What 6G Should Learn From 5G: A Measurement Study of 5G mmWave

Monisha Ghosh
Professor, EE Department, University of Notre Dame
Policy Outreach Director, SpectrumX

Collaborators: Muhammad Rochman (UChicago)
Vanlin Sathya (UChicago, Celona)
William Payne (UChicago)
Damian Fernandez (FIU)
Norlen Nunez (FIU)
Ahmed Ibrahim (FIU)
Acknowledgements: NSF Grants CNS-1618836, CNS-1618692

UNIVERSITY OF NOTRE DAME

SPECTRUMX
An NSF Spectrum Innovation Center

WIRELESS INSTITUTE

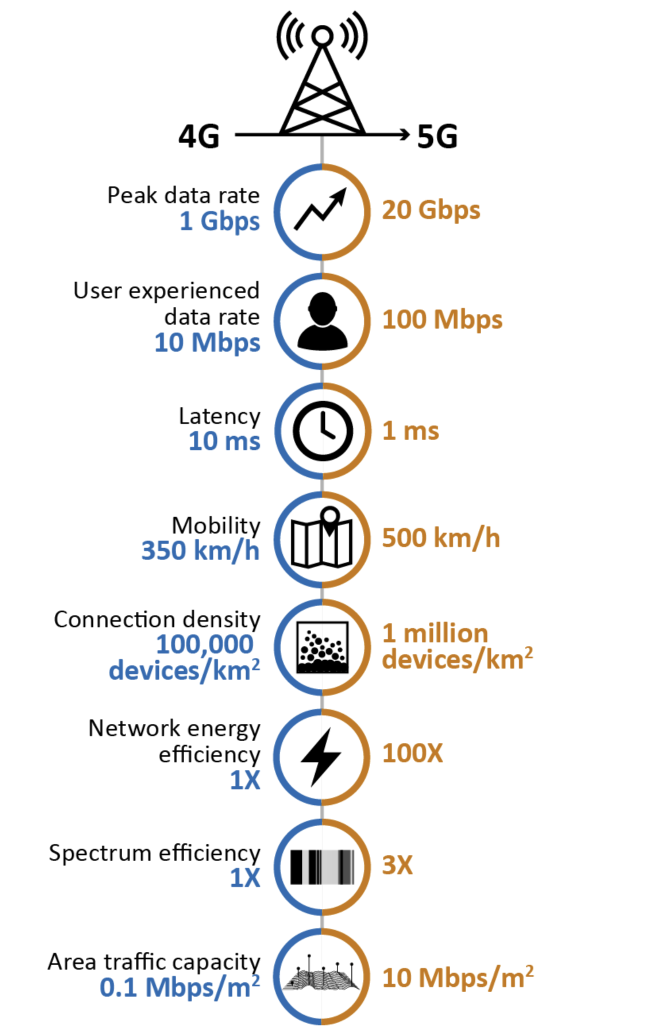
Topics

- State of 5G mmWave deployments in the US, focused on Verizon, which has the most extensive mmWave deployments in urban areas in the US.
- Coverage measurements in Chicago: C-band Vs. mmWave
- Thermal effects of 5G mmWave in handsets.
- Key takeaways and recommendations for 6G.

Recap: 4G Vs 5G metrics

- As we start defining 6G, it is worthwhile to look back at 4G and 5G and ask, at the very least, the following questions:
  - Were the 4G peak data rate and latency targets met?
  - Will the 5G peak data rate and latency targets be met?
- If the answer to the above questions are "NO", we need to know why, as we design 6G.
- **The good news:** user experienced data rates have/will mostly be met. Perhaps this should be the metric for commercial broadband? Or were they set too low?
- Question for researchers: how do we know if what is deployed is meeting predicted expectations?

Figure 5: 5G performance goals compared to 4G/LTE across key measures



Source: GAO analysis of International Telecommunication Union documentation. | GAO-21-26SP

Why should academics measure deployed 5G networks, in all bands?

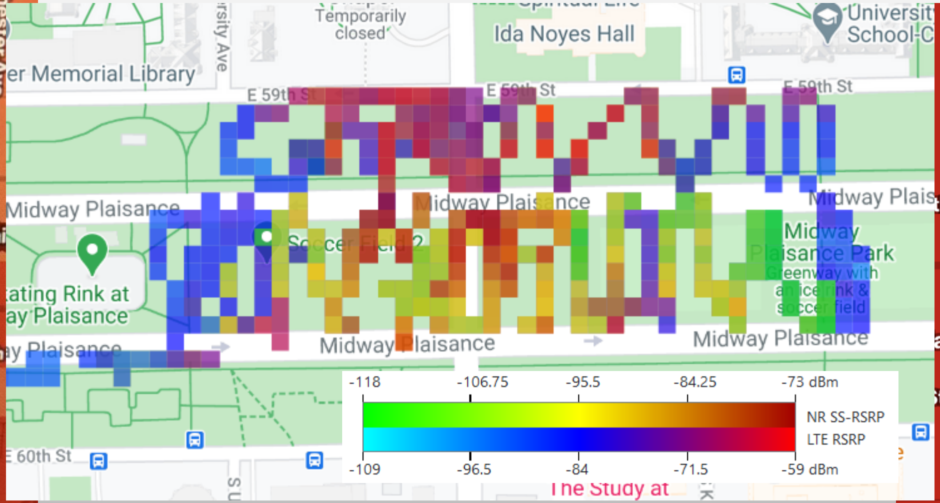
- A quote, possibly misattributed to Yogi Berra:

  "In theory there is no difference between theory and practice. In practice there is."
- **What about the many mmWave channel modeling efforts?:** essential to start designing and deploying systems, but we cannot stop there. Key contributors to the mmWave channel: handset limitations and environment impact cannot be fully modeled by limited measurement campaigns. Mid-band propagation modeling with realistic massive MIMO deployments are also necessary.
- **Aren't carriers performing post-deployment measurements?**: most certainly, but most researchers do not have access to these results. AI/ML research is limited without access to data.
- **Pros:** as 5G mid-band and mmWave deployments increase, we can measure the channel in realistic environments: e.g. BSs on lampposts on street corners, in stadiums etc. using measurements made with handsets, which are part of the channel.
- **Cons:** controllability and repeatability are difficult. Data collection, curation and analysis needs to be ongoing as deployments mature.

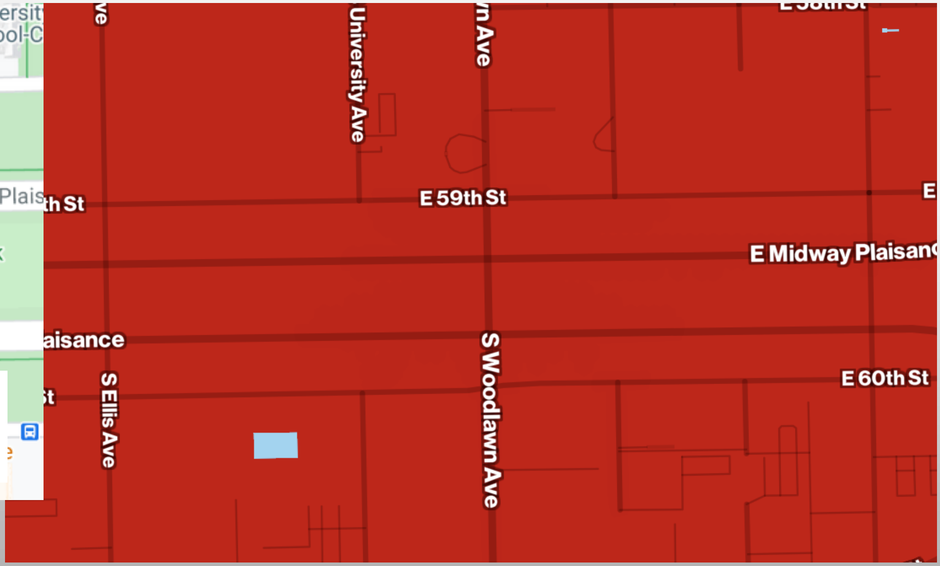
5G mmWave deployments today

- Fairly extensive coverage in downtown, stadiums and airports (indoors) in many cities.
- **Verizon:** with the roll-out of C-Band on January 19, 2022, the maps on the website do not differentiate anymore between mmWave and C-Band. However, our measurements starting from 2020, record the evolution of areas of mmWave coverage in Chicago.

5G mmWave coverage, Verizon, 2021 January



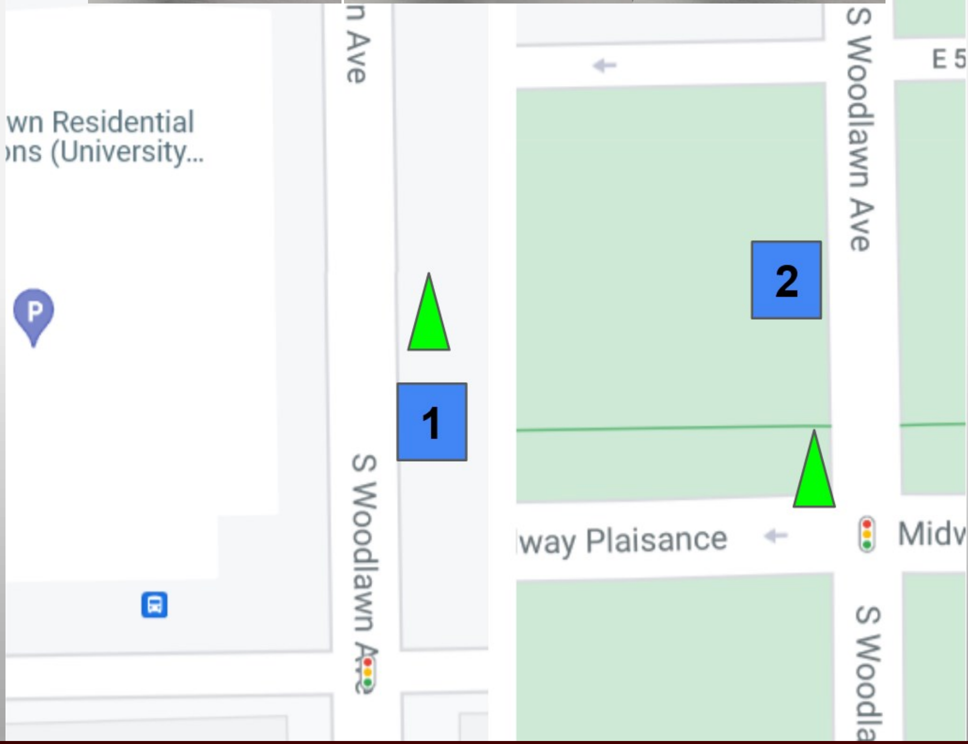
5G mmWave actual coverage 2021 January



5G UW coverage today

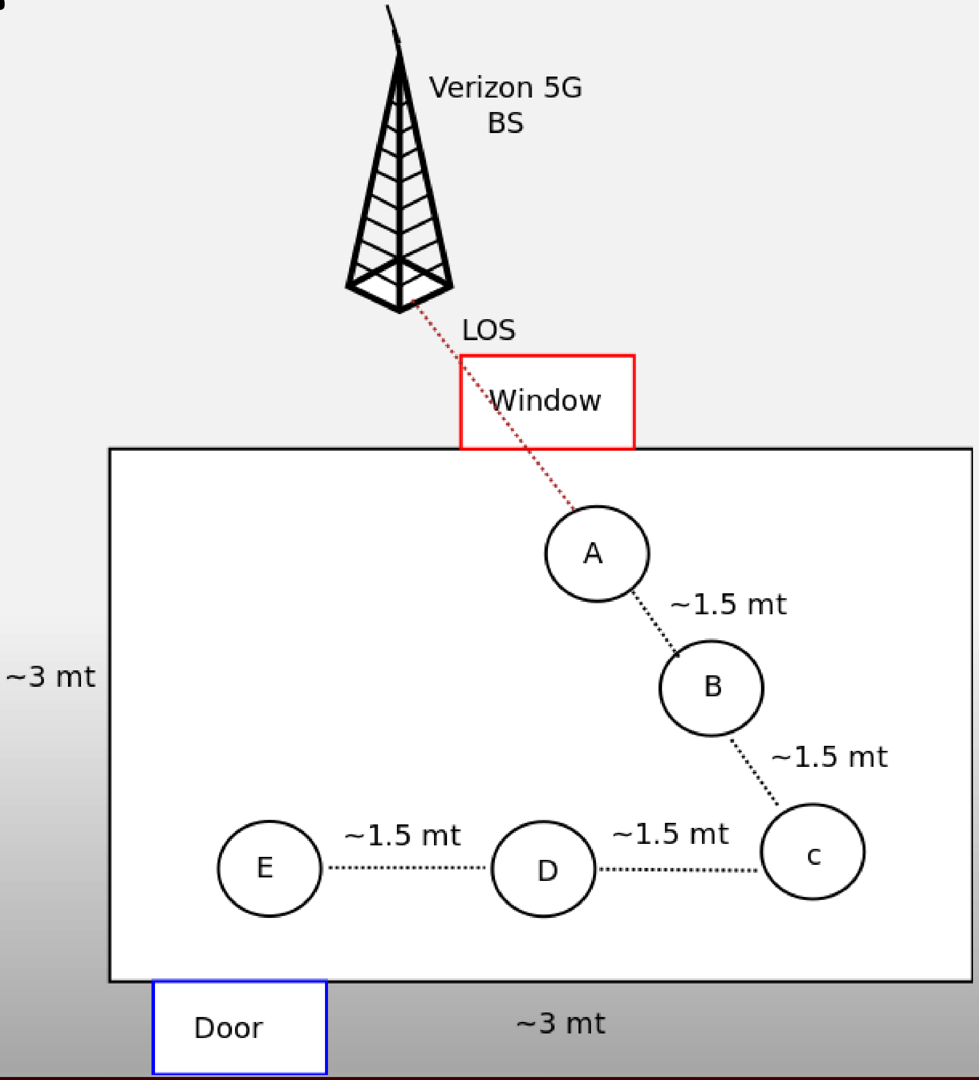
mmWave measurements on UChicago campus

- 2 Verizon 5G mmWave BSs
- One is in an open area; the other is opposite a dorm on campus: ideal for indoor/outdoor experiments.
- Extensive measurements using 5G mmWave smartphones: Pixel 5, Pixel 6 Pro, Samsung S21 and a number of apps:
  - FCC Speedtest and iperf testing
  - SigCap: https://people.cs.uchicago.edu/~muhiqbalcr/sigcap/
  - Network Signal Guru (NSG)
  - QualiPoc, by Rohde & Schwarz
- Throughput, latency and signal strength measurements, along with other parameters.



How well does mmWave propagate indoors?

- Experiments in the dorm across the street from the mmWave pole.
- Rooms E206, E 306, E406, E506 and E606 were directly opposite the pole, on different floors.
- Measurements in 5 different locations within each room.



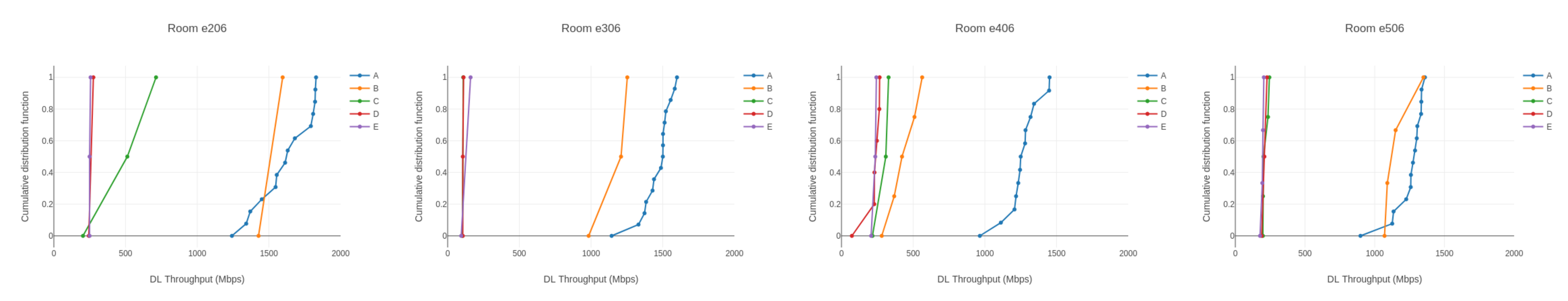
Beam information on the different floors, from NSG

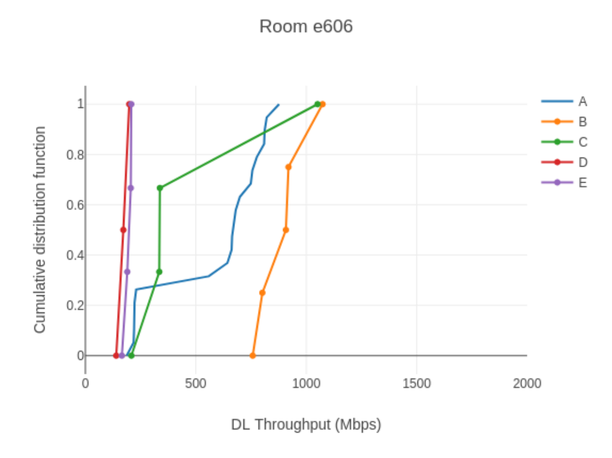
Floors	Beam Index	Bandwidth	No of Channels	Frequency Band
Floor 2	4	400 MHz	4	28 GHz
Floor 3	20	400 MHz	4	28 GHz
Floor 4	20	400 MHz	4	28 GHz
Floor 5	24	400 MHz	4	28 GHz
Floor 6	27	400 MHz	4	28 GHz

Notes: Verizon NR-FR1 operates on 10 MHz bandwidth in band 850.
CBRS and LAA were also deployed on this pole, and often “5G” throughput would aggregate the one true 5G low-band carrier with 2 – 4 4G carriers.

- In this, and other locations, beam indices were fixed:
  - UE was handed off from one beam to the other as it moved.
  - Each beam used only one aggregated carrier.

Throughput comparison on different floors

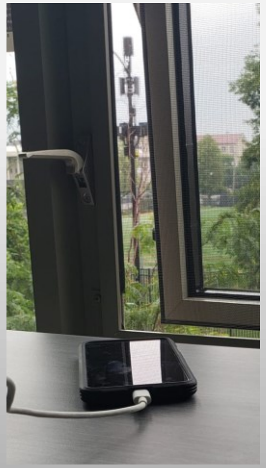




- The UE is connected to 5G mmWave when in LoS, otherwise connected to low-band.
- On most cases, locations with LoS (A, B) have a higher throughput.
- Clearly, indoor coverage from outdoor mmWave BSs is a problem: signal repeaters to bring mmWave indoors are essential.

Further experiments on indoor propagation

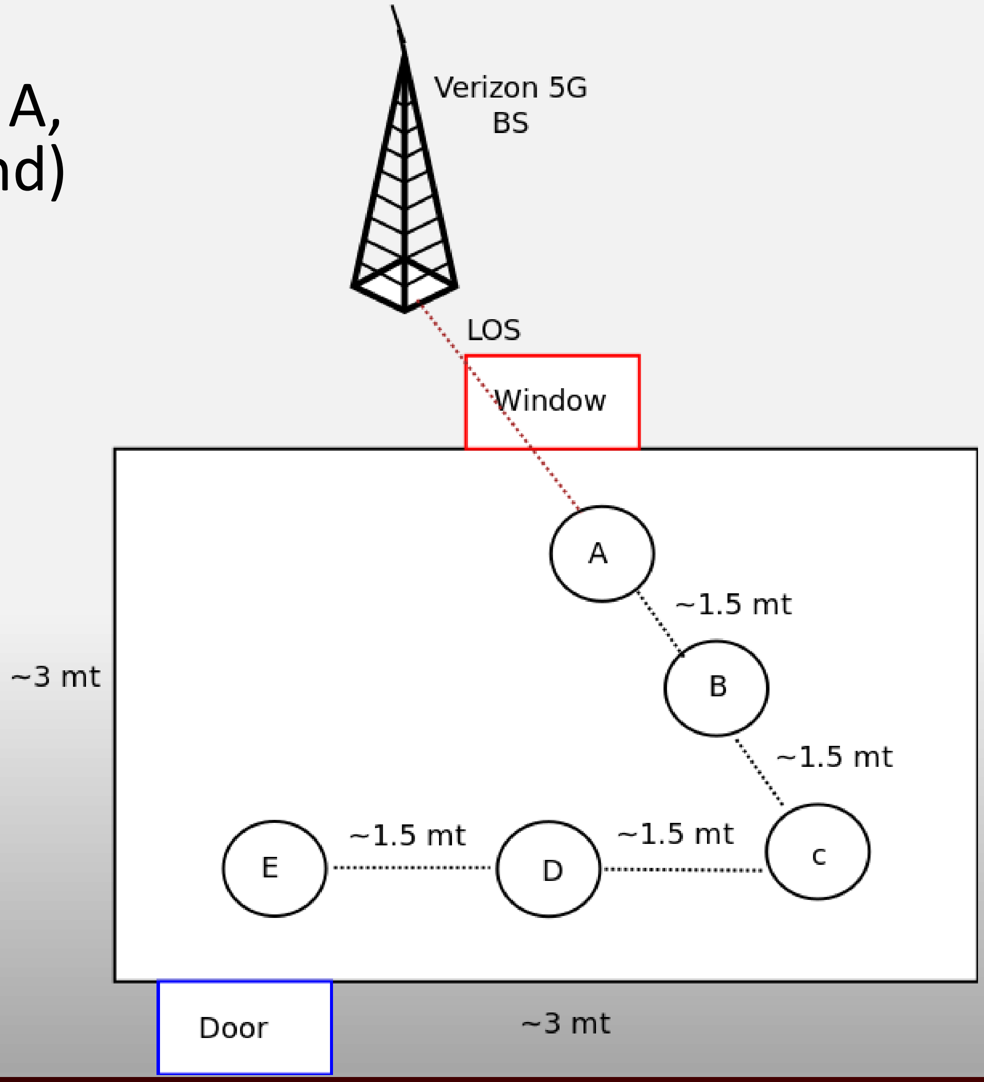
- In room E206 in the dorm, put one Pixel 5 in location A, connected to Verizon 5G (either mmWave or low-band)
- 10 minutes of FCC ST (DL, UL, Latency) with 1 minute interval (~10 runs)
- Vary the window opening and study the effect.


Gap 1

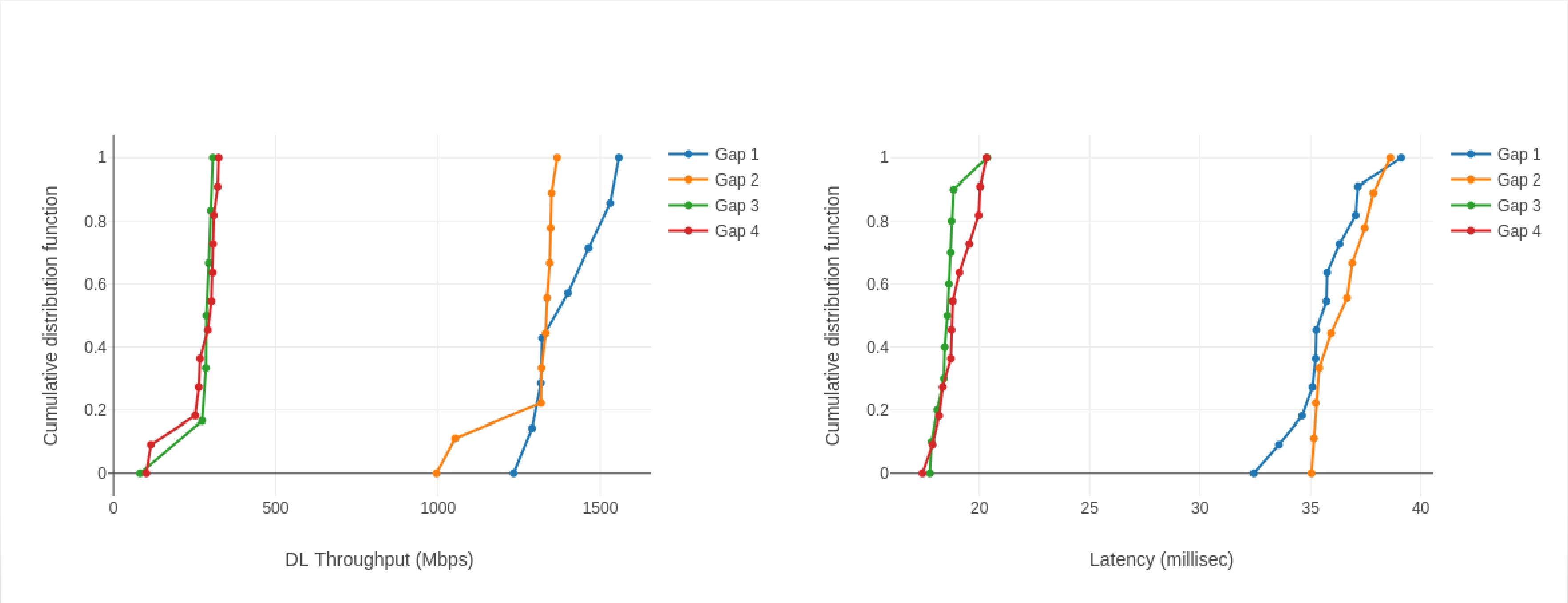

Gap 2


Gap 3


Gap 4



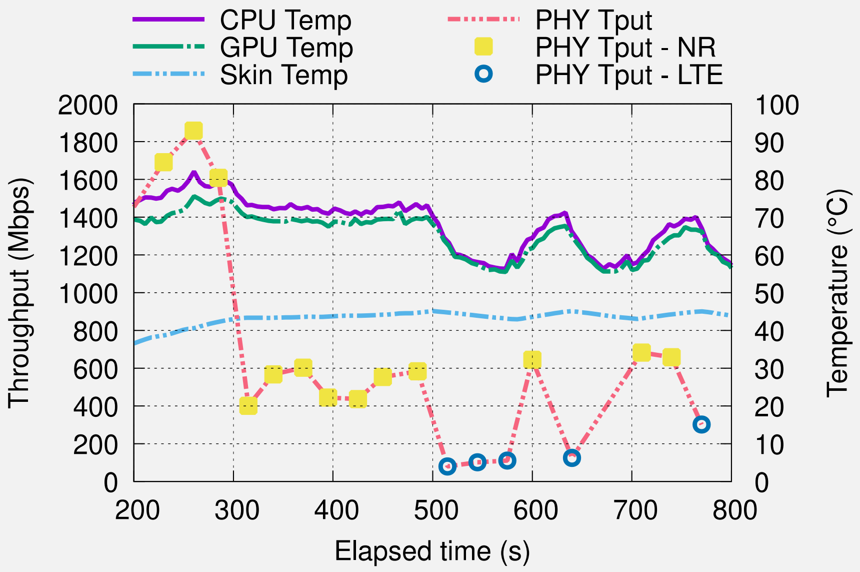
Throughput and latency results as a function of window opening

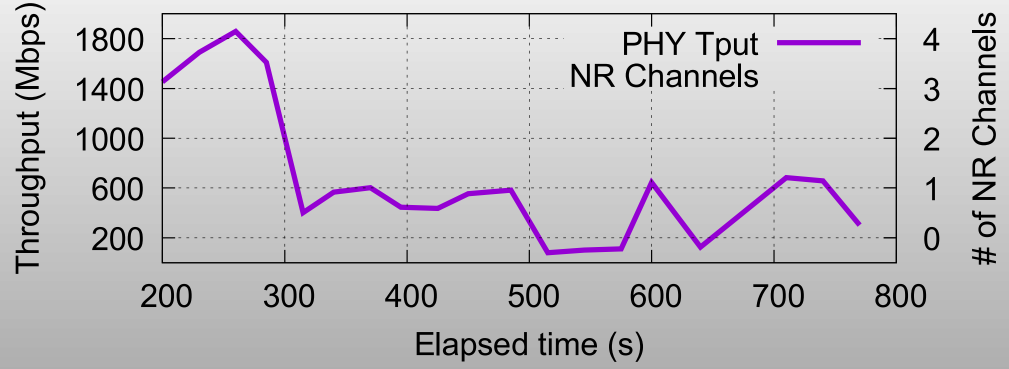


- When the window is partially open and LOS exists to the BS, the UE is connected to 5G mmWave, leading to median throughput of ~1300 Mbps.
- As the window closes, the UE is connected to 5G low-band, leading to lower throughput ~ 250Mbps
- Latency of mmWave is higher than low-band 5G: possible due to non-standalone.

Sustained throughput over 5G mmWave

- Most reported speedtest results on 5G mmWave are from measurements that last for 5 – 10 secs.
  - Give impressive results from 1 – 4 Gbps, may be even higher, aggregating 4 – 8 carriers.
- What happens when a large download activates the mmWave connection for a longer time? As skin temperature of the phone rises, the mmWave BS reduces the level of aggregation for 4 to 1 before finally handing off to 4G.
  - Corroborated by inspecting RRC messages between UE and BS indicating thermal events.
  - Corroborated by IR imaging.





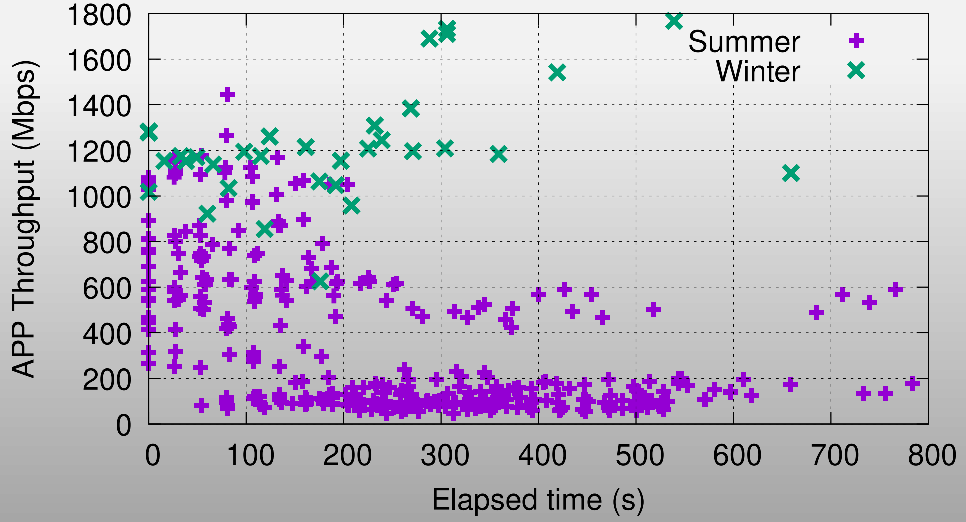
mmWave Thermal IR Experiment Videos

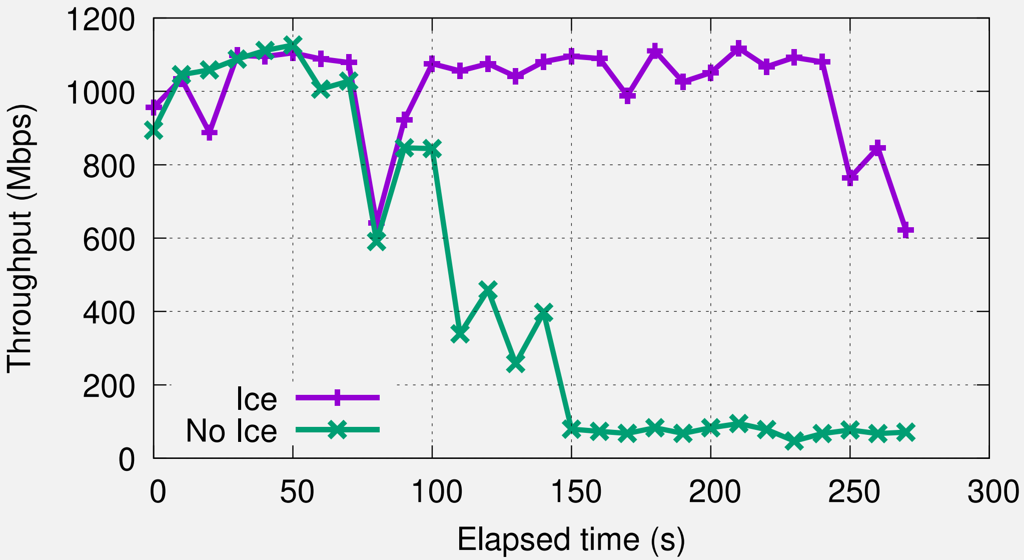
Muhammad Iqbal Rochman*, Monisha Ghosh†

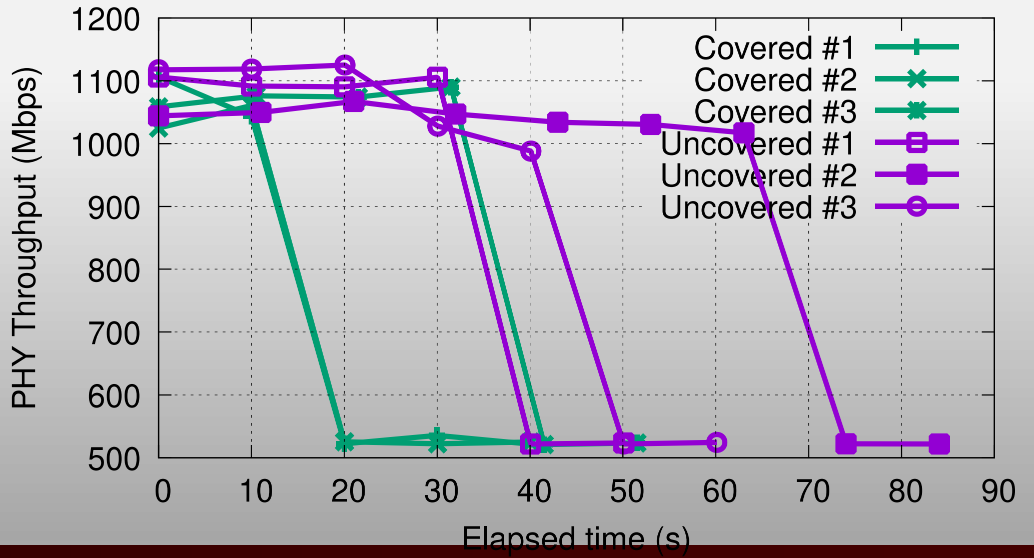
*Department of Computer Science, University of Chicago
†Department of Electrical Engineering, University of Notre Dame

Thermal effects of 5G mmWave

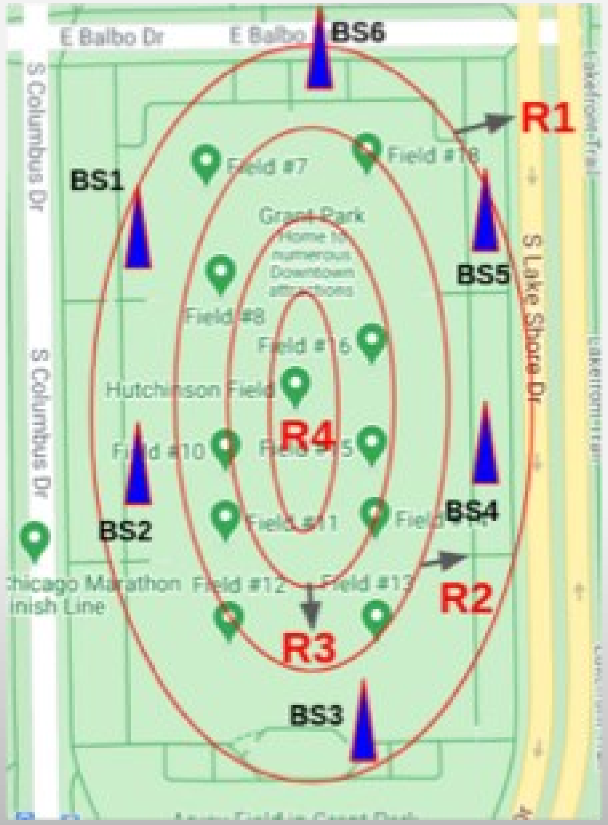
- In order to confirm that indeed temperature rise was responsible for the throughput drop, two experiments were performed, in Miami:
  - Phone was put on an ice-pack.
  - The phone cover was removed.
- Measurements were taken in summer and winter, in Chicago.



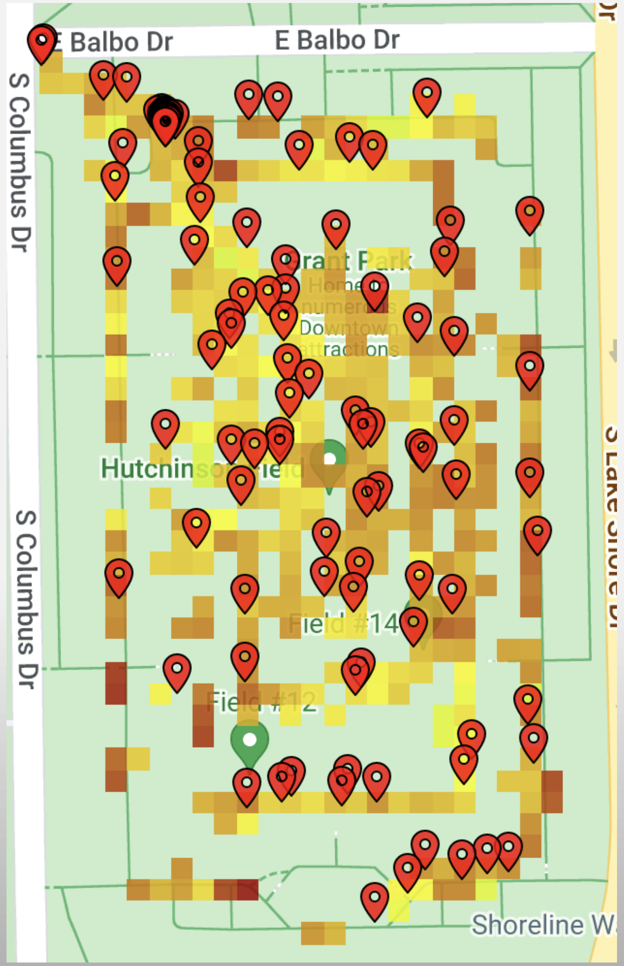




Study of dense mmWave deployment in Hutchinson Field, Chicago

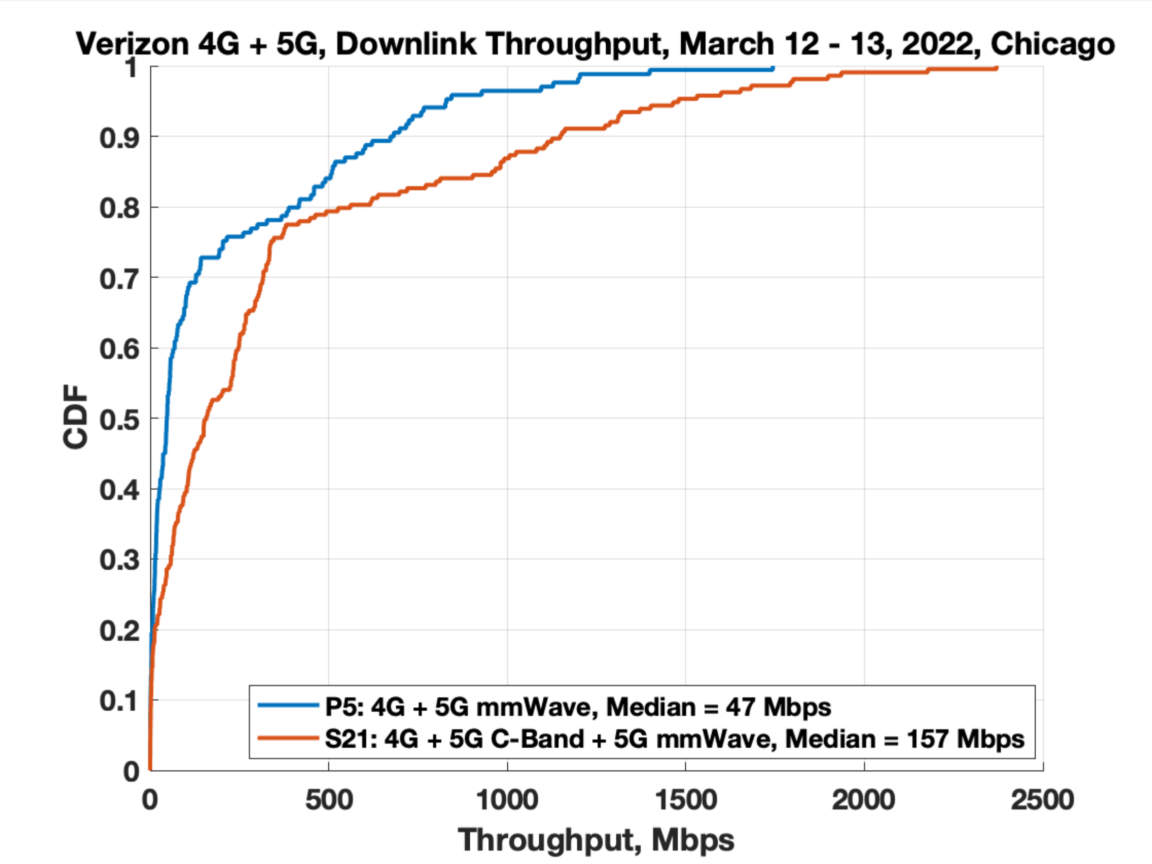


- 6 mmWave BSs on lamp-posts in a 0.1 sq. km area. CBRS and LAA were also deployed on the poles.
- Average distance between BSs ~ 140 m
- 39 GHz (Band n260), 4 carrier aggregation
- Measurements taken in 2020-2021: very few people in the area.
- With this density, and no buildings, coverage of mmWave was fairly good.
- However, it is unclear if the presence of crowds will affect throughput: we plan to return to the area in summer of 2022 to take measurements during outdoor events.

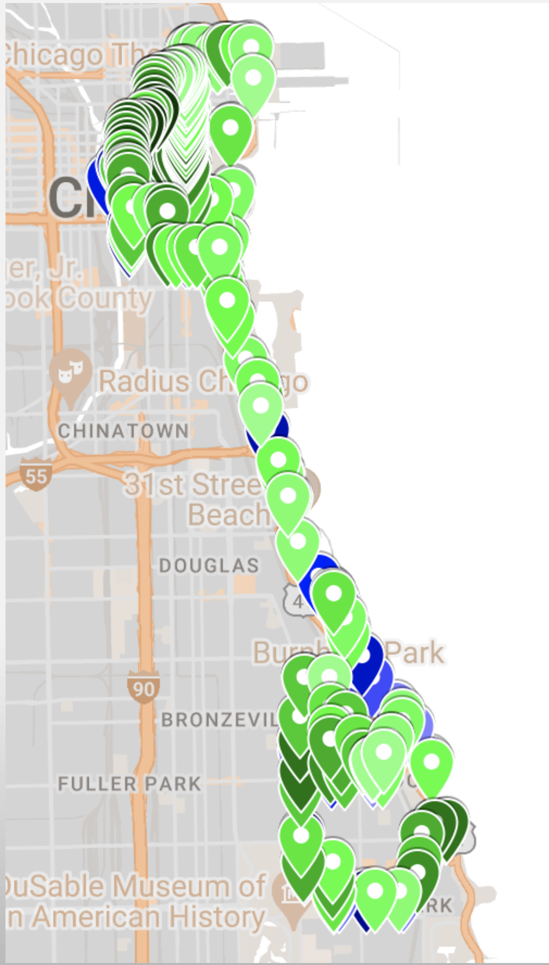


https://people.cs.uchicago.edu/~muhiqbalcr/sigcap/maps/grant-park-may-jun-2021/nr-heatmap.html

Comparison of 5G mmWave and C-Band, Chicago



- The Pixel 5 is mmWave capable, but not C-Band capable. 5G on Pixel 5 is low band and DSS.
- S21 is both C-Band and mmWave capable
- C-Band increases median throughput (from 47 to 157 Mbps. High peak throughputs are from mmWave in both P5 and S21.



https://people.cs.uchicago.edu/~muhiqbalcr/2022-chicago/nr-heatmap.html

https://www.google.com/maps/d/u/0/edit?mid=1pJtmW721Dv1wpgivqHweVGyXOEksO8zm&usp=sharing

Key takeaways and lessons for the future

- Coverage of each small cell mmWave BS is about 1/2 a city block. Extremely dense deployments required for seamless coverage: what is the bits/sec/Hz/area/**$**?
- Sustained throughputs of > 1 Gbps over mmWave in consumer hand-sets are limited today by thermal heating: more research needs to be done on reducing power consumption of mmWave on UEs and/or developing better cooling mechanisms.
- Latencies are still high: this could be due to non-standalone operation.
- Median throughput of 5G is higher with C-Band, but mmWave gives higher max throughput. Future Gs will be a mix of frequencies, with higher frequencies having a role, but will not be the primary mode.
- Indoor coverage of mmWave is extremely limited, unless BSs are mounted indoors.
- Increased body loss with mmWave: how will mmWave perform in crowded areas?

Lessons for the future: rethinking NextG

- **Rethink the PHY for high frequencies:** is OFDM, with it's high PAPR the right waveform? Frequency diversity in narrow beams is limited, so perhaps a return to single carrier and constant envelope modulation should be explored? More energy efficient, leading to higher sustained throughputs.
- **What is the right deployment scenario?** Are outdoor, mobile cellular networks the right application for high frequencies and NextG? Most data is consumed indoors. Clearly the indoor/outdoor reception will be even more severely impacted than mmWave and coverage will be further reduced.
- **Are the right channel sounding measurements being carried out?** With the even narrower beam-widths, the environment will play an even greater role in performance. Channel measurements in realistic environment AND constrained UEs should drive system design, not idealized measurements.
- **Frequencies between 7 – 24 GHz:** The FCC TAC Workgroup on Advanced Spectrum Sharing is examining this frequency range for next generation wireless, **BUT**, these bands will require sharing. Cellular standards as developed by 3GPP are not natively designed for operating in shared spectrum. There is already 1.2 GHz of unlicensed spectrum at 6 GHz available for sharing.
- **Finally:** develop coexistence with passive applications (such as radio-astronomy and weather satellites) now, rather than later. Repeats of 5G/weather-radar and 5G/FAA controversies are undesirable.

Papers on mmWave measurements

1. M. I. Rochman, D. Fernandez, N. Nunez, V. Sathya, A. S. Ibrahim, M. Ghosh and W. Payne, ”Impact of device thermal performance on 5G mmWave communication systems,” https://arxiv.org/pdf/2202.04830.pdf
2. A. Narayanan, M. I. Rochman, A. Hassan, B. S. Firmansyah, V. Sathya, M. Ghosh, F. Qian and Z.-L. Zhang, ”A comparative measurement study of commercial 5G mmWave deployments,” Infocom 2022. https://5gbeams.umn.edu/
3. M. I. Rochman, V. Sathya, N. Nunez, D. Fernandez, M. Ghosh, A. S. Ibrahim and W. Payne, "A Comparison Study of Cellular Deployments in Chicago and Miami Using Apps on Smartphones," ACM WiNTECH 2021.