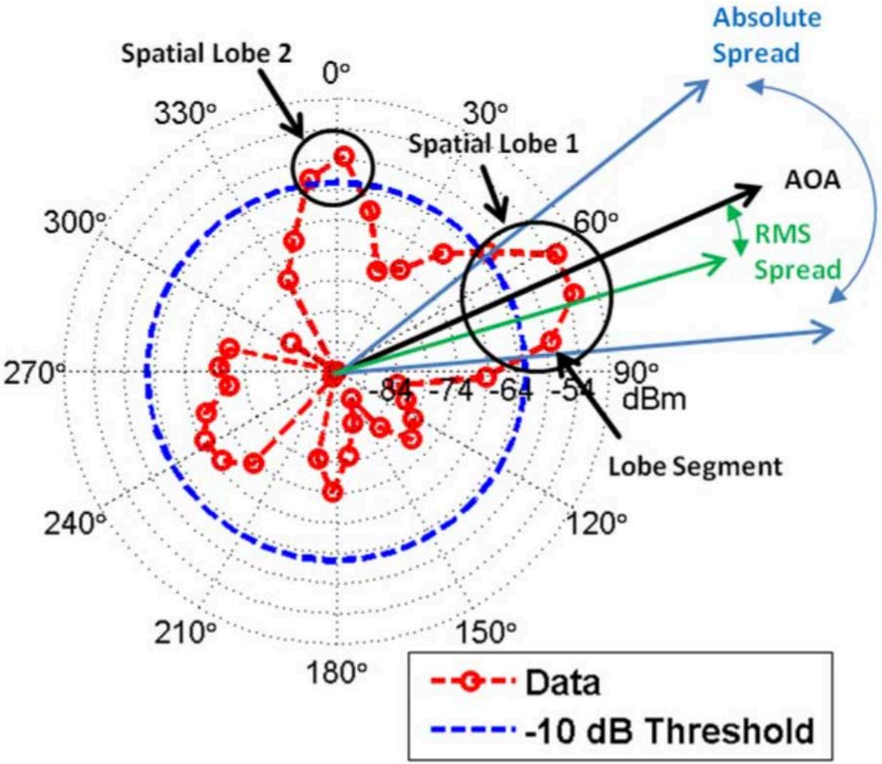
3GPP, "Study on channel model for frequencies from 0.5 to 100 GHz," 3rd Generation Partnership Project (3GPP), TR 38.901 V14.2.0, Sep. 2017.

M. K. Samimi and T. S. Rappaport, "3-D millimeter-wave statistical channel model for 5G wireless system design," *IEEE Transactions on Microwave Theory and Techniques*, vol. 64, no. 7, pp. 2207–2225, Jul. 2016.

S. Sun et al., "A novel millimeter-wave channel simulator and applications for 5G wireless communications," in Proceedings of the IEEE International Conference on Communications (ICC), Paris, France, 2017

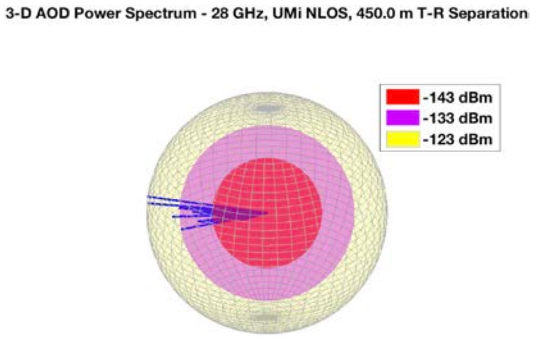
NYUSIM Cluster Definition Based on mmWave Field Measurements

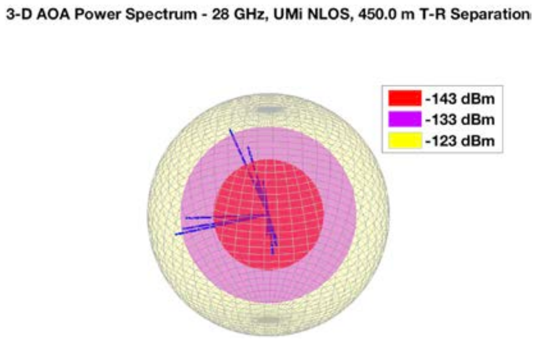


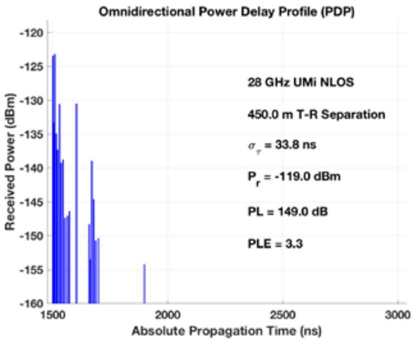


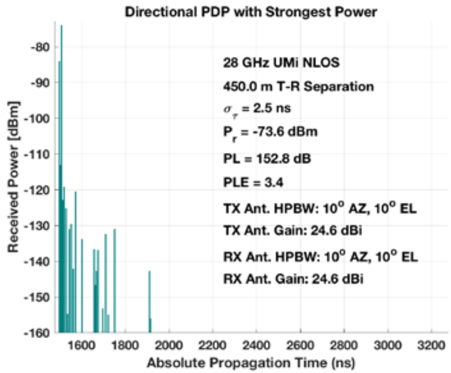
M. K. Samimi and T. S. Rappaport, "3-D millimeter-wave statistical channel model for 5G wireless system design," *IEEE Transactions on Microwave Theory and Techniques*, vol. 64, no. 7, pp. 2207–2225, Jul. 2016.

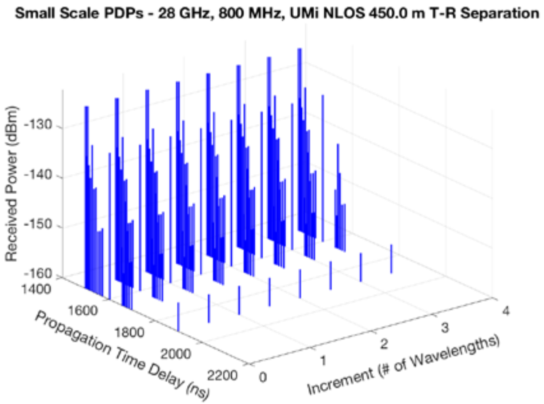
NLOS Output Figures from NYUSIM

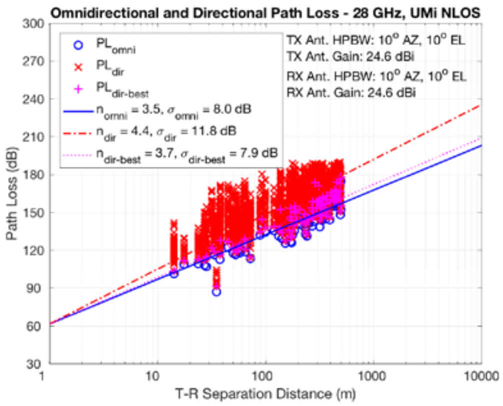












All data provided to users in "OmniPDPInfo.txt", "OmniPDPInfo.mat", "DirPDPInfo.txt", and "DirPDPInfo.mat" [1][2]

[1] S. Sun *et al.*, "A novel millimeter-wave channel simulator and applications for 5G wireless communications," in *Proceedings of the IEEE International Conference on Communications (ICC)*, Paris, France, 2017, pp. 1-7.
[2] NYUSIM download link: http://wireless.engineering.nyu.edu/nyusim/

NYUSIM vs. 3GPP Channel Model --- Eigenvalues of $\mathbf{HH}^H$

Channel eigenvalues represent power gains of parallel sub-channels, directly related to spectral efficiency

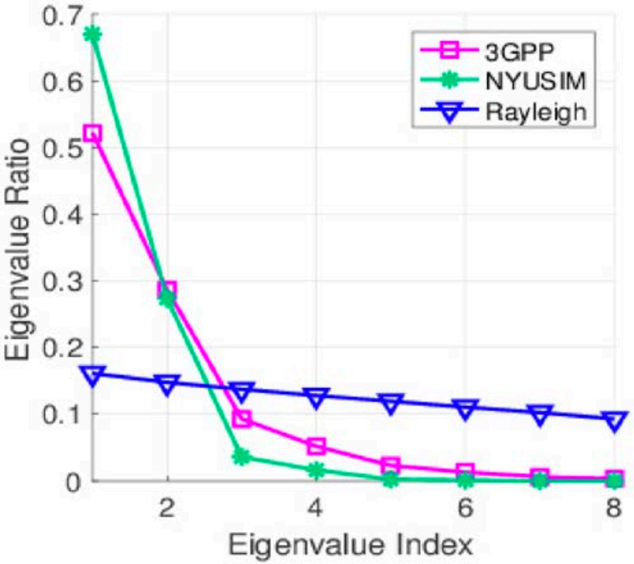
Eigenvalues of $\mathbf{HH}^H$ are squares of singular values of $\mathbf{H}$

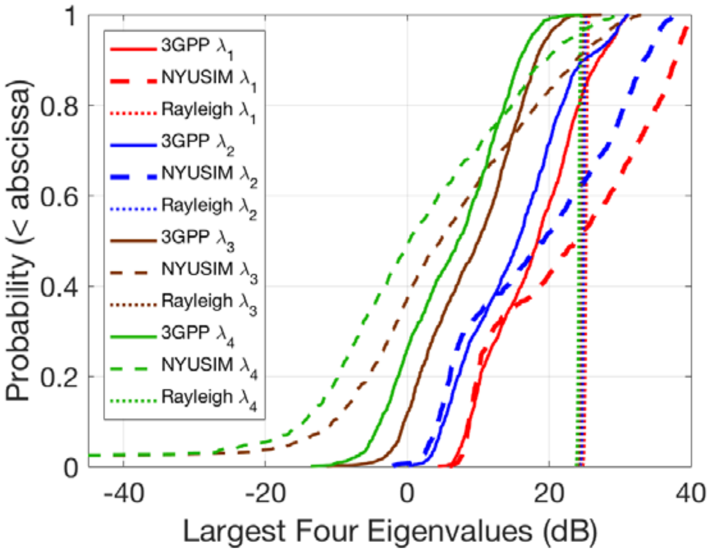
3GPP: *Yields more eigen-channels but with weaker powers in dominant eigen-channels*
NYUSIM: *Produces few but strong dominant eigen-channels*

$$\eta_i = \frac{\eta_i'}{\sum_{i=1}^{N_\mathrm{R}} \eta_i'}$$

η_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.
[2] International Telecommunications Union (ITU), \Guidelines for evaluation of radio interface technologies for IMT-2020," REP. Revision 2 to Document 5D/TEMP/347-E, Niagara Falls, Canada, Jun. 2017.
[3] O. E. Ayach, S. Rajagopal, S. Abu-Surra, Z. Pi, and R. W. Heath, "Spatially sparse precoding in millimeter wave mimo systems," *IEEE Transactions on Wireless Communications*, vol. 13, pp. 1499{1513, Mar. 2014.
[4] T. S. Rappaport, R. W. Heath, Jr., R. C. Daniels, and J. N. Murdock, Millimeter Wave Wireless Communications. Pearson/Prentice Hall 2015.
[5] T. S. Rappaport, S. Sun, and M. Shafi, "5G channel model with improved accuracy and efficiency in mmWave bands," *IEEE 5G Tech Focus*, vol. 1, no. 1, Mar. 2017.

4G and 5G BS Antenna Comparison

4G LTE Advanced Pro [1,2]:

- ≤ 64 antenna elements
- 1-2 Gbps data rate
- ~10 ms latency
- Digital beamforming

5G NR [3, 4]:

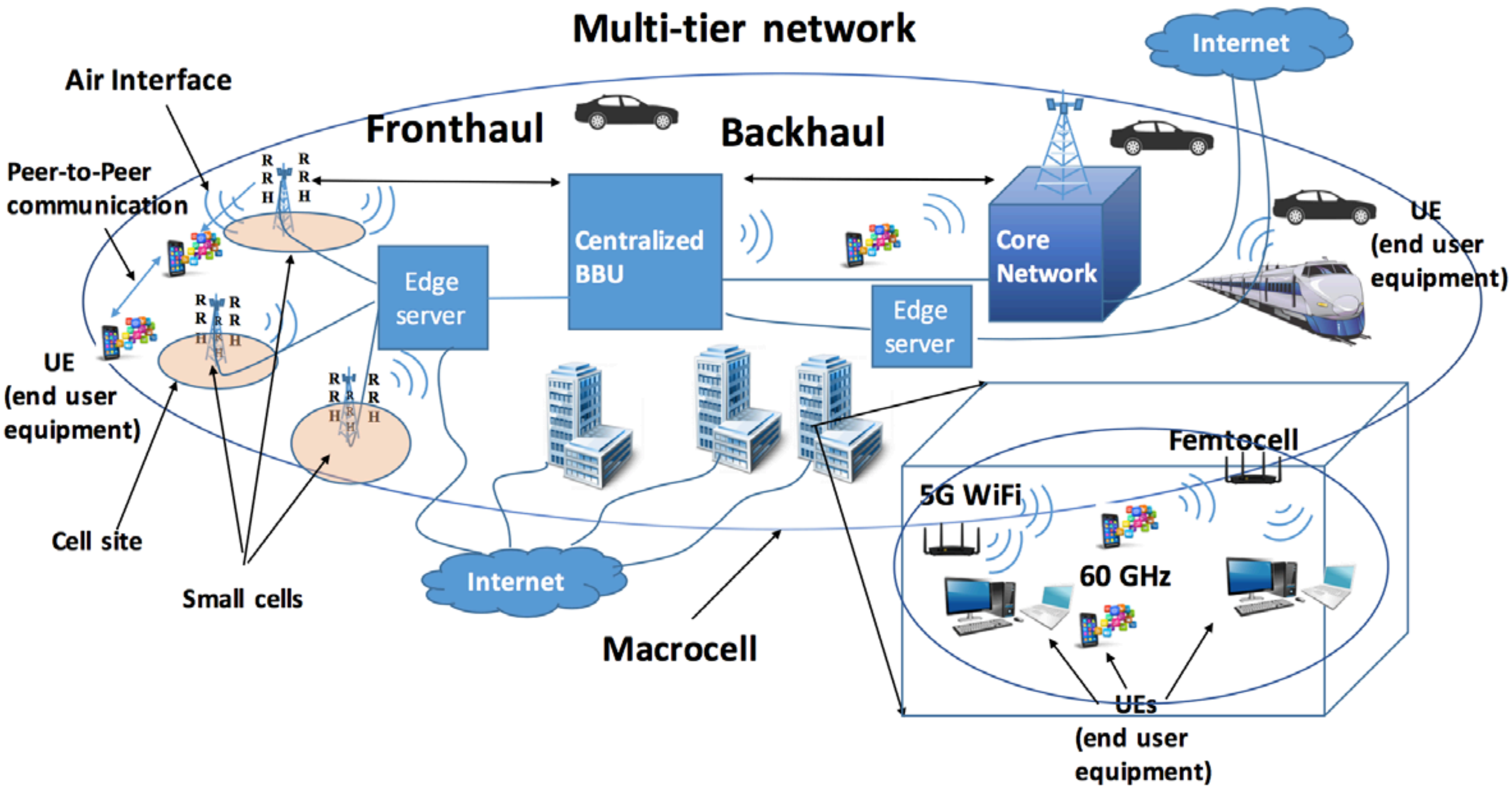
- ≥ 256 antenna elements (same size)
- BS Placement: site-specific sensitivity
- > 10 Gbps data rate
- < 1 ms latency
- Hybrid beamforming [4] (most possible)

[1] 3GPP TR36.897 V13.0.0: “Study on elevation beamforming / full-dimension (FD) multiple input multiple output (MIMO) for LTE,” Jun. 2015.
[2] 3GPP TR 36.819 V11.2.0, “Coordinated multi-point operation for LTE physical layer aspects,” Sep. 2013.
[3] 3GPP TR 38.802 V14.2.0: “Study on new radio access technology – physical layer aspects,” Sep. 2017.
[4] S. Sun, T. S. Rappaport, and M. Shafi, ”Hybrid beamforming for 5G millimeter-wave multi-cell networks,” in Proceedings of the IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS), Honolulu, HI, USA, Apr. 2018.

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

	LTE	5G NR (eMBB)
Number of Streams	SISO	SISO
BW	20 MHz	800 MHz
Subcarrier spacing	15KHz	240KHz
FFT size	2048	2048
Number of Occupied Subcarrier	1200	~1600
Spectral Occupancy	90%	98%
Slot Duration	0.5 ms [7symbols]	65us [14 symbols]
Antenna	Omni	64 Beams

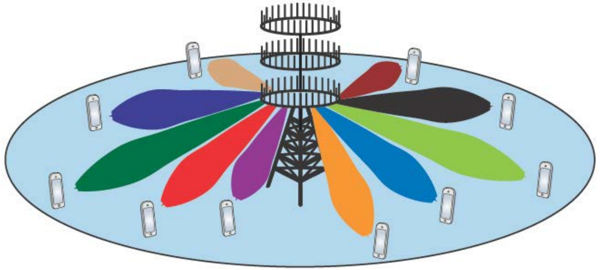
5G Multi-tier network [1]



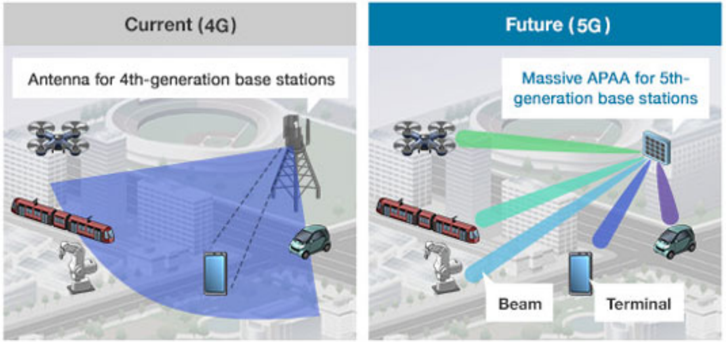
[1] T. S. Rappaport, Y. Xing, G. R. MacCartney, A. F. Molisch, E. Mellios and J. Zhang, "Overview of Millimeter Wave Communications for Fifth-Generation (5G) Wireless Networks—With a Focus on Propagation Models," in *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 12, pp. 6213-6230, Dec. 2017.

5G Base Stations and Network Architecture [1]

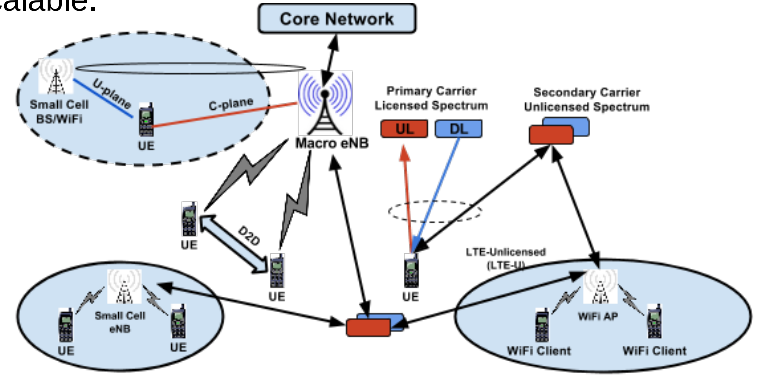
5G base stations (Nokia 5G AirScale Base Station [2]).



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



The directionality of 5G base stations.



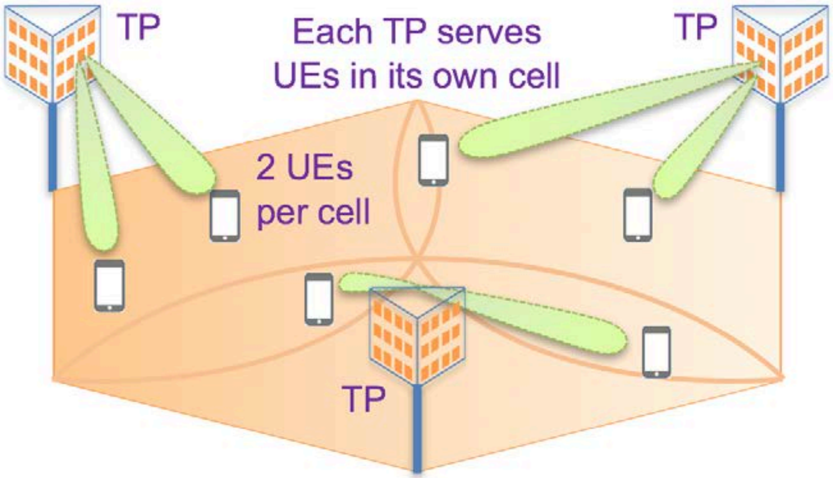
Heterogeneous 5G networks, Small cells and WiFi [3]

[1] 3GPP TR 38.802 V14.2.0: “Study on new radio access technology – physical layer aspects,” Sep. 2017.
[2] https://networks.nokia.com/products/airscale-base-station
[3] http://www.openairinterface.org/?page_id=458

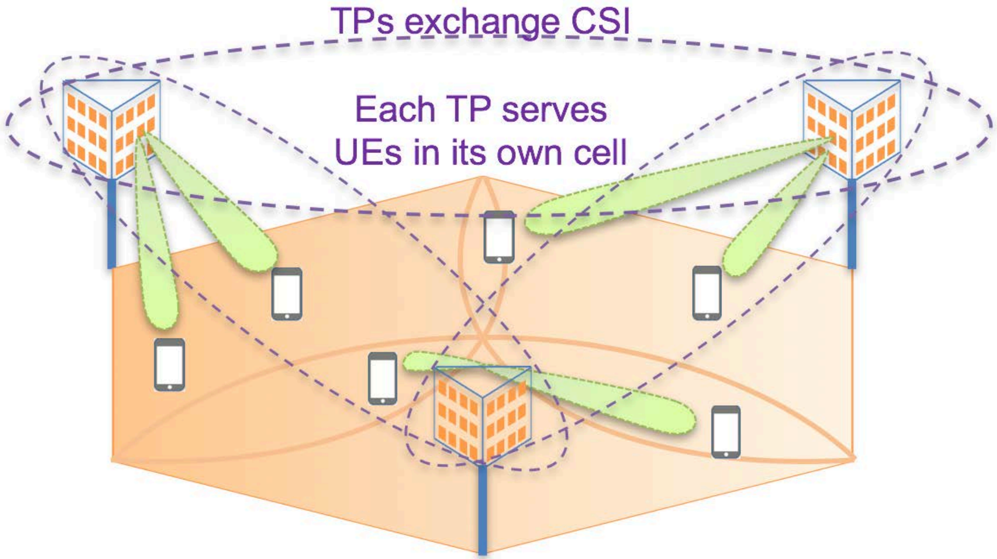
Multi-Cell Multi-Stream Downlink Hybrid Beamforming for 5G Small Cells

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

Non-CoMP



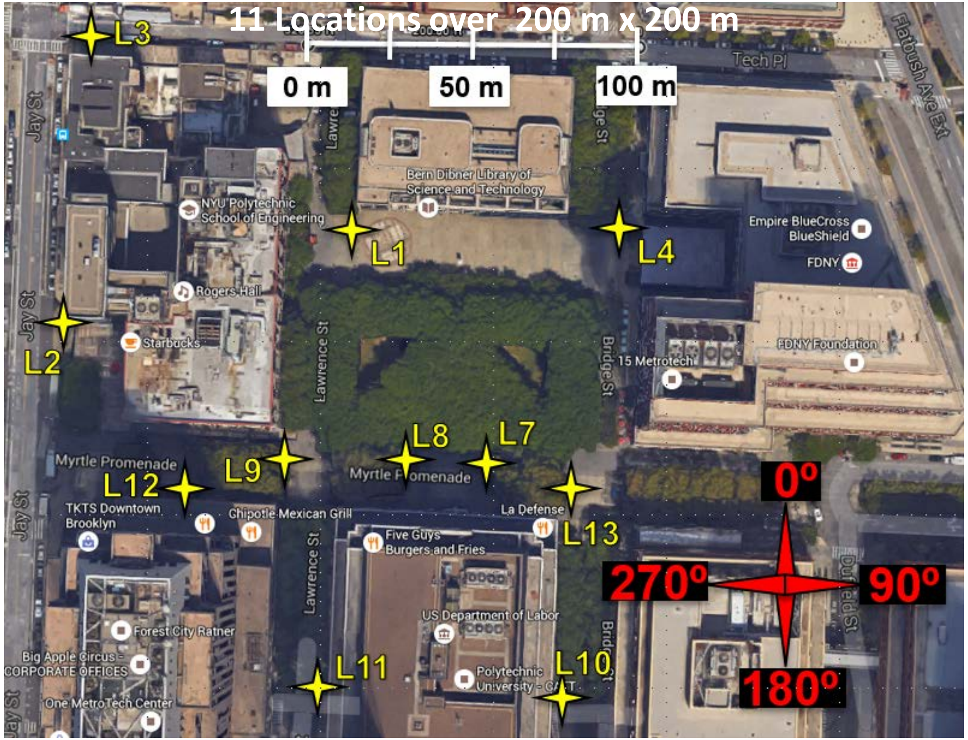
CoMP
（coordinated scheduling/beamforming）[1]



[1] 3GPP, “Coordinated multi-point operation for LTE physical layer aspects,” 3rd Generation Partnership Project (3GPP), TR 36.819 V11.2.0, Sep. 2013.

Base Station Diversity and CoMP Measurements at NYU

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



G. R. MacCartney, Jr., T. S. Rappaport, and A. Ghosh “Base Station Diversity Propagation Measurements at 73 GHz Millimeter-Wave for 5G Coordinated Multipoint (CoMP) Analysis,” in 2017 IEEE Globecom Workshops (GC Wkshps), Singapore, Dec. 2017, pp. 1-7.

- 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

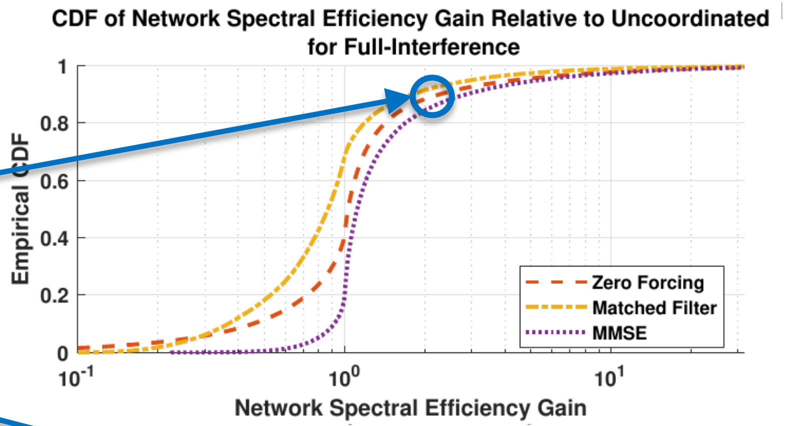
TX height: 4 m
RX height: 1.4 m

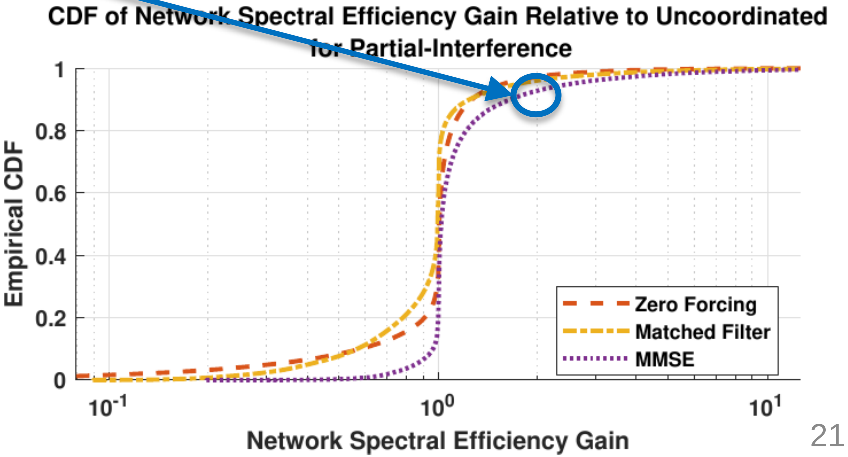
RX Location	TX Location	T-R Dist (m)
L1	L3,L4,L7,L11,L13	$80 \leq d \leq 140$
L2	L3,L9,L12	$61 \leq d \leq 78$
L3	L2	77
L4	L1,L3,L7,L10,L13	$80 \leq d \leq 170$
L7	L1,L2,L4,L10	$72 \leq d \leq 72$
L8	L1,L7,L9	$21 \leq d \leq 133$
L9	L1,L2,L4,L11	$63 \leq d \leq 78$
L10	L4,L7,L13	$59 \leq d \leq 123$
L12	L1,L2,L4,L7,L11	$61 \leq d \leq 149$
L13	L1,L4,L10	$59 \leq d \leq 107$

Nearest Neighbor TX Distance Stats over all RX Locations			
Nearest Neighbor	1	2	3
Mean [m]: $\bar{d}$ / Median [m]: $\tilde{d}$	62/61	74/78	93/87
STD [m]: σ_d	18	14	20
Range [m]: $d \in$ [min, max]	[21,80]	[41,87]	[78,140]

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.





G. R. MacCartney, Jr., T. S. Rappaport, and Sundeep Rangan "Rapid Fading Due to Human Blockage in Pedestrian Crowds at 5G Millimeter-Wave Frequencies," 2017 IEEE Global Communications Conference (GLOBECOM), Singapore, Dec. 2017.

G. R. MacCartney, Ph.D. Thesis, "Millimeter-Wave Base Station Diversity and Human Blockage in Dense Urban Environments for Coordinated Multipoint (CoMP) Applications, May 2018, New York University

28 GHz Millimeter Wave Cellular Communication

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

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

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's 5G Fixed Wireless Trials

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

Fixed Wireless Broadband Tower [3]

[1] http://about.att.com/story/5g_trail_with_magnolia_waco.html
[2] http://about.att.com/story/att_expanding_fixed_wireless_5g_trials_to_additional_markets.html
[3] http://internet-access-guide.com/fixed-wireless-rural-americas-best-choice-for-broadband/

Verizon’s 5G Fixed Wireless Trials

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

- Ann Arbor, Mich., Atlanta, Ga., Bernardsville, N.J., Brockton, Mass., Dallas and Houston, Texas, Denver, Colo., Miami, Fla., Seattle, Wash., and Washington DC

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

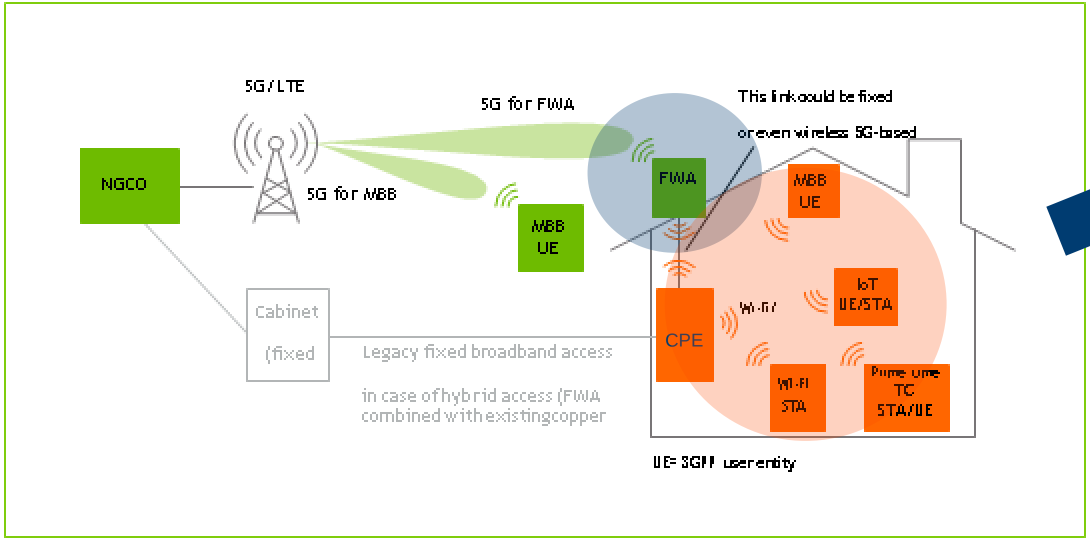
- Trials of fixed 5G service are progressing better than expected (28 and 39 GHz) [2]. Well over 1 Gbps, less than 10 ms

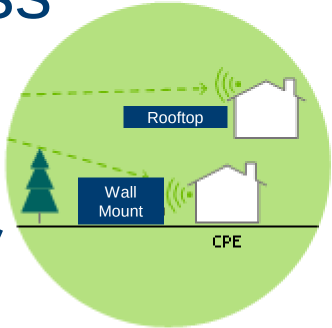
- These systems use first 3GPP implementation (prior to 5GNR)

Verizon 5G trial deployment [3].

[1] https://www.rcrwireless.com/20171219/5g/5g-fixed-wireless-access-makes-major-progress-in-2017-tag17-tag99
[2] https://www.sdxcentral.com/articles/news/verizon-says-fixed-5g-trials-performing-better-expected/2017/10/
[3] https://technewstt.com/pr-ericsson-verizon-5g/

Intel: Examples of Fixed Wireless Access



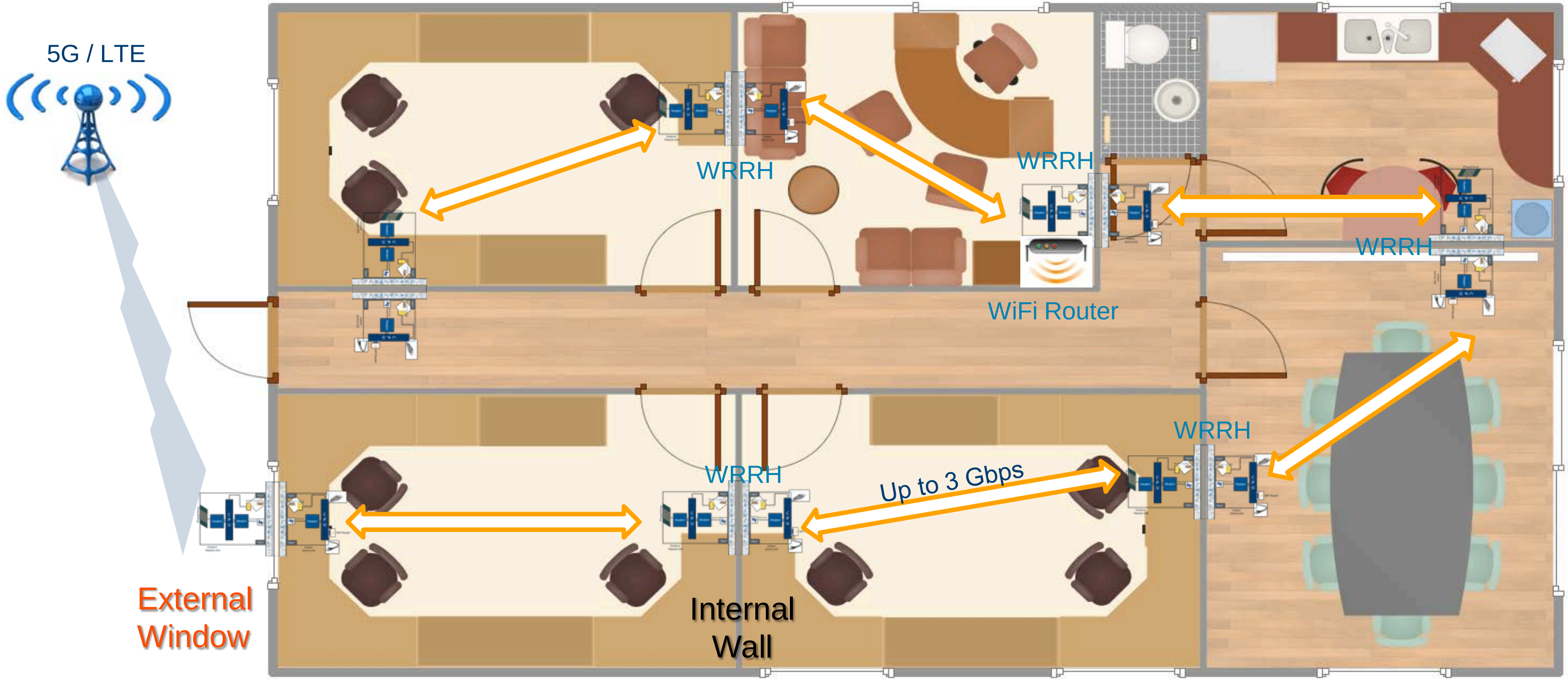


- Typical FWA deployment
- CPE is on rooftop or Wall mounted
- Windows/Wall penetration is difficult
- Wifi distribution is used inside premise
- Multi Gbps networking is limited to WiFi speed

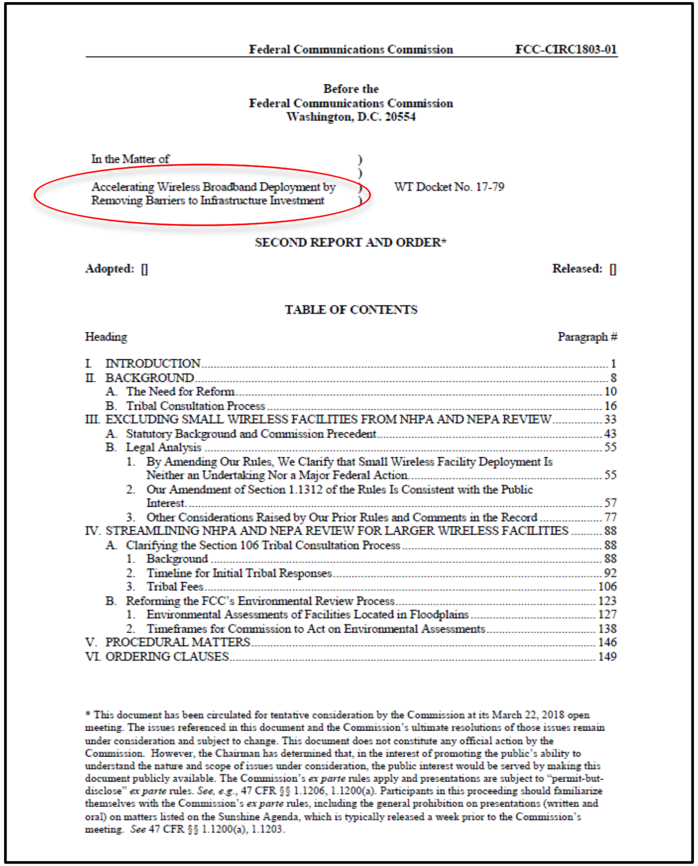
Examples of FWA deployment alternatives

Excerpt from Ericsson Technology review, 5G & Fixed Wireless Access 10-2016

Intel: MGbps In-Home/office Wireless Networking



FCC WT17-79 Amending Rules for Small Cells



Federal Communications Commission FCC-CIRC1803-01

Before the
Federal Communications Commission
Washington, D.C. 20554

In the Matter of

Accelerating Wireless Broadband Deployment by Removing Barriers to Infrastructure Investment

WT Docket No. 17-79

SECOND REPORT AND ORDER*

Adopted: [] Released: []

TABLE OF CONTENTS

* This document has been circulated for tentative consideration by the Commission at its March 22, 2018 open meeting. The issues referenced in this document and the Commission's ultimate resolutions of those issues remain under consideration and subject to change. This document does not constitute any official action by the Commission. However, the Chairman has determined that, in the interest of promoting the public's ability to understand the nature and scope of issues under consideration, the public interest would be served by making this document publicly available. The Commission's *ex parte* rules apply and presentations are subject to "permit-but-disclose" *ex parte* rules. *See, e.g.*, 47 CFR §§ 1.1206, 1.1200(a). Participants in this proceeding should familiarize themselves with the Commission's *ex parte* rules, including the general prohibition on presentations (written and oral) on matters listed on the Sunshine Agenda, which is typically released a week prior to the Commission's meeting. *See* 47 CFR §§ 1.1200(a), 1.1203.

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

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

- 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**.

[1] https://apps.fcc.gov/edocs_public/attachmatch/DOC-349528A1.pdf
[2] https://api.ctia.org/docs/default-source/default-document-library/small-cell-deployment-regulatory-review-costs_3-12-2018.pdf

FCC Input From Sponsors of NYU WIRELESS

NYU TANDON SCHOOL OF ENGINEERING

NYU WIRELESS

Acknowledgement to our NYU WIRELESS Industrial Affiliates and NSF

NSF

at&t
CableLabs
CROWN CASTLE
ERICSSON
HUAWEI
intel
INTERDIGITAL
KEYSIGHT TECHNOLOGIES
L3 communications
NATIONAL INSTRUMENTS
nextlink
NOKIA
oppo
QUALCOMM
SiBEAM
Sprint
UMC
verizon

Key Regulatory Needs from Industry

- **Great technology must be deployed rapidly and efficiently (time/$)**

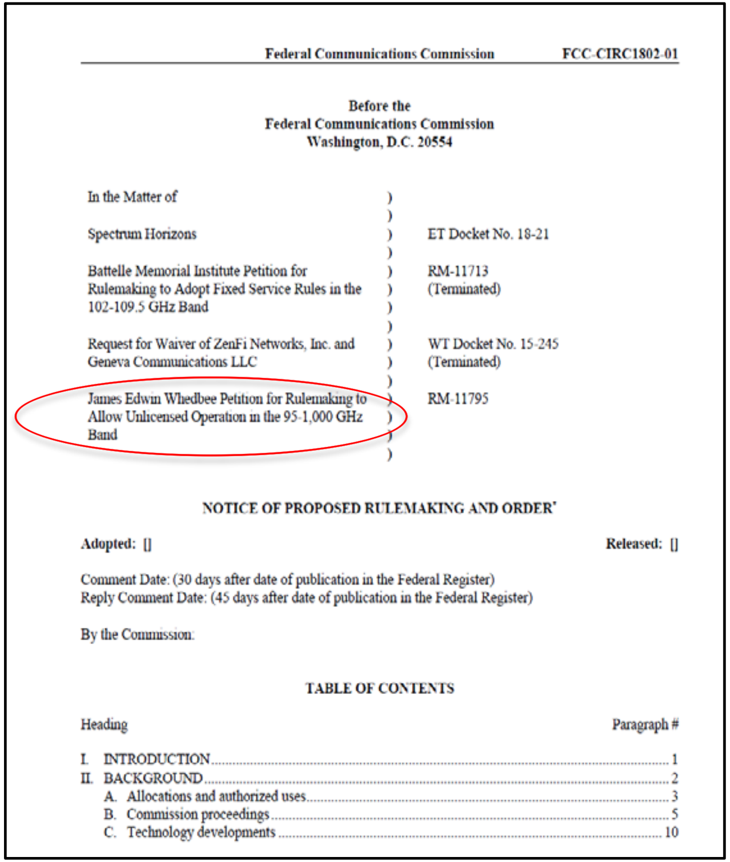
- **FCC small-cell Order is excellent first step, but must aggressively auction more prime (< 6 GHz) and mmW spectrum: want39 GHz w/24 & 28 GHz 2018**

- **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**

FCC RM-11795 Proposes ‘Spectrum Horizons’ > 95 GHz


Federal Communications Commission FCC-CIRC1802-01

Before the
Federal Communications Commission
Washington, D.C. 20554

In the Matter of	
Spectrum Horizons	ET Docket No. 18-21
Battelle Memorial Institute Petition for Rulemaking to Adopt Fixed Service Rules in the 102-109.5 GHz Band	RM-11713 (Terminated)
Request for Waiver of ZenFi Networks, Inc. and Geneva Communications LLC	WT Docket No. 15-245 (Terminated)
James Edwin Whedbee Petition for Rulemaking to Allow Unlicensed Operation in the 95-1,000 GHz Band	RM-11795

NOTICE OF PROPOSED RULEMAKING AND ORDER*

Adopted: [] Released: []

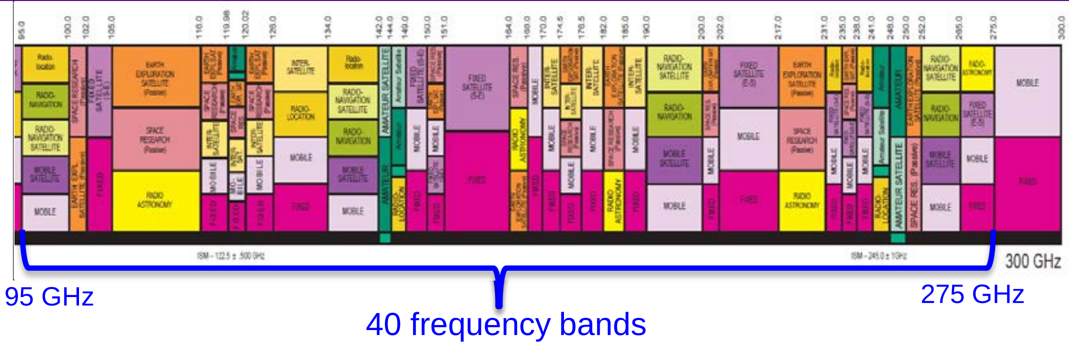
Comment Date: (30 days after date of publication in the Federal Register)
Reply Comment Date: (45 days after date of publication in the Federal Register)

By the Commission:

TABLE OF CONTENTS

Heading Paragraph #

https://apps.fcc.gov/edocs_public/attachmatch/DOC-348982A1.pdf



- 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**.

Conclusions

- 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 – its real!
- Key Regulatory Needs: Small Cells and Auctions for Spectrum
- mmW is “tip of the iceburg” as FCC, other countries move to THz

NYU WIRELESS Industrial Affiliates

Acknowledgement to our NYU WIRELESS Industrial Affiliates and NSF

Thank You!

Selected References

[1] 3GPP, “Coordinated multi-point operation for LTE physical layer aspects,” 3rd Generation Partnership Project (3GPP), TR 36.819 V11.2.0, Sep. 2013.
[2] D. Lee et al., “Coordinated multipoint transmission and reception in LTE-advanced: deployment scenarios and operational challenges,” IEEE Communications Magazine, vol. 50, no. 2, pp. 148–155, Feb. 2012.
[3] S. Schwarz and M. Rupp, “Exploring coordinated multipoint beamforming strategies for 5G cellular,” IEEE Access, vol. 2, pp. 930–946, 2014.
[4] M. Sadek et al., “A leakage-based precoding scheme for downlink multiuser MIMO channels,” IEEE Transactions on Wireless Communications, vol. 6, no. 5, pp. 1711–1721, May 2007.
[5] D. Maamari et al., “Coverage in mmWave cellular networks with base station co-operation,” IEEE Transactions on Wireless Communications, vol. 15, no. 4, pp. 2981–2994, Apr. 2016.
[6] N. A. Muhammad et al., “Multi-cell coordination via disjoint clustering in dense millimeter wave cellular networks,” in 2017 IEEE International Conference on Communications (ICC), May 2017, pp. 1–6.
[7] G. Zhu et al., “Hybrid beamforming via the kronecker decomposition for the millimeter-wave massive MIMO systems,” IEEE Journal on Selected Areas in Communications, vol. 35, no. 9, pp. 2097–2114, Sep. 2017.
[8] ITU-R, “Guidelines for evaluation of radio interface technologies for IMT-2020,” Tech. Rep. M.2412-0, Oct. 2017.
[9] F. W. Vook et al., “Performance characteristics of 5G mmWave wireless-to-the-home,” in 2016 50th Asilomar Conference on Signals, Systems and Computers, Nov. 2016, pp. 1181–1185.
[10] T. S. Rappaport, R. W. Heath, Jr., R. C. Daniels, and J. N. Murdock, Millimeter Wave Wireless Communications. Pearson/Prentice Hall 2015.
[11] 3GPP, “Study on channel model for frequencies from 0.5 to 100 GHz,” 3rd Generation Partnership Project (3GPP), TR 38.901 V14.3.0, Dec. 2017.
[12] S. Sun et al., “A novel millimeter-wave channel simulator and applications for 5G wireless communications,” in IEEE International Conference on Communications (ICC), May 2017, pp. 1–7.
[13] 3GPP, “Technical specification group radio access network; Study on 3D channel model for LTE (Release 12),” 3rd Generation Partnership Project (3GPP), TR 36.873 V12.2.0, Jun. 2015.
[14] O. E. Ayach et al., “Spatially sparse precoding in millimeter wave MIMO systems,” IEEE Transactions on Wireless Communications, vol. 13, no. 3, pp. 1499–1513, Mar. 2014.
[15] I. E. Telatar, “Capacity of multi-antenna Gaussian channels,” Europ. Trans. Telecommun., vol. 10, no. 6, pp. 585–596, Nov.-Dec. 1999.
[16] N. Song et al., “Coordinated hybrid beamforming for millimeter wave multi-user massive MIMO systems,” in 2016 IEEE Global Communications Conference (GLOBECOM), Dec. 2016, pp. 1–6.
[17] T. S. Rappaport et al., “5G channel model with improved accuracy and efficiency in mmWave bands,” IEEE 5G Tech Focus, vol. 1, no. 1, Mar. 2017.
[18] S. Sun, “Channel modeling and multi-cell hybrid beamforming for fifth-generation millimeter-wave wireless communications,” Ph.D. dissertation, New York University, New York, May 2018.
[19] 5GCM, “5G channel model for bands up to 100 GHz,” Technical Report, Oct. 2016. [Online]. Available: http://www.5gworkshops.com/5GCM.html.
[20] T. S. Rappaport et al., “Wideband millimeter-wave propagation measurements and channel models for future wireless communication system design (Invited Paper),” IEEE Transactions on Communications, vol. 63, no. 9, pp. 3029–3056, Sep. 2015.
[21] M. K. Samimi and T. S. Rappaport, “3-D millimeter-wave statistical channel model for 5G wireless system design,” IEEE Transactions on Microwave Theory and Techniques, vol. 64, no. 7, pp. 2207–2225, Jul. 2016.

Selected References

- T. S. Rappaport et al., "Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!" IEEE Access, vol. 1, pp. 335–349, May 2013.
- T. S. Rappaport, R. W. Heath, Jr., R. C. Daniels, and J. N. Murdock, Millimeter Wave Wireless Communications. Pearson/Prentice Hall, 2015.
- G. R. MacCartney, Jr. et al., "Path loss models for 5G millimeter wave propagation channels in urban microcells," in 2013 IEEE Global Communications Conference (GLOBECOM), Dec. 2013, pp. 3948-3953.
- F. Boccardi et al., "Five disruptive technology directions for 5G," IEEE Communications Magazine, vol. 52, no. 2, pp. 74–80, Feb. 2014.
- 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.
- International Telecommunications Union, "Guidelines for evaluation of radio interface technologies for IMT-2020," Geneva, Switzerland, Rec. ITU-R M.2412-0, Oct. 2017.
- Aalto University, AT&T, BUPT, CMCC, Ericsson, Huawei, Intel, KT Corporation, Nokia, NTT DOCOMO, New York University, Qualcomm, Samsung, University of Bristol, and University of Southern California, "5G channel model for bands up to 100 GHz," 2016, Oct. 21. [Online]. Available: http://www.5gworkshops.com/5GCM.html
- T. S. Rappaport, J. N. Murdock, and F. Gutierrez, "State of the art in 60-GHz integrated circuits and systems for wireless communications," Proceedings of the IEEE, vol. 99, no. 8, pp. 1390-1436, Aug. 2011.
- S. Sun et al., "Investigation of prediction accuracy, sensitivity, and parameter stability of large-scale propagation path loss models for 5G wireless communications (Invited Paper)," IEEE Transactions on Vehicular Technology, vol. 65, no. 5, pp. 2843–2860, May 2016.
- S. Collonge, G. Zaharia, and G. El Zein, "Influence of the human activity on wide-band characteristics of the 60 GHz indoor radio channel," IEEE Transactions on Wireless Communications, vol. 3, no. 6, pp. 2396–2406, Nov. 2004.
- M. Jacob, C. Mbianke, and T. Kurner, "A dynamic 60 GHz radio channel model for system level simulations with MAC protocols for IEEE 802.11ad," in IEEE International Symposium on Consumer Electronics (ISCE 2010), June 2010, pp. 1–5.
- ——, "Human body blockage - guidelines for TGad MAC development," doc.: IEEE 802.11-09/1169r0, Nov. 2009.
- G. R. MacCartney, Jr. et al., "Millimeter-wave human blockage at 73 GHz with a simple double knife-edge diffraction model and extension for directional antennas," in 2016 IEEE 84th Vehicular Technology Conference (VTC2016-Fall), Sept. 2016, pp. 1–6.
- A. Maltsev et al., "Channel Models for 60 GHz WLAN Systems," doc.: IEEE 802.11-09/0334r8, May 2010.
- G. R. MacCartney, Jr. and T. S. Rappaport, "A flexible millimeter-wave channel sounder with absolute timing," IEEE Journal on Selected Areas in Communications, vol. 35, no. 6, pp. 1402–1418, June 2017.
- T. S. Rappaport et al., "Wideband millimeter-wave propagation measurements and channel models for future wireless communication system design (Invited Paper)," IEEE Transactions on Communications, vol. 63, no. 9, pp. 3029–3056, Sept. 2015.
- G. R. MacCartney, Jr., T. S. Rappaport, and Sundeep Rangan "Rapid Fading Due to Human Blockage in Pedestrian Crowds at 5G Millimeter-Wave Frequencies," 2017 IEEE Global Communications Conference (GLOBECOM), Singapore, Dec. 2017.
- A. Ghosh et al., "Millimeter-wave enhanced local area systems: A high-datarate approach for future wireless networks," IEEE Journal on Selected Areas in Communications, vol. 32, no. 6, pp. 1152-1163, June 2014.
- T. A. Thomas et al., "3D mmWave channel model proposal," in IEEE 80th Vehicular Technology Conference (VTC2014-Fall), Sept. 2014, pp. 1-6.

Selected References

- T. S. Rappaport et al., “Cellular broadband millimeter wave propagation and angle of arrival for adaptive beam steering systems (Invited Paper),” in 2012 IEEE Radio and Wireless Symposium (RWS), Jan. 2012, pp. 151-154.
- G. R. MacCartney, Jr. and T. S. Rappaport, “73 GHz millimeter wave propagation measurements for outdoor urban mobile and backhaul communications in New York City,” in 2014 IEEE International Conference on Communications (ICC), June 2014, pp. 4862-4867.
- Federal Communications Commission, “Spectrum Frontiers R&O and FNPRM: FCC16-89,” July 2016. [Online]. Available: https://apps.fcc.gov/edocs public/attachmatch/FCC-16-89A1 Rcd.pdf
- T. S. Rappaport et. al, “Small-scale, local area, and transitional millimeter wave propagation for 5G communications,” IEEE Transactions on Antennas and Propagation, Dec. 2017.
- METIS, “METIS Channel Model," METIS2020, Deliverable D1.4 v3, July 2015. [Online]. Available: https://www.metis2020.com/wp-content/uploads/deliverables/METIS D1.4 v1.0.pdf
- MiWeba, “WP5: Propagation, Antennas and Multi-Antenna Technique; D5.1: Channel Modeling and Characterization,” Tech. Rep. MiWEBA Deliverable D5.1, June 2014. [Online]. Available: http://www.miweba.eu/wp-content?uploads/2014/07/MiWEBA D5.1 v1.011.pdf
- J. Kunisch and J. Pamp, “Ultra-wideband double vertical knife-edge model for obstruction of a ray by a person,” in 2008 IEEE International Conference on Ultra-Wideband, vol. 2, Sept. 2008, pp. 17–20.
- K. Haneda et al., “5G 3GPP-like channel models for outdoor urban microcellular and macrocellular environments,” in 2016 IEEE 83rd Vehicular Technology Conference (VTC2016-Spring), May 2016, pp. 1-7.
- K. Haneda et al., “Indoor 5G 3GPP-like channel models for office and shopping mall environments,” in 2016 IEEE International Conference on Communications Workshops (ICCW), May 2016, pp. 694-699.
- 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
- C. B. Peel, B. M. Hochwald, and A. L. Swindlehurst, “A vector-perturbation technique for near-capacity multiantenna multiuser communication-part i: channel inversion and regularization,” IEEE Transactions on Communications, vol. 53, no. 1, pp. 195-202, Jan. 2005.
- F. Kaltenberger et al., “Capacity of linear multi-user MIMO precoding schemes with measured channel data,” in 2008 IEEE 9th Workshop on Signal Processing Advances in Wireless Communications, July 2008, pp. 580-584.

Other Selected References

[1] **S. Sun**, T. S. Rappaport, and M. Shafi, "Hybrid beamforming for 5G millimeter-wave multi-cell networks," to appear in *Proceedings of the IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS),* Honolulu, HI, USA, Apr. 2018.
[2] **S. Sun**, T. S. Rappaport, M. Shafi, and H. Tataria, "Analytical framework of hybrid beamforming in multi-cell millimeter-wave systems," submitted to *IEEE Transactions on Wireless Communications*, Feb. 2018.
[3] **S. Sun**, T. S. Rappaport, M. Shafi, Pan Tang, Jianhua Zhang, and Peter J. Smith, "Propagation models and performance evaluation for 5G millimeter-wave bands," submitted to *IEEE Transactions on Vehicular Technology*, Jan. 2018.
[4] **S. Sun** and T. S. Rappaport, "Millimeter wave MIMO channel estimation based on adaptive compressed sensing," in *Proceedings of the IEEE International Conference on Communications Workshops (ICC Workshops),* Paris, France, 2017, pp. 47-53.
[5] **S. Sun**, H. Yan, G. R. MacCartney, and T. S. Rappaport, "Millimeter wave small-scale spatial statistics in an urban microcell scenario," in *Proceedings of the IEEE International Conference on Communications (ICC),* Paris, France, 2017, pp. 1-7.
[6] **S. Sun**, G. R. MacCartney, and T. S. Rappaport, "A novel millimeter-wave channel simulator and applications for 5G wireless communications," in *Proceedings of the IEEE International Conference on Communications (ICC)*, Paris, France, 2017, pp. 1-7.
[7] **S. Sun** *et al.*, "Investigation of Prediction Accuracy, Sensitivity, and Parameter Stability of Large-Scale Propagation Path Loss Models for 5G Wireless Communications," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 5, pp. 2843-2860, May 2016.
[8] **S. Sun** *et al.*, "Propagation path loss models for 5G urban micro- and macro-cellular scenarios," in *Proceedings of the IEEE 83rd Vehicular Technology Conference (VTC Spring),* Nanjing, China, 2016, pp. 1-6.
[9] **S. Sun**, G. R. MacCartney, and T. S. Rappaport, "Millimeter-wave distance-dependent large-scale propagation measurements and path loss models for outdoor and indoor 5G systems," in *Proceedings of the 10th European Conference on Antennas and Propagation (EuCAP),* Davos, Switzerland, 2016, pp. 1-5.
[10] **S. Sun**, G. R. MacCartney, M. K. Samimi, and T. S. Rappaport, "Synthesizing omnidirectional antenna patterns, received power and path loss from directional antennas for 5G millimeter-wave communications," in *Proceedings of the IEEE Global Communications Conference (GLOBECOM),* San Diego, CA, 2015, pp. 1-7.
[11] **S. Sun**, T. A. Thomas, T. S. Rappaport, H. Nguyen, I. Z. Kovacs and I. Rodriguez, "Path loss, shadow fading, and line-of-sight probability models for 5G urban macro-cellular scenarios," in *Proceedings of the IEEE Globecom Workshops (GC Wkshps),* San Diego, CA, 2015, pp. 1-7.
[12] **S. Sun**, T. S. Rappaport, T. A. Thomas, and A. Ghosh, "A preliminary 3D mm-wave indoor oce channel model," in *Proceedings of the International Conference on Computing, Networking and Communications (ICNC),* Garden Grove, CA, 2015, pp. 26-31.
[13] **S. Sun**, T. S. Rappaport, R. W. Heath, A. Nix, and S. Rangan, "MIMO for millimeter-wave wireless communications: beamforming, spatial multiplexing, or both?," *IEEE Communications Magazine*, vol. 52, no. 12, pp. 110-121, Dec. 2014.
[14] **S. Sun** and T. S. Rappaport, "Wideband mmWave channels: Implications for design and implementation of adaptive beam antennas," in *Proceedings of the IEEE MTT-S International Microwave Symposium (IMS2014),* Tampa, FL, 2014, pp. 1-4.
[15] **S. Sun**, G. R. MacCartney, M. K. Samimi, S. Nie, and T. S. Rappaport, "Millimeter wave multi-beam antenna combining for 5G cellular link improvement in New York city," in *Proceedings of the IEEE International Conference on Communications (ICC),* Sydney, NSW, 2014, pp. 5468-5473.
[16] **S. Sun** and T. S. Rappaport, "Multi-beam antenna combining for 28 GHz cellular link improvement in urban environments," in *Proceedings of the IEEE Global Communications Conference (GLOBECOM),* Atlanta, GA, 2013, pp. 3754-3759.