Real-world Evaluation of Dense Deployments in the Unlicensed 6 GHz band, Indoors and Outdoors

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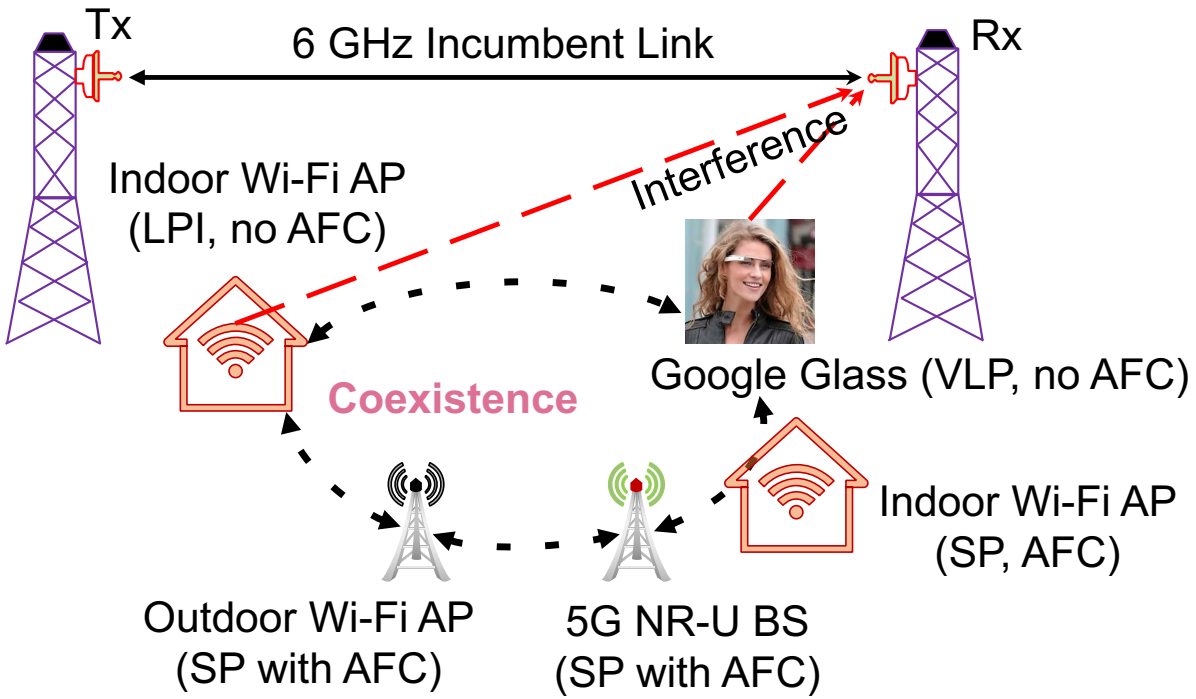
Disclaimer: Opinions expressed are my own and are not necessarily supported by my affiliated institutions.

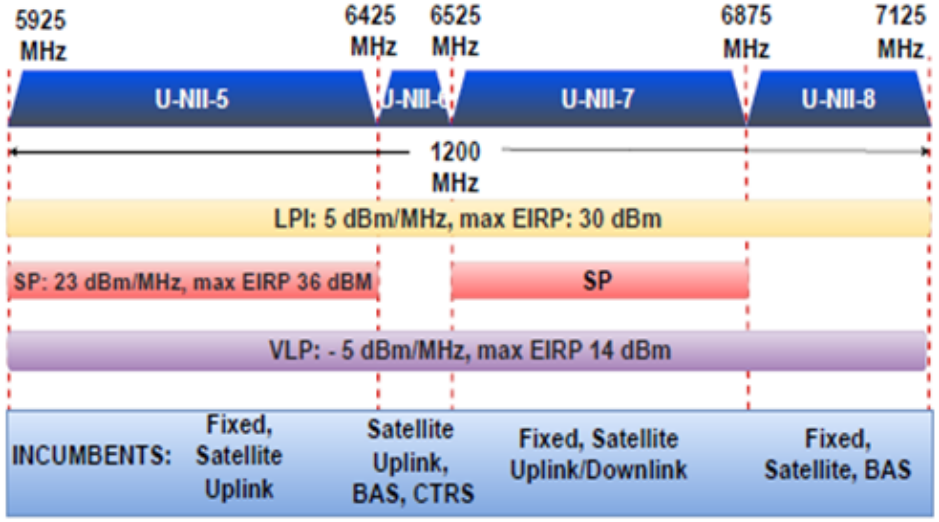
Topics

- Introduction and Motivation
- Deployments studied
- Measurement Tools and Methodology
- Results
  - Wi-Fi usage in the stadium: 5 GHz vs 6 GHz
  - Coexistence of outdoors SP and indoor LPI deployments
  - Comparison of Wi-Fi and cellular in the stadium
  - Comparison of Wi-Fi at airports.
- Conclusions

6 GHz Developments in the U.S.

- Since 2020, the 6 GHz band (5.925 - 7.125 GHz) has been adopted fully in the U.S. for unlicensed but shared.





Spectrum bands and U.S. Regulations in 6 GHz.

- SP deployments could only begin once the Automatic Frequency Control (AFC) systems were deployed and certified by the Federal Communications Commission (FCC) in February 2024.
- Most SP deployments today are enterprise deployments such as stadiums.

Goals and Contributions

- Starting in 2023, my research group has been engaged in careful measurements of deployed Wi-Fi 6E in 6 GHz to understand coverage and potential for interference to fixed link incumbents.
  - University of Michigan, ~ 16,000 Wi-Fi 6E APs, all LPI
  - University of Notre Dame, ~ 900 SP Wi-Fi 6e APS in the stadium + hundreds of LPI APs in buildings
  - Measurements in urban areas, including airports.

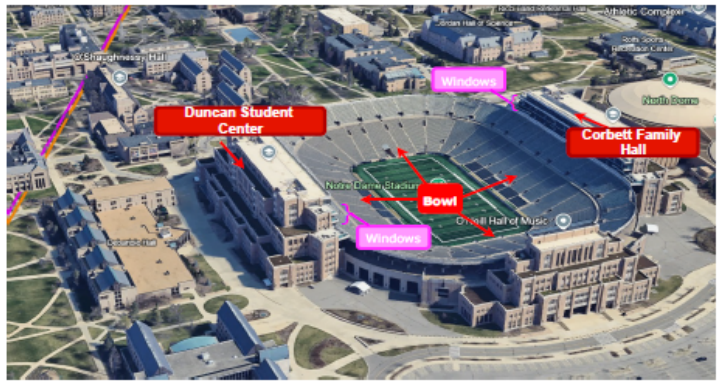
- Our main contributions are:
  - A first of its kind detailed data set of labeled indoor and outdoor measurements of SP and LPI APs.
    - https://sigcap.spectrumx.org/
  - Comparison of 6 GHz usage, 5 GHz usage and cellular when the Notre Dame stadium is at full capacity with 80,000 attendees.
  - Detailed analyses of coexistence of outdoor SP with indoor LPI under different conditions: fully occupied stadium and empty stadium.
  - Building Entry Loss measured with real APs.

Stadium Deployment

- The ND stadium consists of an open bowl area and three adjacent buildings anchored to the south, east, and west sides.
- There are three distinct environments: outdoors in the bowl area, indoors near windows in floors 7 - 9 of Corbett and Duncan, and indoor interior in floors 1 - 6 of the two building.
- About 900 SP Wi-Fi 6E APs (Aruba AP-634) are installed outdoors in the stadium bowl: two SP APs are placed within a case and mounted on the handrail that splits the stadium section.

Measurement Environment.

Environment	Description
Out (Stadium Bowl)	The open area of the stadium bowl, with SP deployments
II (Indoor Interior)	Floors 1 - 2, Duncan Student Center, with concrete walls and no windows facing the stadium.
INW (Indoors near Windows)	Floors 7 - 9, Duncan Student Center and Corbett Family Hall, featuring long hallways with large double-pane low-E windows and glass doors to the stadium bowl.



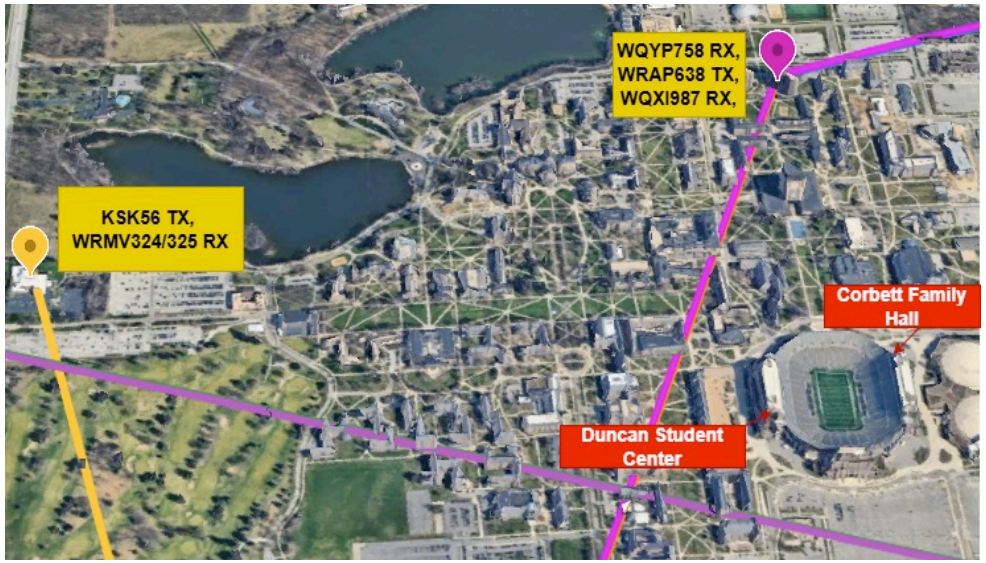
Measurement locations.

(a) Stadium bowl. (b) APs mounted on a handrail.

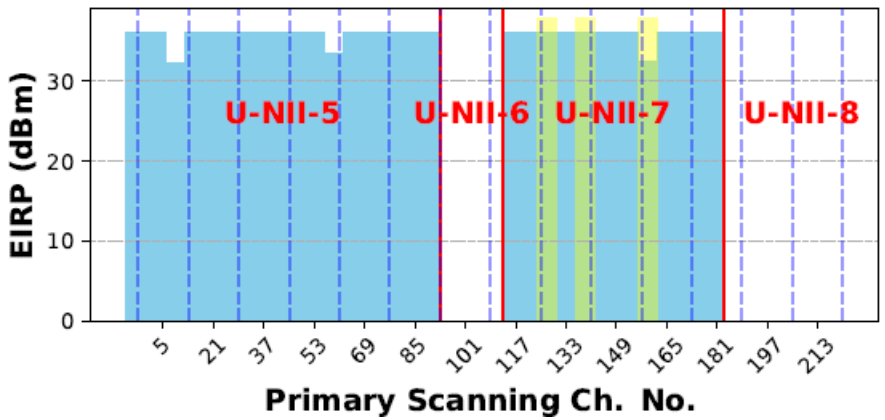
Wi-Fi 6E deployment at ND stadium.

6 GHz Fixed Links at the University of Notre Dame

- With approximately 1300 Wi-Fi 6E APs installed indoors and outdoors in a small area, aggregate interference could potentially affect incumbents.
- There are five fixed links in the vicinity of the stadium. Three of these fixed links are deployed on the roof of Grace Hall, a building on the ND campus.
- Two of these links are receivers (WQXI987 at frequency 6655 MHz and WQYP758 at 6595 MHz with 30 MHz bandwidth) with transmitters positioned at a significant distance away from the campus, and one is a transmitter, WRAP638 on 6755 MHz with the receiver in South Bend. These frequencies are shown as yellow bars.



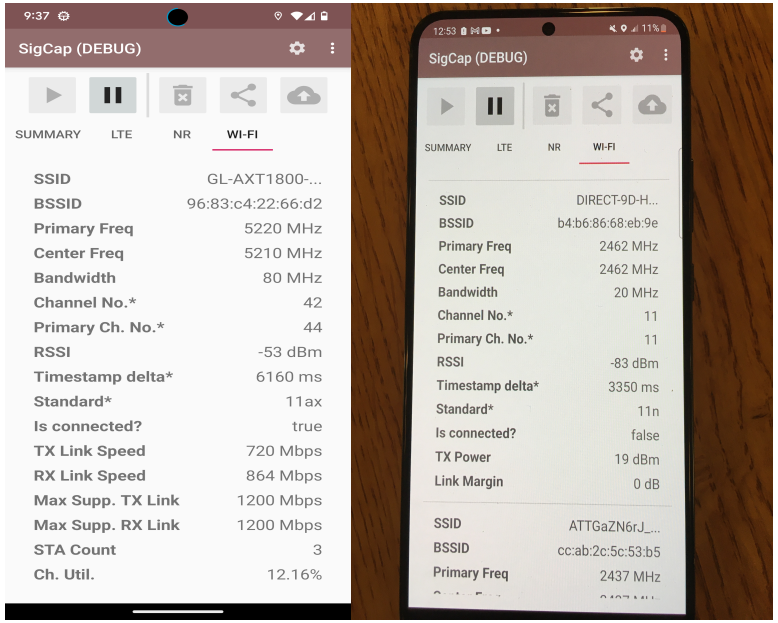
6 GHz fixed links at ND stadium.



AFC plot from Cambium. Yellow bars are the receive frequencies of the three fixed links in the vicinity.

Measurement Tools

- Smartphones with SigCap.
- All RSSI measurements were on the 20 MHz beacon channel.
- Outdoor walking measurements were conducted in the bowl using phones equipped with SigCap.
- Indoor Measurements were conducted using SigCap phones, in floors 7 - 9 of Corbett and floors 1, 2, 7 - 9 of Duncan.
- The spectrum analyzer, with an antenna designed for 4- 8 GHz, was placed on the balcony of the 9th floor of Duncan Student Center.



SigCap User Interface.

Measurement tools and features.

App./Tool	Features	Devices
SigCap	BSSID, Tx power, # of connected clients, frequency, channel utilization, RSSI, GPS, Tx and Rx link-speeds when connected	3 × Google P8, 2 × Samsung S22, 1 × Samsung S24
SA	Spectrum power captured over 100 kHz bins	1 × Keysight FieldFox, Model N9951A Handheld SA

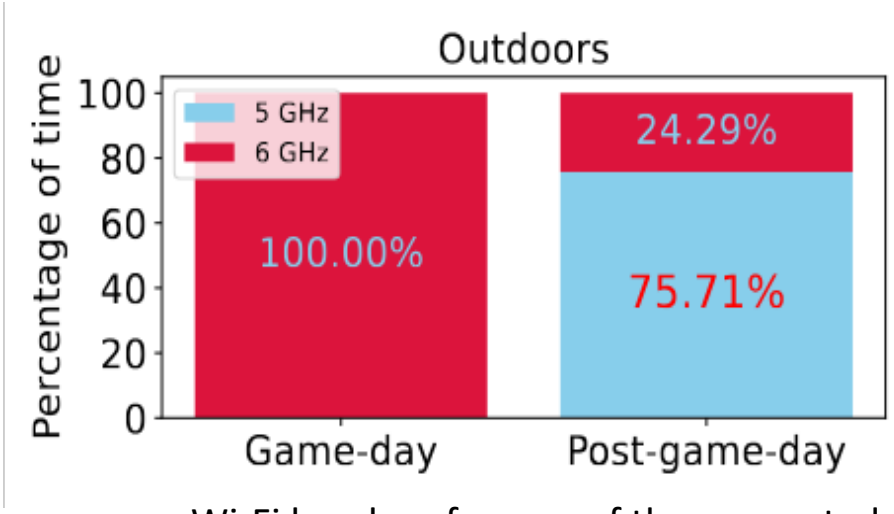
(a) Outdoor walking campaign

(b) Outdoor fixed location campaign

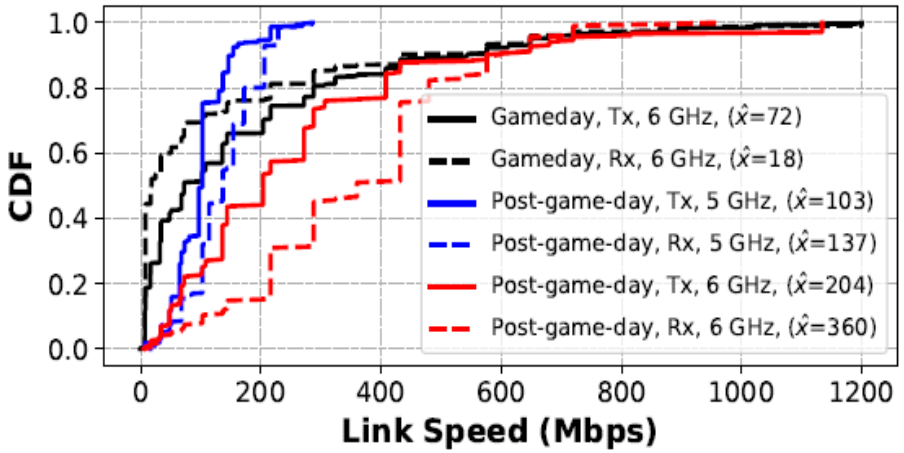
(c) Indoor walking campaign

Measurement campaigns.

5 GHz vs. 6 GHz: Wi-Fi Usage and Link Speed



Wi-Fi band preference of the connected measurement phones.

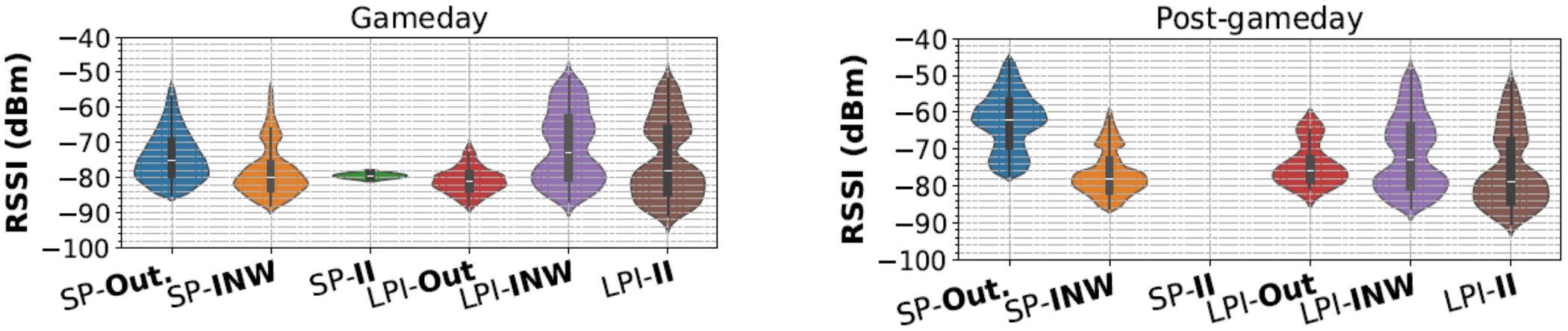


Data rates for the measurement phones.

- **Key takeaway :** The 6 GHz band is crucial for improving connectivity in dense deployments: the 5 GHz band is almost completely saturated on game-day.
  - Based on the connection status of only the measurement phones used during the measurements, not all phones present in the stadium during game-day (80k).

- From the Notre Dame Office of Information Technologies: 14% of client connections in the stadium on game-day were over the 6 GHz band- this rate of adoption is fairly high since only the newer phone models incorporate Wi-Fi 6E.

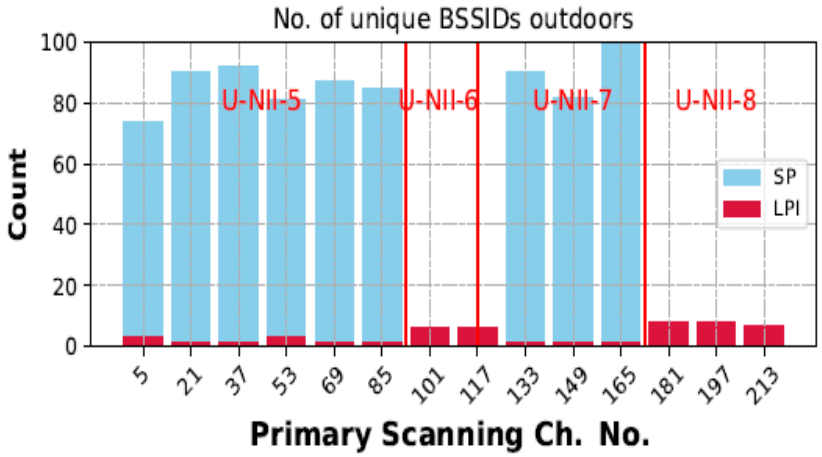
Coexistence of outdoor SP and indoor LPI deployments: RSSI



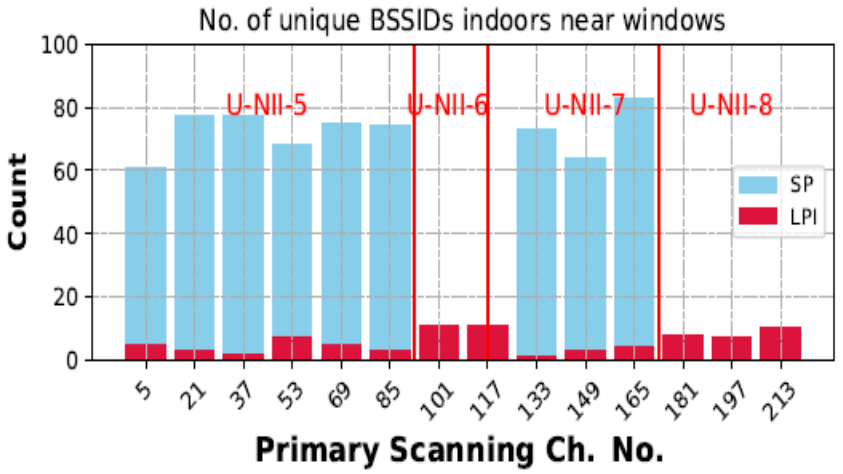
Measured RSSI levels over the 20 MHz primary scanning channels measured during walking measurements on game-day and post-game-day. SP/LPI-Out: measured outdoors from SP/LPI APs, SP/LPI-INW: measured indoors near windows from SP/LPIAPs, SP/LPI-II: measured indoors interior from SP/LPI APs.

- **Key Takeaway:** SP operations outdoors and LPI operations indoors affect each other in the INW environment- further highlighting the importance of careful channel assignments
  - Comparable RSSI levels in SP APs measured indoors near windows (SP-INW) and LPI APs measured indoors near windows (LPI-INW)
- **Key takeaway:** Indoor interior environments, with their physical separation, are well insulated from outdoor SP operations, enabling outdoor and indoor interior deployments to operate simultaneously without negatively impacting each other's performance.

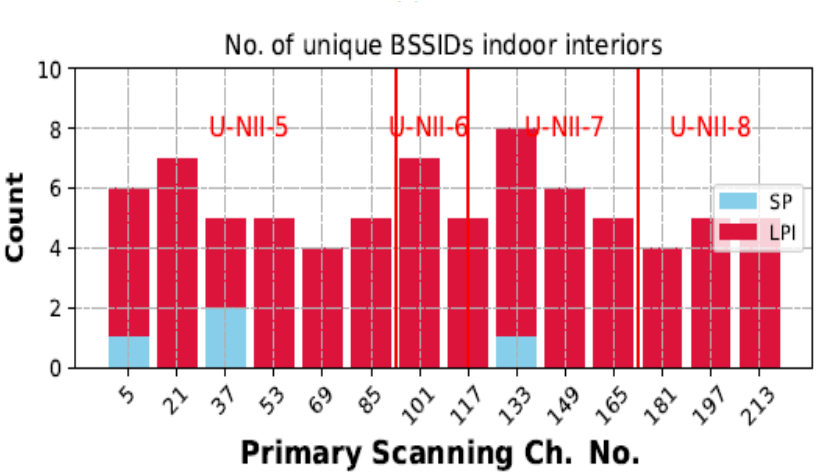
Number of Unique BSSIDs on Game-day



Outdoors



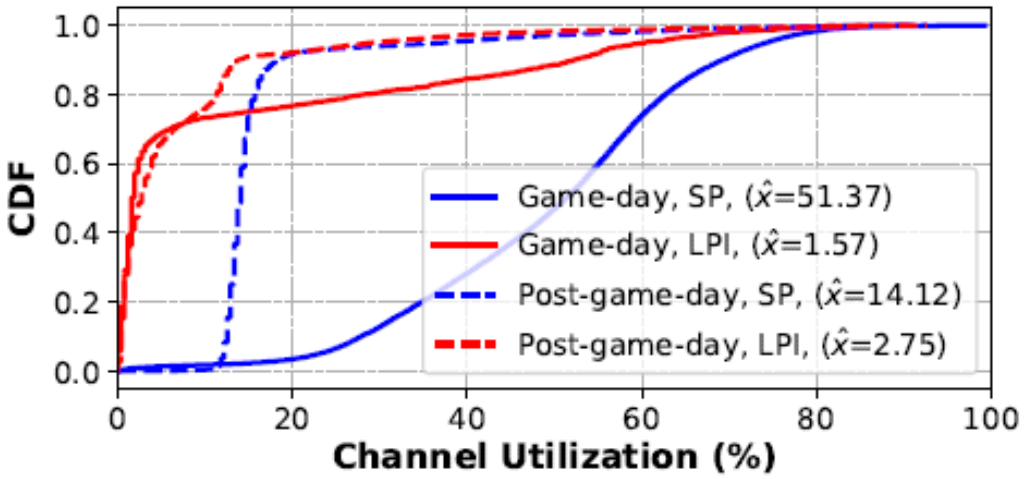
Indoors near windows

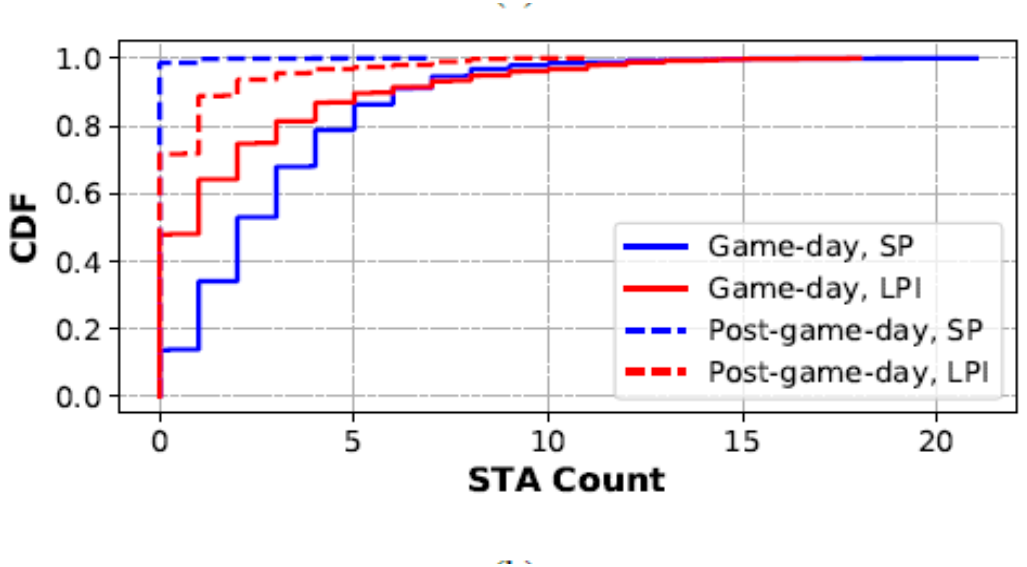


Indoor Interiors

- The indoors near windows environment is very similar to outdoors.
- The indoor interior environment is quite isolated from the outdoors since almost no beacons from SP APs are received there.
- A similar pattern is observed in the post-game-day measurements.

Channel Utilization and STA Count





CDF plots of channel utilization and STA count on game-day and post-game-day.

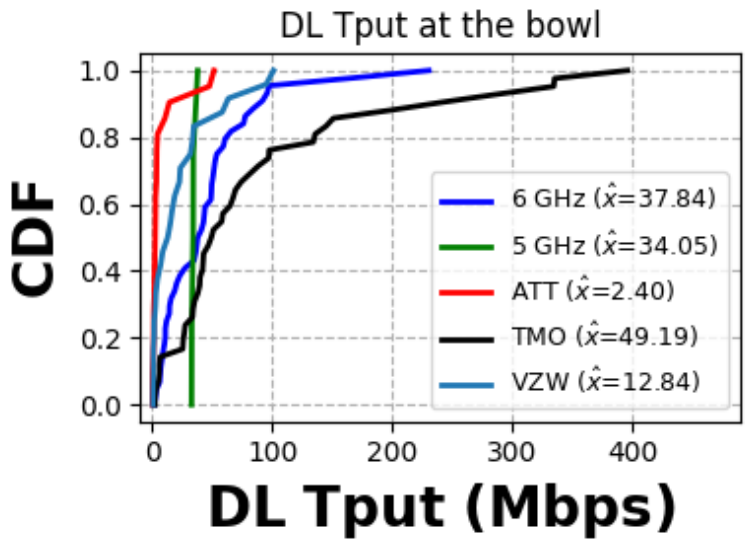
- The SP APs deployed outdoors in the bowl are used more intensely during the game-day, median channel utilization of 51 %.
- The median level of channel utilization on post-game-day (%14) is due to the beacon transmission caused by the dense deployment itself.
  - STA count on post-game-day is very low.

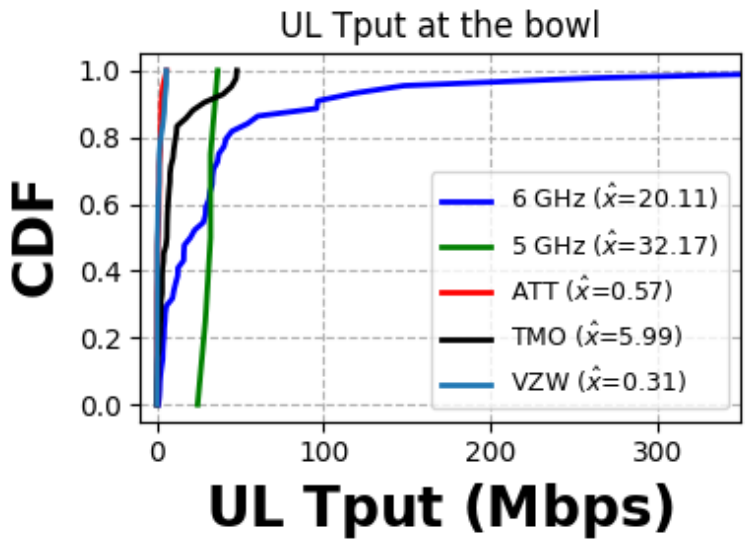
Connection Ratios for SP and LPI for indoors near windows (INW) environment

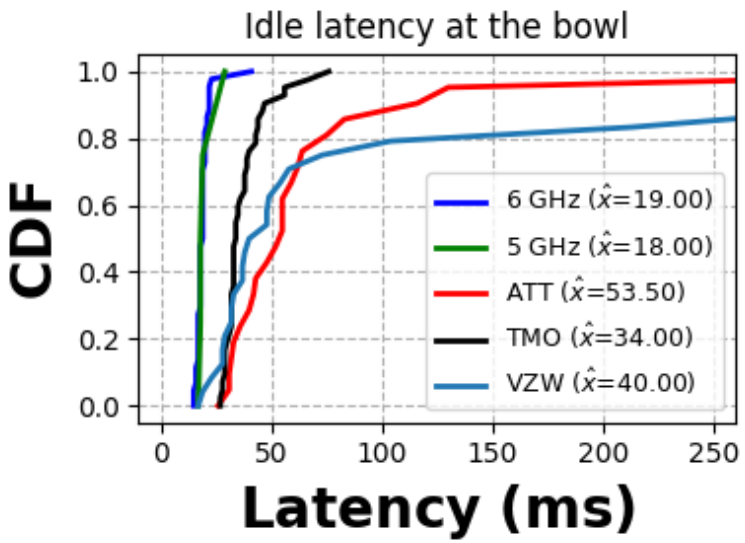
Meas	INW 6 GHz Connections	
	to SP AP	to LPI AP
Game-day	29.24%	70.76% **UNII-Band Ratios:** U-NII-5 and U-NII-7: 67.5% U-NII-6 and U-NII-8: 32.5%
Post-game-day	69.1%	30.9% **UNII-Band Ratios:** U-NII-5 and U-NII-7: 72.3% U-NII-6 and U-NII-8: 27.7%

- **Key Takeaway:** Similar RSSI levels from SP APs measured in both INW and outdoor environments enable indoor phones to connect to the outdoor SP APs.
- **Key Takeaway:** The degree of usage of outdoor networks will impact connections within INW environments.
  - There were more connections to U-NII-6 and U-NII-8 (32.5%) compared to post-game-day (27.7%).

Comparison in the stadium between Wi-Fi and cellular



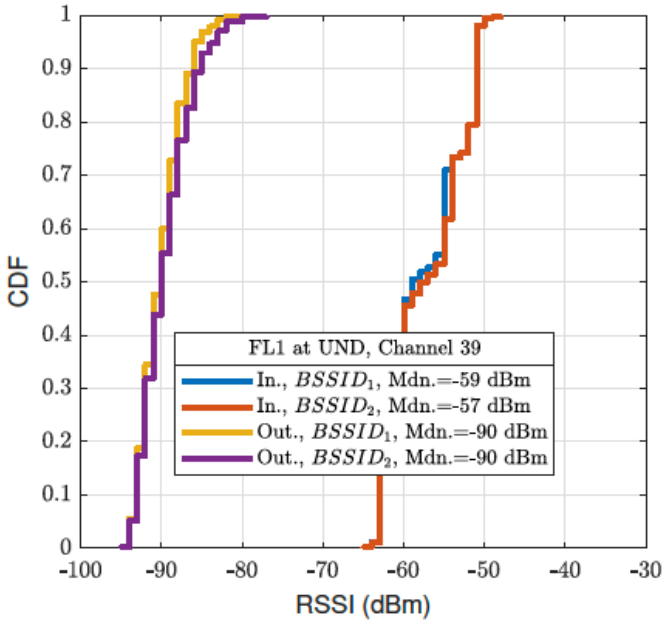


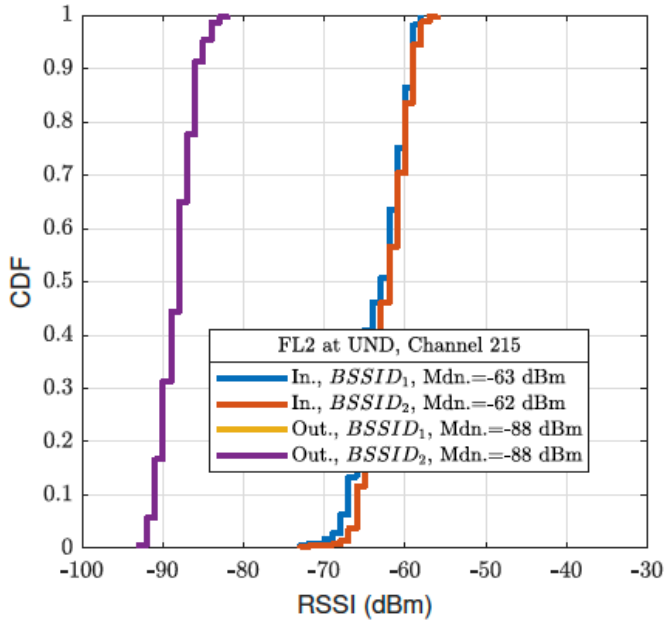


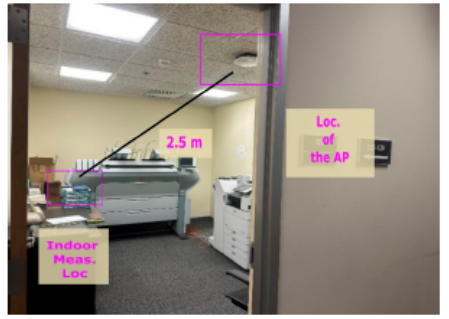
Measurement environment: Ookla speedtests, the stadium has a 5G DAS for T-Mobile

- **Key Takeaway:** Measurements with a full stadium (~80,000) indicate that Wi-Fi offers improved uplink and latency over all cellular carriers. Downlink throughput of only TMO is better due to the DAS.

Measured Building Entry Loss (BEL) at UND





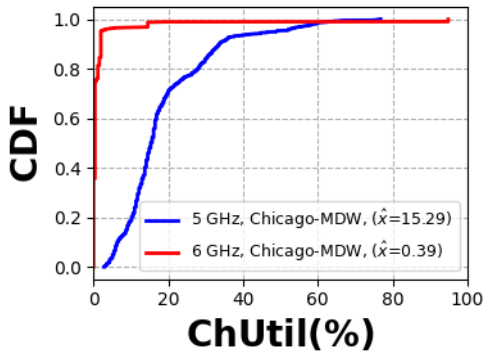


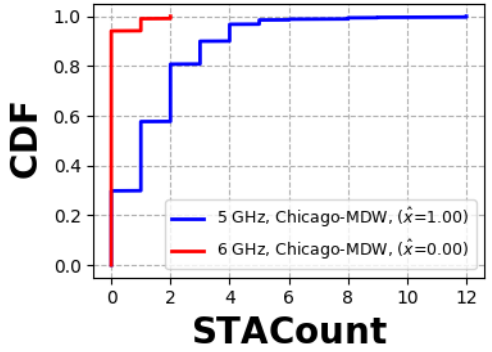
(a) For FL1.

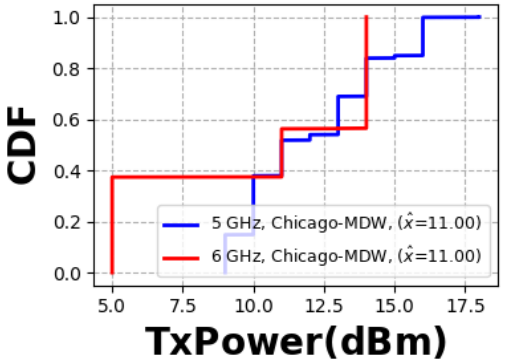
(b) For FL2.

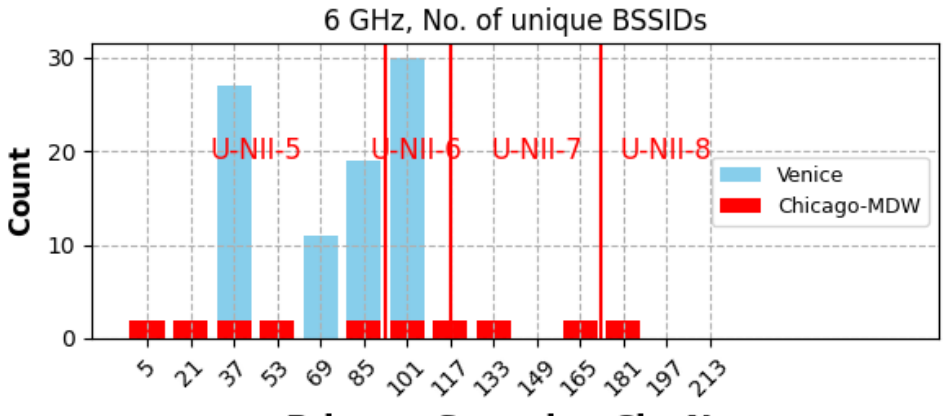
- Measured BEL through typical enterprise construction is 25 – 30 dB
  - This loss will also apply to cellular signals from outside.
  - The high BEL allows sharing between LPI devices and fixed link microwave incumbents.

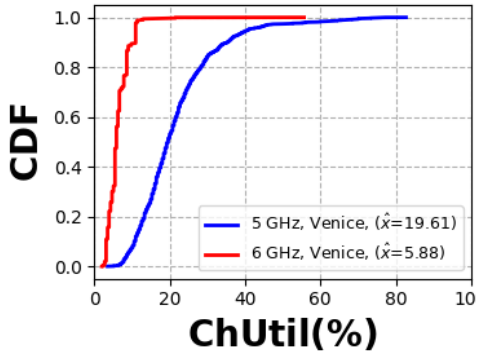
Wi-Fi Usage at Chicago Midway vs. Venice

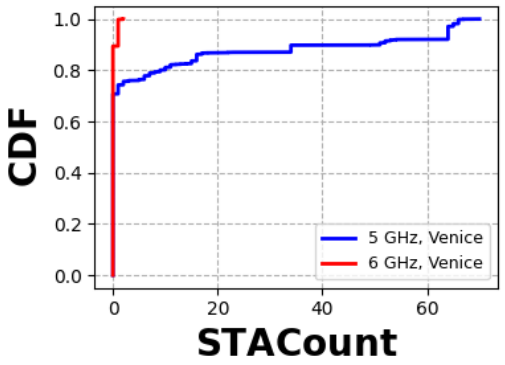


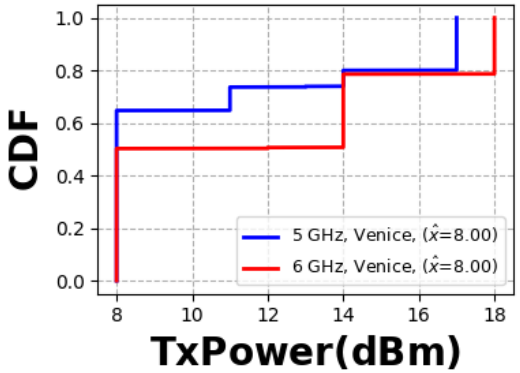


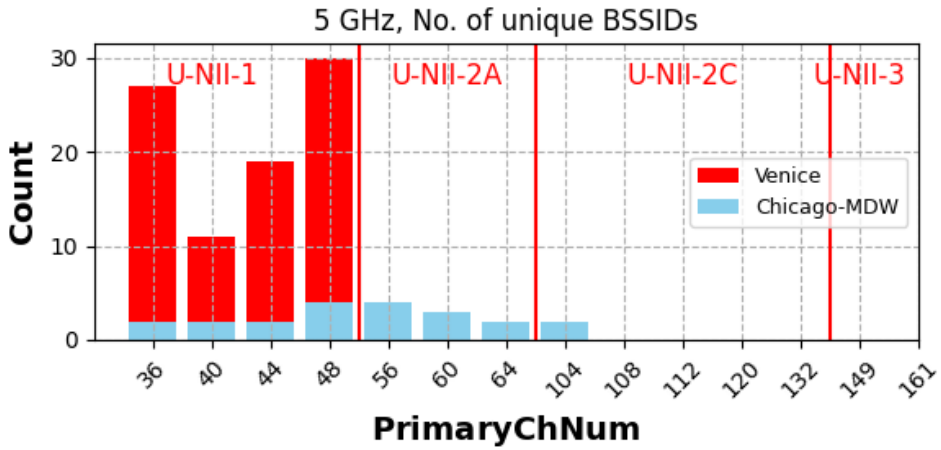






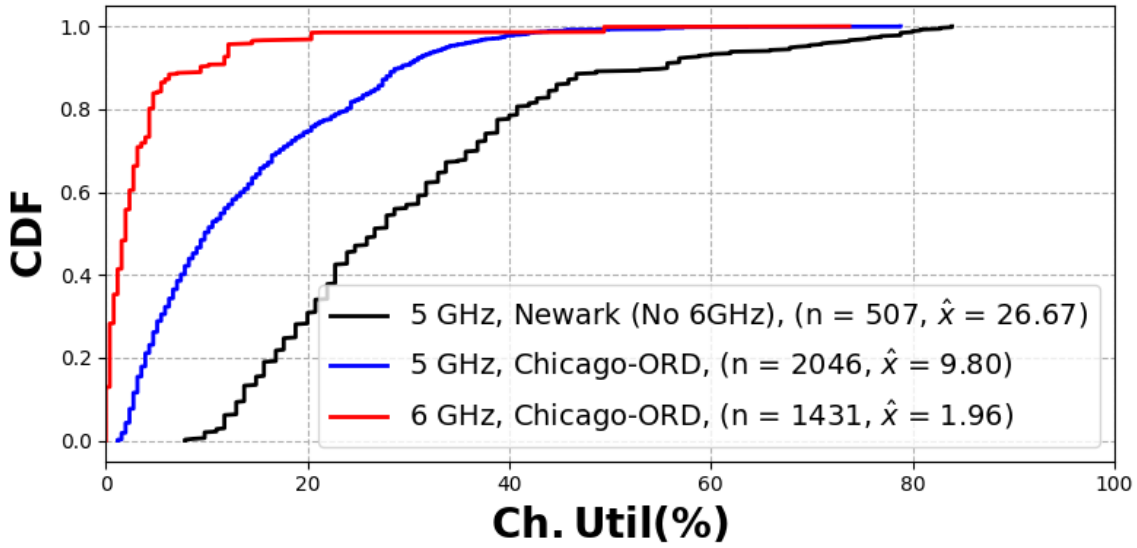






- Considering only airport SSIDs, the bandwidth is 20 MHz in Venice and 40 MHz in Chicago for both the 5 GHz and 6 GHz bands.
- In Venice, only the lower 6 GHz band is used, and with a smaller bandwidth, this results in higher channel utilization—**5.88% compared to 0.39% in Chicago.**

Wi-Fi Usage at Chicago ORD vs. Newark EWR



Airport	Considered SSIDs	Frequency	BW
Chicago ORD	_Free_ORD_Wi-Fi, Boingo Hotspot	6 GHz	40 MHz
Chicago ORD	_Free_ORD_Wi-Fi, Boingo Hotspot	5 GHz	40 MHz
Newark	_Free EWR Wi-Fi Boingo Hotspot	5 GHz	40 MHz

- Considering only airport SSIDs, it is clear that 6 GHz deployments in airports can relieve congestion on 5 GHz while adding more capacity.
- Mid-band NR was not available in either location, even in n41 (2.5 GHz)
- Highly unlikely that 6 GHz cellular will penetrate indoors. Allocating the upper half to cellular will severely disadvantage dense deployments such as airports.

Conclusions and key takeaways

- The first-of-its-kind, comprehensive measurements and analyses presented clearly indicate that the entire 6 GHz band is crucial for dense deployments:
  - Our 6 GHz capable measurement phones were always connected to 6 GHz during game-day since only 14% of the clients had this capability and hence were likely on 5 GHz.

- Frequencies used with high power outdoors may be unavailable for LPI use indoors, especially near windows.
  - Even with the SP APs transmitting at a median level of 27 dBm, 9 dB less than the allowed 36 dBm.
  - Hybrid sharing should consider use of 5G NR-U instead, which does have a similar protocol as CSMA/CA.

- The building entry loss of 25 - 30 dB will not allow good indoor coverage by cellular systems even with large antenna arrays
  - Physics of propagation and building losses imply that 6 GHz cannot propagate indoors well.
  - Even C-band (3.7 – 3.98 GHz) has poor indoor coverage, unless deployed densely.

Papers on 6 GHz sharing

1) S. Dogan-Tusha, A. Tusha, M. I. Rochman, H. Nasiri, J. R. Palathinkal, M. Atkins and M. Ghosh, "Evaluation of Indoor/Outdoor Sharing in the Unlicensed 6 GHz Band," *2025 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)*, London, United Kingdom, 2025, pp. 1-9, doi: 10.1109/DySPAN64764.2025.11115954. https://arxiv.org/abs/2505.18359
2) S. Doğan-Tusha, A. Tusha, M. I. Rochman, H. Nasiri and M. Ghosh, "Spectrum Sharing Characterization Using Smartphones: Exploring 6 GHz Sharing Through Large-Scale Wi-Fi 6E Measurements," in *IEEE Communications Magazine*, vol. 63, no. 2, pp. 70-76, February 2025, doi: 10.1109/MCOM.001.2400325.
3) S. Dogan-Tusha, A. Tusha, H. Nasiri, M. I. Rochman and M. Ghosh, "Spectrum Sharing in 6 GHz: How is it working out?," *2024 IEEE 25th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, Lucca, Italy, September 2024, pp. 791-795, doi: 10.1109/SPAWC60668.2024.10694058.
4) M. Ghosh, "Evolution of Sharing in 6 GHz," in *IEEE Wireless Communications*, vol. 30, no. 5, pp. 4-5, October 2023, doi: 10.1109/MWC.2023.10325444
5) S. Dogan-Tusha, A. Tusha, H. Nasiri, M. I. Rochman and M. Ghosh, "Indoor and Outdoor Measurement Campaign for Unlicensed 6 GHz Operation with Wi-Fi 6E," *2023 26th International Symposium on Wireless Personal Multimedia Communications (WPMC)*, Tampa, FL, USA, 2023, pp. 1-6, http://dx.doi.org/10.1109/WPMC59531.2023.10338962
6) S. Dogan-Tusha, M. I. Rochman, A. Tusha, H. Nasiri, J. Helzerman and M. Ghosh, “Evaluating the interference potential in 6 GHz: an extensive measurement campaign of a dense indoor Wi-Fi 6E network,” WiNTECH ‘23, Proceedings of the 17th ACM Workshop on Wireless Network Testbeds, Experimental evaluation & Characterization, October 6, 2023, https://dl.acm.org/doi/abs/10.1145/3615453.3616518