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Spectrum Sharing in 6 GHz: How is it working out?

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***Abstract*—It has been over four years since the 6 GHz (5.925 - 7.125 GHz) band was released for unlicensed use on a shared basis. During this period, the Federal Communications Commission (FCC) has issued two Report and Order (R&O) and Further Notice of Proposed Rulemaking (FNPRM) to facilitate the efficient use of the band between unlicensed devices and licensed incumbents. The former has implemented two power regulations for unlicensed operations, low power indoor (LPI) and standart power (SP). The latter enables the operation of very low power (VLP) devices in two segments of the 6 GHz band, U-NII-5 and U-NII-7, and seeks comment for client-to-client (C2C) communications, VLP operations in U-NII-6 and U-NII-8, and geofenced VLP operations with a high power level. In this paper, we first discuss spectrum sharing in the 6 GHz band with reference to the two R&Os. We assess the outcomes of two extensive measurement campaigns conducted at the University of Michigan (UMich) and the University of Notre Dame (UND) in relation to the regulations and proposals outlined in the second R&O and FNPRM. Later, we assess the enabling signal level for C2C communications in the 6 GHz band to offer insights into the optimum threshold. Our findings show outdoor median RSSI levels of -84 dBm and -81 dBm at UMich during driving and walking measurements, respectively. At UND, outdoor median RSSI levels are -79.5 dBm for connected BSSIDs and -89 dBm for all received BSSIDs.**

***Index Terms*—6 GHz, unlicensed spectrum, low power indoor, standard power, very low power, client-to-client communications, enabling signal level.**

I. Introduction

The U.S. Federal Communications Commission (FCC) has allocated the 6 GHz band on April 24, 2020 via the Report and Order (R&O) and Further Notice of Proposed Rulemaking (FNPRM) that allows unlicensed use of spectrum on a shared basis with the existing incumbents [1]. This band, spanning from 5.925 GHz to 7.125 GHz, comprises four 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 given in Table I. This allocation addresses the rising need for bandwidth in emerging wireless applications and use cases, and the severe congestion in the 2.4 GHz and 5 GHz bands.

The first R&O adopts new unlicensed standard power (SP) and low power indoor (LPI) use rules for the 6 GHz band [2]. Meanwhile, the FNPRM suggests allowing a new category of unlicensed devices, very low power (VLP) devices, to operate across the entire band, and an increase in power spectral density (PSD) for LPI devices [3]. LPI operation is permitted across the entire 6 GHz band without an Automatic Frequency Control (AFC) system, as illustrated in Fig. 1. Wi-Fi 6E access points (APs) operating under LPI regulations are required to

TABLE I: Unlicensed Operation over the 6 GHz Band.

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

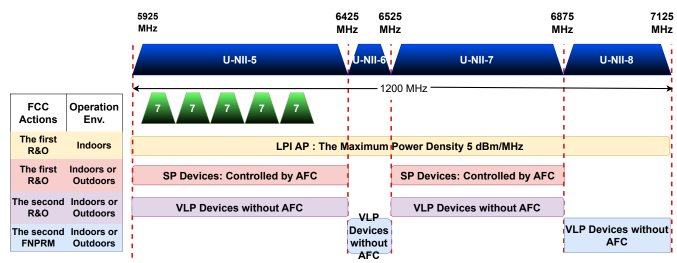


Fig. 1: Channelization of the 6 GHz band.

adhere to a maximum PSD of 5 dBm/MHz. Client devices (STAs) are mandated to transmit at a level 6 dB lower than the APs to accommodate their potential mobility. Table II summarizes the respective maximum transmit power for LPI APs and STAs considering the channel bandwidth. SP APs are allowed only over U-NII-5 and U-NII-7 bands using AFC to protect the incumbents and can be deployed indoors or outdoors [4]. Following the R&O, the deployment of LPI APs occurred rapidly, and a significant number of LPI devices are currently in use across the U.S. [5]. While SP operations with AFC are not yet active, the FCC has initiated the process for authorizing automated frequency coordinators in the 6 GHz band.

On September 28, 2023, the FCC has released the second R&O and FNPRM on the unlicensed use of the 6 GHz band while ensuring continued protection of the existing incumbent from potential harmful interference [6]. The second R&O permits VLP operations in two U-NII bands, U-NII-5 and U-NII-7. VLP devices can operate indoors or outdoors without requiring AFC system, but can not be deployed outdoors as part of the fixed infrastructures. To protect the transmission of the incumbents in these bands, VLP devices are allowed to operate with 14 dBm EIRP and a PSD of -5 dBm/MHz.

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

The second FNPRM seeks comment for i) authorization of VLP devices in the remaining portions of the 6 GHz band, U-NII-6 and U-NII-8 ii) geofenced VLP devices with high power level, and iii) enabling client-to-client (C2C) in the 6 GHz, allowing direct communication of STAs with each other. VLP devices support a broad spectrum of mobile devices, incorporating body-worn devices, and virtual/augmented reality technologies, to enhance healthcare, learning and entertainment opportunities. VLP operations on U-NII-5 and U-NII-7 has facilitated the flexible utilization of the 6 GHz band while ensuring the protection of incumbent users, and it is expected to roll-out swiftly. Proponents of unlicensed operations in the 6 GHz, such as Wireless Alliance, Apple Inc., Broadcom Inc. Google LLC, Intel Corporation, Meta Platforms, Microsoft Corporation, Qualcomm Inc., have presented several studies demonstrating that VLP operations will not induce harmful interference to the incumbents [7] [8]. On the other hand, the existing incumbents in U-NII-6 and U-NII-8, such as electronic news-gathering (ENG) services, Broadcast Auxiliary Service (BAS), and satellite services, express concerns about potential harmful interference that could disrupt their operations.

The second FNPRM suggests the operation of VLP devices with a total power of up to 21 dBm EIRP under geofencing, aiming to protect incumbent services while also opening doors for new use cases and applications of VLP operations at higher power levels. The geofencing system delineates exclusion zones for high-power VLP devices around sites where incumbents operate considering the power level of VLP devices, mobility/stationary scenarios, and the frequencies used by the incumbents.

The first R&O prohibits the direct communication between STAs in the 6 GHz band. C2C communications may be enabled under when client devices establish a direct communication link between each other, bypassing the indoor AP, based on the received signal strength of an “enabling signal” transmitted by an AP. Such a mode can improve Wi-Fi 6E performance, for example, reducing latency between client devices by avoiding the extra hop in transmissions via the AP. However, the threshold at which the enabling signal should be received is crucial: if set too low, it might enable outdoor clients to communicate with each other at LPI levels thus potentially increasing the probability of interference to incumbents, and if set too high it may preclude indoor clients from communicating with each other. Within the context of C2C communications in the 6 GHz spectrum, the second FNPRM therefore requests comments to address the following crucial questions: i) defining the C2C enabling signal and its characteristics, ii) enabling signal level, iii) enabling signal refresh interval, and iv) on whether client devices should be limited to receiving an enabling signal from the same AP or from any authorized APs. The recent proposals submitted to the FCC recommended using -82 dBm/20 MHz as enabling signal level [9]. Randomness in the wireless environment can cause variations in the Received Signal Strength Indicator (RSSI) of the enabling signal received by a client device, even when the device remains stationary. Consequently, establishing a high RSSI threshold may result in unreliable C2C connectivity. Defining an optimal enabling signal level is crucial for establishing a robust C2C communications while maintaining the protection of the incumbents.

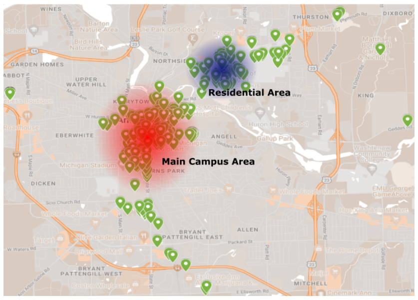
Universities serve as ideal locations for assessing 6 GHz LPI deployments, facilitating statistical evaluations instead of relying solely on single-point, worst-case analyses. Data obtained from real-world deployments can offer valuable insights and essential information to help navigate the discussions outlined earlier. In this regard, this paper recaps the extensive measurement campaigns at the University of Michigan (UMich) and the University of Notre Dame (UND) to shed light on the outdoor emissions caused by the deployment of Wi-Fi 6E LPI APs, and potential interference to the incumbent links in the area. Later, we pivot our attention towards an analysis of C2C connectivity at 6 GHz to provide insights to offer insights into determining the appropriate enabling signal level.

The paper is organized as follows: Section II outlines the measurements conducted at UMich and highlights the primary findings regarding outdoor emissions from Wi-Fi 6E LPI APs. Section III delves into the measurements carried out at UND and discusses the key insights into outdoor connectivity at 6GHz. In Section IV, our most recent analysis regarding an appropriate enabling signal level for C2C communications in the 6GHz band is presented. Lastly, concluding remarks and potential future directions are provided in Section V.

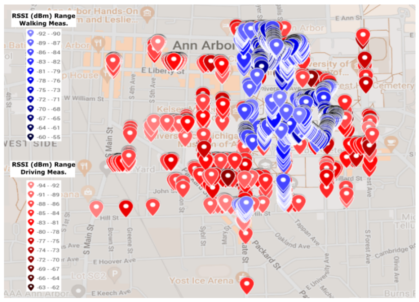
II. Measurements at UMich

Measurement Environment: In 2023, extensive measurement campaigns were conducted at UMich, deploying over 16,000 Wi-Fi 6E LPI APs across numerous university buildings, operating under the 6 GHz LPI regulations given in Table I. Outdoor measurements were conducted in the main campus area (MCA) and residential area (RA) through driving, walking, and drone measurements. Fig. 2 illustrates the Wi-Fi 6E deployment in the MCA and RA. These measurements took place throughout the year in multiple campaigns: Scenario 1 (S1) and Scenario 2 (S2) took place at the MCA in January and May, 2023, respectively, while Scenario 3 (S3) was carried out at the RA in May for a less dense indoor Wi-Fi 6E network.

Summary of Measurement Tools and Methodology: Data collection during the measurement campaigns was performed using Android smartphones (Pixel 6 and Samsung Galaxy S22+) running SigCap, as described in previous studies [10], [11], [12]. SigCap is a custom Android app developed by the authors that passively collects wireless signal parameters from the APIs without requiring root access, including both cellular

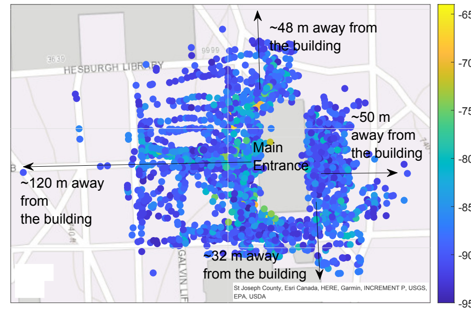


(a) Wi-Fi deployment at UMich. Green Pins: Buildings with Wi-Fi 6E LPI APs.

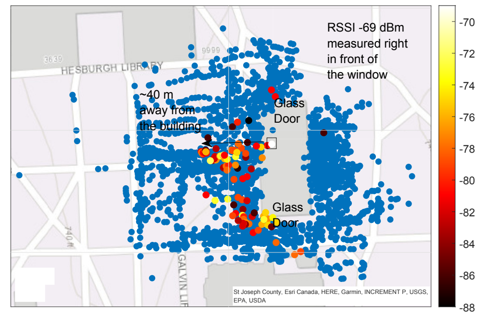


(b) Driving and walking meas. in the MCA. Red Pins: Driving, Blue Pins: Walking.

Fig. 2: The main campus area (MCA) and the residential area (RA) in UMich.



(a) For walking measurements at 6 GHz.



(b) For outdoor 6 GHz connection.

Fig. 3: Outdoor RSSI heatmap at 6 GHz during walking measurements.

and Wi-Fi [10]. GPS signal is used to get timestamps and location parameters. During the measurements, we collected the following Wi-Fi parameters every 5 seconds: RSSI, Basic Service Set Identifier (BSSID), channel bandwidth, operating frequency, and optional parameters transmitted in beacon frames, including transmitted signal power and technology, number of stations connected to each BSSID, and channel utilization (indicating the percentage of time the BSSID sensed the channel to be busy). These parameters are reported for every BSSID detected by the phone, regardless of whether it's connected to any of them. This capability facilitates an easy collection of detailed information on all 6 GHz channels utilized by Wi-Fi 6E in a specific location. It is important to note that RSSI value is measured solely on the Wi-Fi beacon, which operates on a 20 MHz bandwidth. Cumulative distribution function (CDF) is used to perform statistical analyses of measurements conducted at the MCA and RA.

Main Takeaways: The main objective of this study is to assess the possibility of interference originating from a real-world densely deployed 6 GHz LPI network to outdoor fixed links. Our detailed analyses revealed the relationship between observed outdoor RSSI levels and factors including the number of APs, their location concerning nearby windows, and altitude via drone measurements. We observed that majority of LPI APs located inside buildings cannot be connected outdoors. A limited number of APs performing line-of-sight (LOS) through windows can lead to an elevated outdoor RSSI levels in very few specific locations. Only 5% of the indoor BSSIDs were observed outdoors in an area near solid brick walls. Across all the drone measurements, a consistent decrease in both the number of samples and RSSI values was observed as altitude increases, relaxing the risk of interference on the fixed links. A high level of outdoor RSSI occurs around the historical structures and buildings with single-pane windows due to the low signal loss.

III. Measurements at UND

Measurement Environment: UND has begun upgrading the Wi-Fi infrastructure and we have been conducting extensive measurements in and around the Office of Information Technology (OIT) building with 70 LPI Wi-Fi 6E APs. Though not as expansive as the deployment at UMich, this single-building deployment allows us to concentrate on characterizing outdoor RSSI footprint of a typical deployment of Wi-Fi 6E LPI APs, as shown in Fig. 3. The measurements at UND were exclusively conducted while walking [13].

Summary of Measurement Tools and Methodology: We utilized end-user devices, including smartphones and laptops, to collect signal parameters across different environments. Our approach involved employing three tools: in addition to SigCap running on smartphones used at UMich, we utilized Speedtest by Ookla and Wireshark to extract diverse signal parameters. Speedtest by Ookla is widely used for assessing network performance via gathering network parameters including downlink/uplink throughput and latency [14]. We utilized a Lenovo ThinkPad P16 Gen1 equipped with the Intel(R) Wi-Fi AX211 Wi-Fi adapter running Wireshark, which is an open-

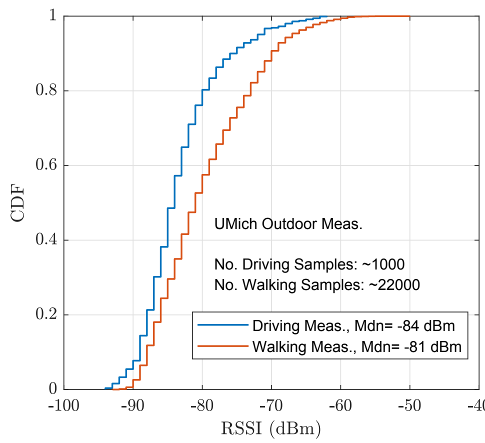


Fig. 4: CDFs of RSSI at UMich while driving and walking.

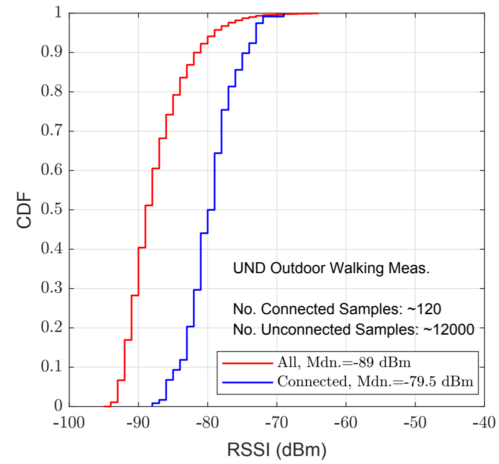


Fig. 5: CDFs of Outdoor RSSI at UND.

source tool empowered to collect beacon and data frames from Wi-Fi network [15].

Main Takeaways: Assessing the potential for aggregate interference at a specific location: we observed that despite 70 Wi-Fi 6E APs, each with two BSSIDs, 4 was the median number of unique BSSIDs observed outdoors. We measured BSSIDs within a maximum distance of 120 meters from the OIT building. Most of outdoor 6 GHz connections occurred near by glass doors and windows, extending up to a range of 40 m. Throughput measurements indicated a median outdoor downlink (DL) throughput of 25 Mbps, while speed tests failed to complete for RSSI values below -86 dBm. We observed building entry loss ranging from 25 dB to 35 dB under the solid brick wall considering the distance between the measurement location and the exterior wall.

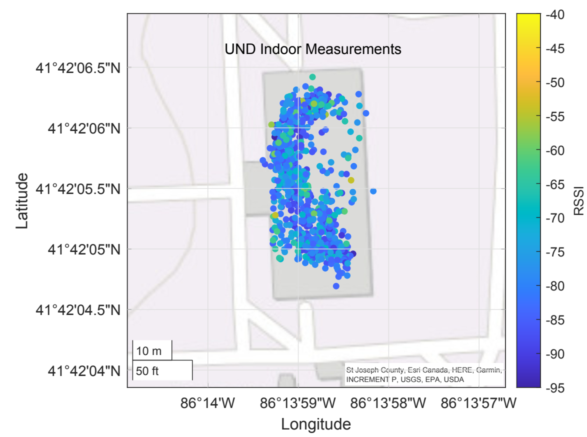


Fig. 6: Measurement locations inside OIT building at UND.

IV. Analysis on C2C Communications in 6 GHz

As Wi-Fi 6E usage increases, measurements from real-world deployments can provide much-needed data to guide the process of determining an appropriate signal level for C2C communication in 6 GHz. This section presents our analyses on the enabling signal level for C2C connectivity in 6 GHz via the measurements at the UMich and UND.

Enabling C2C mode is an active research area for unlicensed 6 GHz operations. Clients receiving an enabling signal from any Wi-Fi 6E AP can establish direct communication amongst themselves. However, it is crucial to carefully adjust the level of the enabling signal to ensure that outdoor client devices do not transmit to each other. In the proposals submitted to the FCC, -86 dBm/20 MHz and -82 dBm/20 MHz are suggested as enabling signal levels [9].

Analysis of the beacon RSSI over 20 MHz offers insight into outdoor RSSI levels actually observed in a realistic setting, while the enabling signal proposed for C2C does not have to be the existing Wi-Fi beacon. Fig. 4 summarizes the CDF of the beacon RSSI measured in the areas shown in Fig. 2, while driving and walking. Since most of the university campus area offers only pedestrian access, there are fewer measurements made while driving as compared to walking, and, in general, the driving measurements were taken further away from the buildings resulting in lower median RSSI values being observed: -84 dBm while driving and -81 dBm while walking.

Fig. 5 shows the CDF plots of the measured outdoor RSSI at UND (i) when the device was connected to a BSSID and (ii) when considering all received BSSIDs. The median RSSI is higher (-79.5 dBm) when the phone is connected compared to the RSSI received from all available BSSIDs (-89 dBm). It should be noted that there are only a handful of samples (1%) where the device could maintain a connection with an indoor AP/BSSID. Comparing with the walking results in Fig. 4 at UMich, we see that the overall outdoor median RSSI at UND for unconnected devices is lower (-89 dBm versus – 81 dBm): this is because there is only one building at UND with Wi-Fi 6E whereas most of the outdoor areas measured at UMich had many surrounding buildings with Wi-Fi 6E deployments.

Fig. 6 shows the area inside the building where measurements were conducted and Fig. 7 shows the CDFs of the RSSI when the device was connected to an AP and when the device

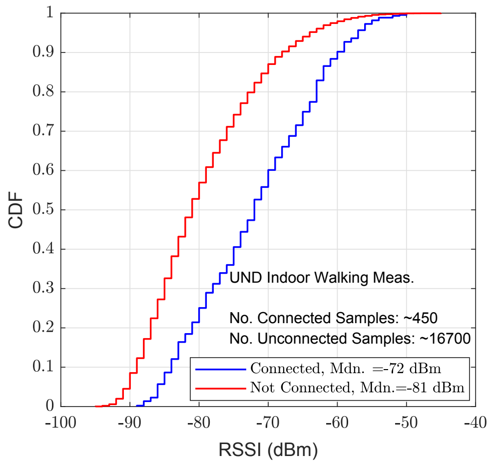


Fig. 7: CDFs of Indoor RSSI at UND.

was not connected to an AP. Again, the former has a higher median value (-72 dBm) compared to the latter (-81 dBm). C2C operation can substantially enhance the performance of LPI Wi-Fi 6E and other indoor unlicensed devices while ensuring continued protection of incumbents.

V. Conclusions & Future Research

VLP operations and C2C communications are crucial for unlicensed operations at 6 GHz as they will facilitate new applications and use cases, and allow efficient use of the 6 GHz band via unlicensed devices. Ensuring these operations occur without causing harmful interference to incumbent users within the band is paramount. It is important to carefully establish the exclusion zones for geofenced VLP operations and enabling signal level for C2C connectivity. This paper presents a perspective on C2C communications, focusing specifically on the enabling signal level. It is based on 20 MHz beacon measurements conducted in two distinct environments: one at UMich characterized by dense deployed LPI APs, and the other at UND in a single building. The measurement results reveal outdoor median RSSI levels of -81 dBm at UMich and -89 dBm at UND for walking measurements. The observed outdoor RSSI level at UND increases by around 10 dB (-79 dBm) when only connected BSSIDs are considered. Hence, the proposed enabling signal level of -86 dBm/20 MHz in the initial comments to the FCC, appears insufficient and may result in outdoor devices being able to communicate with each other. A signal level ranging between -82 dBm/20 MHz and -78 dBm/20 MHz may be more effective in avoiding this scenario. Our future research efforts will focus on outdoor VLP operations, aiming to assess potential interference to incumbents within the 6 GHz band.

Acknowledgements

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