Indoor and Outdoor Measurement Campaign for Unlicensed 6 GHz Operation with Wi-Fi 6E

Seda Dogan-Tusha*, Armed Tusha*, Hossein Nasiri*, Muhammad Iqbal Rochman †, Monisha Ghosh*†
*Department of Electrical and Electronics Engineering, University of Notre Dame IN, USA
†Department of Electrical and Electronics Engineering, University of Chicago, IL, USA
Email: stusha@nd.edu, atusha@nd.edu, hnasiri2@nd.edu, muhiqbalcr@uchicago.edu, mghosh3@nd.edu

***Abstract*—The current Wi-Fi frequency bands (2.4 and 5 GHz bands) are severely congested due to the exponential growth of Wi-Fi-enabled devices with the increasing demands of higher capacity and faster wireless connections. Wi-Fi 6E is a potential solution to meet these needs by employing channels of up to 160 MHz bandwidth in the 6 GHz unlicensed band. However, there is limited research on understanding the effect of Wi-Fi 6E on incumbent users of the band. With this motivation, we conduct a comprehensive measurement campaign for a typical real-world deployment of Wi-Fi 6E Low Power Indoor (LPI) Access Points (APs) in a building. The campaign consists of both walking and fixed location measurements to evaluate outdoor beacon Received Signal Strength Indicator (RSSI), outdoor channel connectivity, and building entry loss (BEL) at 6 GHz band. The measurement results demonstrate outdoor RSSI level ranging from -64 dBm to -95 dBm with a median of -89 dBm, median outdoor downlink (DL) throughput level of 25 Mbps, and 25-33 dB BEL due to solid brick walls. We conclude that (i) outdoor RSSI levels do note pose a threat to incumbent fixed links and (ii) construction material plays a vital role on outdoor RSSI with highest levels observed immediately in front of glass doors and windows.**

***Index Terms*—Wi-Fi 6E, 6 GHz, unlicensed spectrum, low power indoor.**

I. Introduction

To address spectrum congestion in the current 2.4 and 5 GHz Wi-Fi bands, the Federal Communications Commission (FCC) allocated the 6 GHz band for unlicensed use alongside existing incumbents, mainly fixed microwave links, cable television relay services (CTRS), satellite, and mobile Broadcast Auxiliary Services (BAS) [1]. The 6 GHz band is composed of four Unlicensed National Information and Infrastructure (U-NII) bands: U-NII-5 (5.925–6.425 GHz), U-NII-6 (6.425–6.525 GHz), U-NII-7 (6.525–6.875 GHz), and U-NII-8 (6.875–7.125 GHz), as shown in Table I.

Unlicensed devices must comply with two sets of rules to protect incumbents: low power indoor (LPI) and standard power (SP). LPI operation is allowed across the entire 6 GHz band and doesn't require an Automated Frequency Control (AFC) system, but indoor deployment is obligatory for access points (APs). On the other hand, SP APs can be deployed either outdoors or indoors, but require AFC system to prevent interference with incumbents, and can operate only over U-NII-5 and U-NII-7 bands. Wi-Fi 6E APs operating under LPI rules must comply with the maximum power spectral density (PSD) of 5 dBm/MHz [2]. Client devices (STAs) are permitted to transmit at a 6 dB lower level than the APs since they

TABLE I: Unlicensed Operation over 6 GHz.

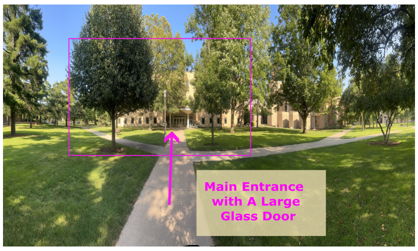
Band	Incumbents	Use Cases	Chann. No.	Freq. (MHz)
U-NII-5	Fixed, Satellite Uplink	LPI, SP	1-97	5925-6425
U-NII-6	Satellite uplink, BAS, CTRS	LPI	101-117	6425-6525
U-NII-7	Fixed, Satellite uplink/downlink	LPI, SP	121-185	6525-6875
U-NII-8	Fixed, Satellite, BAS	LPI	189-233	6875-7125

TABLE II: Max. Tx Power for 6 GHz LPI.

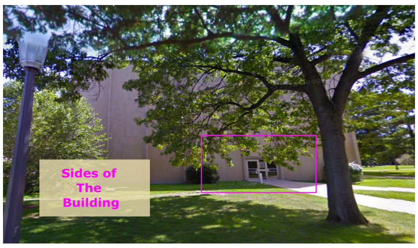
Device Type	Maximum TX Power				
	20 MHz	40 MHz	80 MHz	160 MHz	320 MHz
STA	12 dBm	15 dBm	18 dBm	21 dBm	24 dBm
AP	18 dBm	21 dBm	24 dBm	27 dBm	30 dBm

can be anywhere. Table II shows the corresponding maximum transmit power of LPI APs and STAs as a function of the channel bandwidth.

Existing research focuses on studying coexistence between various Wi-Fi and cellular systems [3], [4], [5]. In [6], Naik *et al.* propose the use of multi-user orthogonal frequency division multiple access (MU-OFDMA) for uplink Wi-Fi 6E to coexist with 5G New Radio Unlicensed (NR-U) technologies. In [7], Rahman *et al.* introduce a game-theory-based framework to improve the coexistence of Wi-Fi with cellular networks. In [8], Voicu *et al.* introduce a hybrid modeling approach that combines stochastic geometry modeling and ns-3 simulations to assess the coexistence of wireless technologies in unlicensed bands, i.e., Wi-Fi and LTE in the 5 GHz band, and Wi-Fi 6E and 5G NR-U in the 6 GHz band. Brunner *et al.* consider the impact of Wi-Fi 6E on ultra-wideband (UWB) communications and ranging in [9]. The results highlight the need for tight synchronization to alleviate the interference effects of Wi-Fi 6E on UWB. In [10], the performance of old and new UWB platforms with the IEEE 802.15.4z amendment have been evaluated and compared in the presence and absence of Wi-Fi 6E activities. In [11], Kim *et al.* investigate adjacent channel interference between Wi-Fi 6E in 6 GHz and C-V2X (Cellular Vehicle-to-Everything) in the adjacent 5.9 GHz. A physical



(a) Frontside of the measurement building: With a large glass door.



(b) Sides of the measurement building: With a glass door, no windows.

(c) Backside of the measurement building: No windows on the first floor.

Fig. 1: Measurement environment at the UND.

protection distance is calculated based on the Reference Signal Received Power (RSRP) of C-V2X, ensuring the coexistence of both technologies without significant interference.

However, with respect to coexistence between Wi-Fi and incumbents in 6 GHz, there is very little academic research, with fixed link operators and unlicensed proponents conducting most of the coexistence studies. In [12], it is demonstrated that a 6 GHz link degrades in fade margin when a Wi-Fi 6E AP is present in the path. In [13], a potential interference analysis over five years for Pacific Gas & Electric's deployments is presented. These studies usually assume worst-case interference situations with Wi-Fi APs placed intentionally in the path of incumbent fixed links.

In [14], we evaluate potential interference from a densely deployed Wi-Fi 6E network over a wide area to existing incumbents via walking, driving and drone measurements. In this paper, we focus on evaluating outdoor signal coverage of a typical Wi-Fi 6E deployment in a single building. The University of Notre Dame (UND) in South Bend has a single building deployed with 70 Wi-Fi 6E LPI APs in the main campus area, which provides a controlled measurement environment to assess outdoor Received Signal Strength Indicator (RSSI) propagation and outdoor connectivity at 6 GHz. The main contributions of this study are listed as follows:

- We performed a comprehensive measurement campaign with walking and fixed location experiments to understand outdoor propagation of a typical deployment of Wi-Fi 6E LPI APs in a building. A heatmap of outdoor RSSI obtained via walking measurements show that outdoor RSSI levels range from -64 dBm to -95 dBm with a median of -89 dBm.
- Outdoor 6 GHz connections are observed mostly in front of glass doors located on three sides of the building, with the minimum RSSI level of -88 dBm. Throughput measurements show median outdoor downlink (DL) throughput of 25 Mbps, and a speed test conducted with a RSSI less than -86 dBm do not complete.
- Evaluating potential aggregate interference at a given location. Despite 70 Wi-Fi 6E LPI APs, each with two Basic Service Set Identifiers (BSSIDs), we show that median value of the number of unique BSSIDs observed outdoors is four.

TABLE III: Measurement tools and devices.

Tool	Wi-Fi Parameters	Devices
SigCap	Time-stamp, location, frequency, RSSI, BSSID, SSID, #STA, Channel Utilization	1 $\times$ Google Pixel 6, 3 $\times$ Samsung S22+
Wireshark	Source/Destination, SSID, BSSID, Frequency, RSSI, Tx Power, Beacon and data packets	Laptop: ThinkPad P16 Gen 1, Wi-Fi Card: Intel(R) Wi-Fi 6E AX211 160 MHz, OS: Ubuntu 22.04 LTS
Ookla	Time-stamp, location, download & upload speed	1 $\times$ Google Pixel 6, 3 $\times$ Samsung S22+

- Assessing the effect of construction material on outdoor RSSI propagation. 20 MHz beacon frames are captured from 120 m away at the front of the building through a large glass door, while the distance reduces to only 32 m outside a solid brick wall. Further, indoor-outdoor measurements at two different locations show 25-33 dB building entry loss (BEL) due to the solid brick wall.

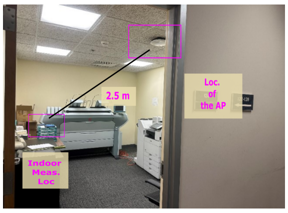
The paper is structured as follows. In Section II, we outline the methodology and tools employed for data collection during the measurement campaign. Section III describes the measurement results and analyses of the outdoor emissions resulting from Wi-Fi 6E LPI APs. Finally, in Section IV, we provide concluding remarks and discuss potential future directions.

II. Tools and Methodology

A. *Measurement Apps & Tools*

We employed end-user devices, such as smartphones and laptops, to capture signal information in various environments. We utilized three tools, SigCap, Ookla and Wireshark on smartphones and laptops respectively, to extract various signal parameters. Table III presents the extracted features and corresponding parameter settings.

1) SigCap: is an Android app developed by the authors that can passively collect GPS and wireless signal data through Android APIs without root access [15]. SigCap extracts time and location parameters from the GPS signal, while utilizing APIs to get signal and network features such as RSRP, Reference Signals Received Quality (RSRQ), RSSI, and frequency bands from 4G, 5G, and Wi-Fi deployments every 5 seconds. While



(a) For FL1.

(b) For FL2.

Fig. 2: Measurement and AP locations for FL1 and FL2.

SigCap has been used extensively in past works to characterize cellular deployment, in this paper we will focus on Wi-Fi 6E and hence added additional parameters which are optionally transmitted in the beacon frames, namely Tx signal power and technology, number of stations connected to each BSSID and channel utilization (percentage of time that the AP sensed the channel to be busy). Fortunately, the Wi-Fi 6E APs deployed at UND broadcast these parameters, thus enabling our analysis.

2) Wireshark: is an open source tool that we utilized for capturing beacon and data frames. A Lenovo ThinkPad P16 Gen1 with the Intel(R) Wi-Fi AX211 Wi-Fi adapter was used to capture packets via Wireshark. Data capturing via both SigCap and Wireshark offers a wider range of Wi-Fi parameters.

3) Speedtest by Ookla: is widely used to test network performance including downlink/uplink throughput, and latency.

B. Methodology

We conducted the measurements in two phases: walking measurement campaign and indoor-outdoor measurement campaigns at two different locations.

1) Walking Measurement Campaign: The campaign took place at the UND during June and July 2023, during which the measurements were conducted while walking around the building shown in Fig. 1. The number of deployed Wi-Fi 6E LPI APs is 70, with 15 dBm Tx power and 80 MHz channel bandwidth. The number of unique BSSIDs is two for each AP. As seen in Figs. 1(a) and 1(b), the front of the building has a big glass door and multiple wide windows, while the side walls have only a glass door and no window. The back wall has no window in the first floor, while small windows are present in the upper floors as shown in Fig. 1(c). Data was collected with SigCap running on the 4 phones given in Table III.

2) Indoor-Outdoor Measurement Campaigns: Measurements were performed at two different environments to assess BEL under solid brick wall.

Fixed Location 1 (FL1): The measurement area of FL1 is a typical room with a single AP on the first floor of the building, as shown in Fig. 2(a). The AP is center-mounted on the ceiling, 3 m away from the exterior wall. The indoor measurement location is 2.5 m away from the AP and the outdoor measurements were carried out right outside the exterior wall.

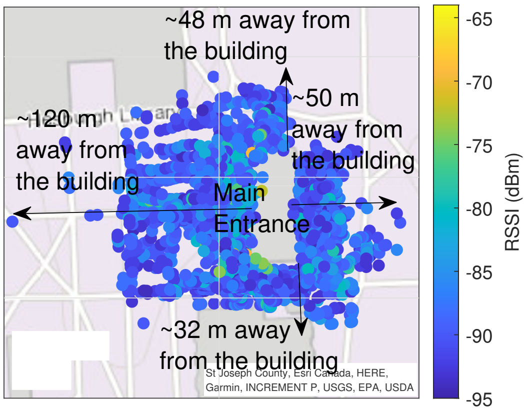
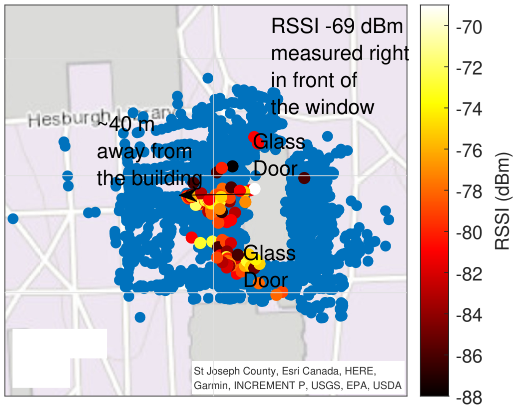
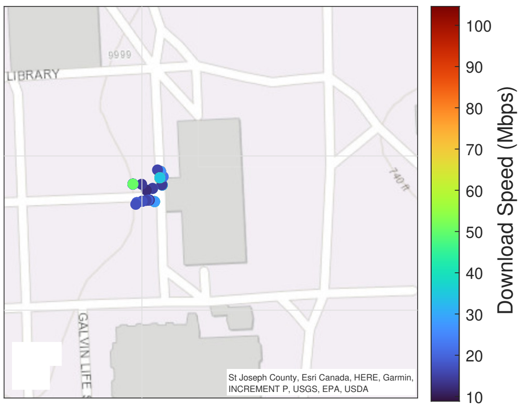


Fig. 3: Outdoor RSSI at 6 GHz via walking measurements.



(a) 6 GHz connection outdoors.



(b) 6 GHz downlink throughput outdoors.

Fig. 4: 6 GHz connection and downlink throughput outdoors.

Fixed Location 2 (FL2): FL2 measurement area is a corridor on the same floor, shown in Fig. 2(b). The AP is on the wall, with antennas pointing downwards, at a distance of 9 m from the exterior wall. Indoor measurements were conducted in front of the exterior wall, while outdoor measurements were performed outside the exterior wall.

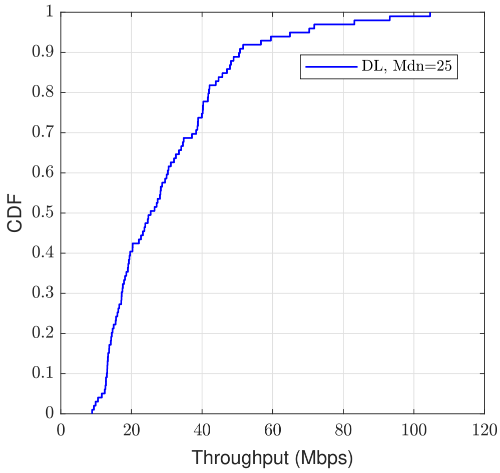


Fig. 5: CDF of downlink throughput at 6 GHz.

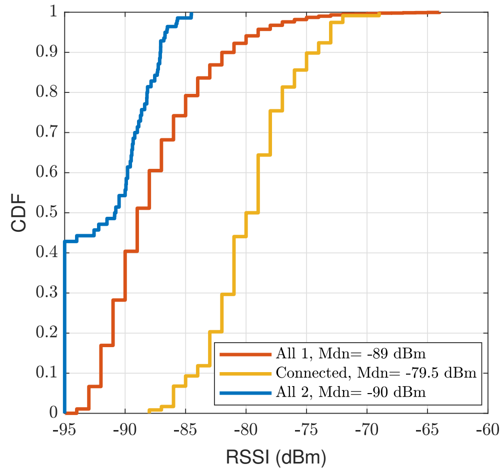


Fig. 7: CDF of outdoor RSSI in walking measurements.

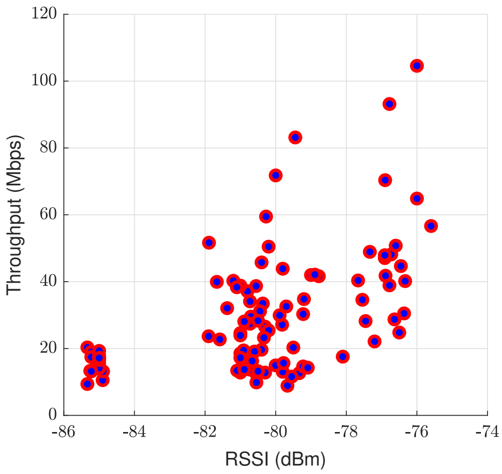


Fig. 6: Downlink throughput vs. RSSI at 6 GHz.

III. Results & Discussions

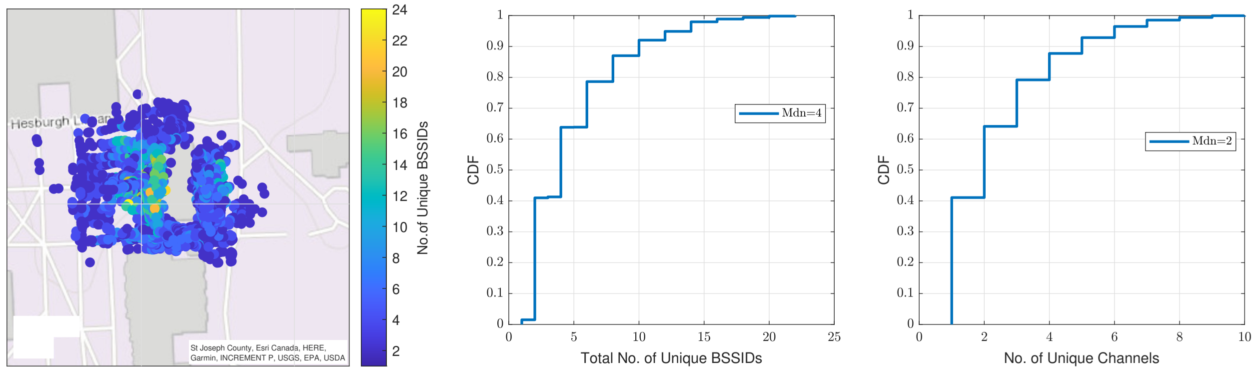
This section presents the statistical analyses of the measurements under various conditions. The discussions are categorized as walking measurements and indoor-outdoor measurements.

A. Walking Measurement Campaign

Fig. 3 shows the outdoor RSSI range measured on 20 MHz beacon frames around the measurement building. RSSI measurements were collected by walking with hand-held phones running SigCap. The measured minimum and maximum RSSI around the building are -95 dBm and -64 dBm, respectively. The glass door and dense windows on the front of the building create a small region with high RSSI, so beacon frames were captured at a distance of 120 m from the building. On the back of the building, however, we observed lower RSSI levels compared to the front as there are no windows on the first floor. The beacon frames were captured at a distance of up to 50 m, potentially transmitted by Wi-Fi 6E LPI APs on upper floors with windows. The distance reduces up to 32 m for the sidewalls of the building with glass doors, but no windows.

Fig. 4 shows the measured outdoor RSSI and DL throughput ranges when phones outside were connected to indoors Wi-Fi 6E LPI APs. As shown in Fig. 4(a), phones were connected to 6 GHz mostly right outside the glass doors, existing on three sides of the building. Due to sporadic connections between phones outside and LPI APs, we were able to run the speed test only at the front of the building, *i.e.*, less than a meter away as illustrated in Fig. 4(b). To provide a detailed analysis of 6 GHz connection outdoors, Fig. 5 shows the CDF plot of DL throughput, while Fig. 6 shows the relation between the throughput and RSSI values. The observed range of DL throughput ranges from 8 Mbps to 104 Mbps with a median level of 25 Mbps. Throughput levels greater than 60 Mbps were observed at high RSSI levels, *i.e.*, -80 dBm and above. However, we were not able to run the speed test at RSSI levels less than -86 dBm. Thus, even though the phone may be connected to a AP, if the RSSI is very low, speedtests do not complete.

Statistical analyses of the campaign are shown in Fig. 7 via CDF plots of the measured RSSI. We observed median outdoor RSSI level of -89 dBm during walking experiments (labelled All 1). Specifically, 80 out of the 140 unique BSSIDs were observed during this outdoor measurements. To further evaluate potential interference from the Wi-Fi 6E deployment to fixed microwave links, we compute average RSSI for each BSSID observed outdoors, and assign the RSSI value of -94 dBm for the BSSIDs not detected outdoors (labelled All 2). Although median RSSI level remains similar, we observed a considerable decrease in the 90th percentile, indicating a greatly reduced potential for interference. The median RSSI level increases to -79.5 dBm when the outside phones are connected to the indoor Wi-Fi 6E APs. As enabling signal levels for client-to-client (C2C) mode at 6 GHz, -86 dBm/20 MHz and -82 dBm/20 MHz are suggested in the proposals submitted to the FCC [16]. Considering median RSSI level

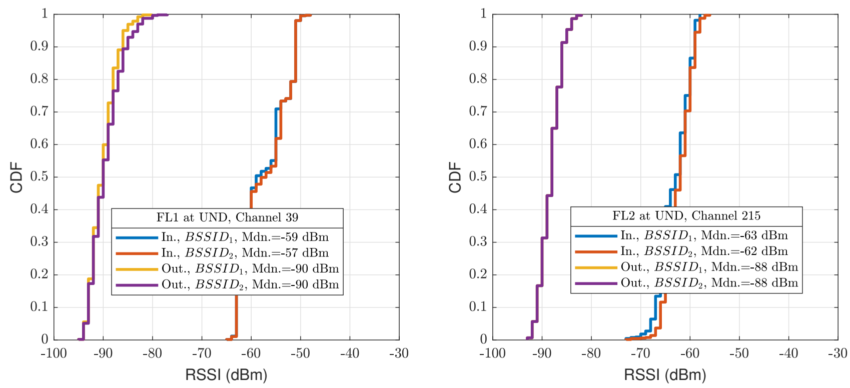


(a) Number of unique BSSIDs measured at a given location.

(b) CDF of the number of unique BSSIDs measured at a given location.

(c) CDF of the number of unique channels measured at a given location.

Fig. 8: CDF plots for walking measurements: Number of unique BSSIDs and channels.



(a) BEL for FL1 at UND.

(b) BEL for FL2 at UND.

Fig. 9: BEL near a solid brick wall at two different measurement environments.

of -79.5 dBm, further measurements and analysis are needed to decide an appropriate enabling signal level that minimizes interference potential to incumbents.

Fig. 8 focuses on the analysis of the number of unique BSSIDs and 80 MHz channels measured outdoors during walking measurements to provide insights into the potential interference impact of a typical Wi-Fi 6E deployment. Fig. 8(a) shows the outdoor heatmap of the number of unique BSSIDs during walking measurements. Although we observed 80 unique BSSIDs outdoors, a high number of BSSIDs were received only outside the front glass door. Figs. 8(b) and 8(c) show the CDF plot of the number of unique BSSIDs and unique 80 MHz channels measured at a specific location. Median number of BSSIDs received outdoors is 4 out of 140 deployed BSSIDs, while the number of unique channels ranges from 1 to 10 with a median value of 2. The lower number of unique BSSIDs and channels indicates a reduced potential for interference from Wi-Fi 6E LPI APs to existing incumbents.

B. Indoor-Outdoor BEL Measurements

Fig. 9 illustrates the results for BEL near a solid brick wall in two different environments. Figs. 9(a) and 9(b) show the CDF of RSSI for two BSSIDs of the APs in FL1 and FL2, respectively. In FL1, we observed BEL ranging from 30 dB to 35 dB, while the BEL in FL is around 25 dB. We observed higher BEL in FL1 due to distance between indoor measurement location and the exterior wall.

IV. Conclusions & Future Research

In this study, we carried out a measurement campaign with walking and fixed location measurements to understand the statistical nature of outdoor propagation from a typical Wi-Fi 6E network at 6 GHz deployed inside a building. We presented detailed measurements and analyses of the behavior of 6 GHz outdoors and potential aggregate interference to incumbent fixed links. Detailed analyses are presented that delve into the relations between outdoor RSSI levels and other factors, including distance, throughput, BEL, and observed number of unique BSSIDs outdoors. Most of the outdoor 6GHz connections occur in front of glass doors on the three sides of the measurement building. Based on the performed indoor-outdoor measurement campaigns at two different locations, we observed 25-33 dB BEL due to solid brick wall. Universities are excellent sites for measurements of dense

LPI deployments: it allows for statistical evaluations rather than a single-point, worst case analysis. Future studies will explore collaborations with fixed-link providers to measure and quantify interference levels at 6 GHz.

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