

Cellular Spectrum Occupancy Probability in Urban and Rural Scenarios at Various UAS Altitudes

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Abstract—The ever-growing demand for wireless connectivity, coupled with limited spectrum resources, has resulted in spectrum congestion and interference. This research investigates the probability of occupancy in common sub-6 GHz cellular network bands based on measurements conducted in urban and rural environments. Specifically, we analyze the spectrum occupancy of various long-term evolution (LTE), 5th generation (5G) and Citizens Broadband Radio Service (CBRS) bands used in the United States, considering both uplink and downlink transmissions at altitudes up to 180 meters. Additionally, we explore the influence of altitude on the probability of spectrum occupancy in these bands. Our findings reveal that the probability of occupancy is generally higher in the downlink compared to the uplink. Moreover, we observe that line-of-sight (LoS) signals play a critical role in higher altitudes. These results provide insights spectrum utilization in various cellular bands across different altitudes, with implications on interference and spectrum coexistence between terrestrial networks and unmanned aerial systems (UASs) in the future.

Index Terms—5G, AERPAW, C-Band, CBRS, drone, helikite, LTE, spectrum monitoring, unmanned aerial vehicles (UAV).

I. INTRODUCTION

The proliferation of wireless communication services and the advent of new technologies have generated a substantial increase in the demand for radio frequency spectrum [1]. The presence of unused exclusively licensed spectrum underscores the importance of adopting a more efficient and dynamic approach to spectrum management. By exploring different usage scenarios and embracing sharing mechanisms, the untapped spectrum can be repurposed to cater to a wider range of users and accommodate diverse communication requirements. For example, the federal communications commission (FCC) introduced the Citizens Broadband Radio Service (CBRS) with the aim of providing a comprehensive solution to address the aforementioned challenges. Departing from the conventional approach of auctioning exclusive rights to the spectrum, CBRS introduced a shared spectrum framework capable of accommodating incumbents, winners of priority access license (PAL) auctions, and non-auctioned general authorized access (GAA) operators simultaneously.

Recent significant advancements in unmanned aerial system (UAS) and space technologies have increased the need for integrating non-terrestrial networks with terrestrial communication networks, calling for new approaches for spectrum coexistence and flexible spectrum usage due to limited spectrum availability [2], [3]. For example, the 6th generation (6G)

Satellite Precursor initiative aims to establish an in-orbit laboratory for early research and development, enabling the satellite industry to align their technologies with terrestrial communication infrastructure and validate key 6G technologies and techniques [4]. The introduction of C-Band 5th generation (5G) cellular service in 3.7-3.98 GHz in the United States raised concerns within the commercial airline and private aircraft communities, which heavily rely on radar altimeters in the aircraft industry [5]. Although the assigned spectrum band for altimeters is between 4.2 GHz and 4.4 GHz, the current versions of altimeters suffer from an out-of-band leakage problem due to their poor design.

Similar coexistence concerns arise regarding spectrum sharing between future 5G networks to be deployed in the 3.1 GHz to 3.45 GHz band and the existing airborne radars that operate within the same spectrum range. The spectrum coexistence challenge in this band is similar to that of CBRS, with the difference that the variety of radars used by the Department of Defense (DoD) includes those used by airborne warning and control system (AWACS) aircrafts [6]. Under the National Spectrum Consortium (NSC), the Partnering to Advance Trusted and Holistic Spectrum Solutions (PATHSS) task group has been recently studying potential spectrum sharing mechanisms between commercial terrestrial networks and incumbent federal operations [6], [7]. Another ongoing debate centers around the use of terrestrial nationwide networks in the L-Band (1-2 GHz) and the potential interference with global positioning system (GPS) systems [8]. All these examples highlight the need for careful spectrum management between terrestrial and non-terrestrial networks, to avoid disruptions and conflicts between applications sharing the same bands.

Spectrum occupancy studies and measurement campaigns are critical to identifying spectrum sharing opportunities in different bands, understanding interference issues, and optimizing spectrum management strategies. Chen *et al.* provide a comprehensive survey of existing research on spectrum occupancy [9]. More recently, Al-Fuqaha *et al.* propose a framework that captures and models short-time spectrum occupancy to assess interference levels for Internet-of-Things (IoT) applications [10]. In the context of mega-satellite networks, Homssi *et al.* review state-of-the-art artificial intelligence techniques for various applications such as channel forecasting, spectrum sensing, signal detection, network optimization, and security [11]. Another study conducted by Maeng *et al.* investigates the performance characteristics of coexisting aerial radar and communication networks utilizing stochastic geometry techniques for spectrum overlay and time-division multiple

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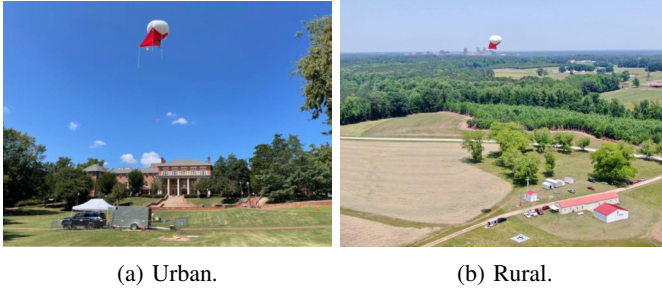


Fig. 1: Helikite experiment scenario for: **(a)** urban environment, and **(b)** rural environment.

access [12]. Furthermore, Azari *et al.* analyze the impact of interference originating from coexisting ground networks on the aerial link, specifically the uplink (UL) of an aerial cell served by a drone base station. By employing a Poisson field of ground interferers, they evaluate the aggregate interference experienced by the drone [13]. In another study [14], the monitoring of spectrum measurements was carried out by utilizing data collected through the deployment of an AERPAW Helikite in sub-6 GHz bands.

This paper focuses on analyzing spectrum occupancy in various U.S. cellular network bands, as well as the CBRS band, by post-processing measurements obtained from experiments conducted in urban and rural environments using the NSF AERPAW platform in Raleigh, NC [15]. Additionally, we investigate the impact of Helikite altitude, a unique airborne platform, on the pattern of signal strength. By leveraging the data collected from the experiments, we aim to gain insights into the utilization of different frequency bands within U.S. cellular networks and the CBRS band. This understanding is especially relevant in the context of unmanned aerial vehicle (UAV) swarms, offering valuable insights into the utilization of spectrum resources and their management for optimal performance in the foreseeable future.

The rest of this paper is organized as follows. In Section II, we describe the data structure and the overall information of the measurement campaign. In Section III, we present the spectrum monitoring results and explain the limitations imposed by the experimental equipment. In Section IV, we explain the probability of spectrum occupancy and presents the results for various sub-6 GHz bands in the urban and rural environments, respectively. Section V studies the effect of altitude on the spectrum occupancy for the frequency bands under consideration. Finally, Section VI highlights the conclusions of this work.

II. MEASUREMENT CAMPAIGN AND DATA STRUCTURE

The experiment conducted in both urban and rural environments involved the use of a Helikite, reaching altitudes of up to 140 m for the urban setting, and up to 180 m for the rural setting. To collect the necessary data, an NI USRP B205mini SDR was mounted on the Helikite, allowing for the execution of a Python script to capture samples at specific center frequencies and sampling rates. The datasets are SigMF compliant and include information on spectrum usage in frequency bands ranging from 89 MHz up to 6 GHz for different altitudes [16], [17]. The dataset encompasses various

TABLE I: Summary of LTE and 5G bands in the United States and considered in this study.

Technology	Band No	Duplex Mode	Uplink Band (MHz)	DL Band (MHz)	Operators
LTE	12	FDD	698 - 716	728 - 746	AT&T, Verizon, T-Mobile
	13	FDD	777 - 787	746 - 756	Verizon
	14	FDD	788 - 798	758 - 768	AT&T, FirstNet
	41 ¹	TDD	2496 - 2690	2496 - 2690	T-Mobile
5G	n5	FDD	824 - 849	869 - 894	AT&T, Verizon
	n71	FDD	663 - 698	617 - 652	T-Mobile
	n77	TDD	3700 - 3980	3700 - 3980	AT&T, Verizon, T-Mobile
CBRS	n48	TDD	3550 - 3700	3550 - 3700	North America

parameters, including time, altitude, power, and the location of the Helikite. A comprehensive description of the experimental configurations and procedures can be found in [18]. Fig. 1 illustrates the Helikite experiment scenarios for urban and rural environments. In particular, an experimental study was conducted in an urban environment using a Helikite, reaching a maximum altitude of 140 m on August 27, 2022. Additionally, a separate experiment was conducted in a rural environment on May 5, 2022, where the Helikite ascended to an altitude of 180 m. Additional information on the specific altitudes attained by the Helikite throughout its operational duration can be found in [14].

III. SUB-6 GHz SPECTRUM MEASUREMENT RESULTS

In this section, we study the measured power for the whole spectrum under consideration (i.e., from 89 MHz up to 6 GHz) in urban environment. We specifically consider the 4G long-term evolution (LTE) and 5G NR bands, as well as the CBRS band, as summarized in Table I. Existing 4G LTE bands, with the exception of Band 5 (850 MHz), can be used for UAS operations in the United States by the subscribers of mobile network operators. Specific guidance for 5G for supporting UAS operations is however yet not available from FCC [20]. FCC rules for the CBRS band do not currently allow airborne transmissions. Due to the potential of using cellular networks for UAS in the future, we exclusively focus on altitude-dependent spectrum occupancy in cellular bands.

First, we present the mean, maximum, and minimum power values across four different altitude ranges. Specifically, we consider $\tilde{h}_1 = [20, 40]$ m, $\tilde{h}_2 = [40, 60]$ m, $\tilde{h}_3 = [100, 120]$ m, and $\tilde{h}_4 = [120, 140]$ m. As illustrated in Fig. 2, a notable decrease in the mean value is observed beyond the 4 GHz frequency range. The RF front end employed in our study utilizes the Analog Devices AD9364 RFIC transceiver, as specified in the datasheet of the USRP B205mini device [21]. The noise figure demonstrates an upward trend at higher frequencies, with values of 3.8 dB and 2 dB observed at 5.5 GHz and 800 MHz, respectively, as reported in [19]. Additionally, it is important to note that the receiver characteristics are influenced by factors such as temperature and carrier frequency. For convenience, Fig. 3 depicts the receiver gain versus the operating frequency for this specific USRP (taken from [19]). For more comprehensive details, additional information can be found in [19], and further research can

¹It is worth mentioning that T-Mobile 5G n41 also uses the same spectrum.

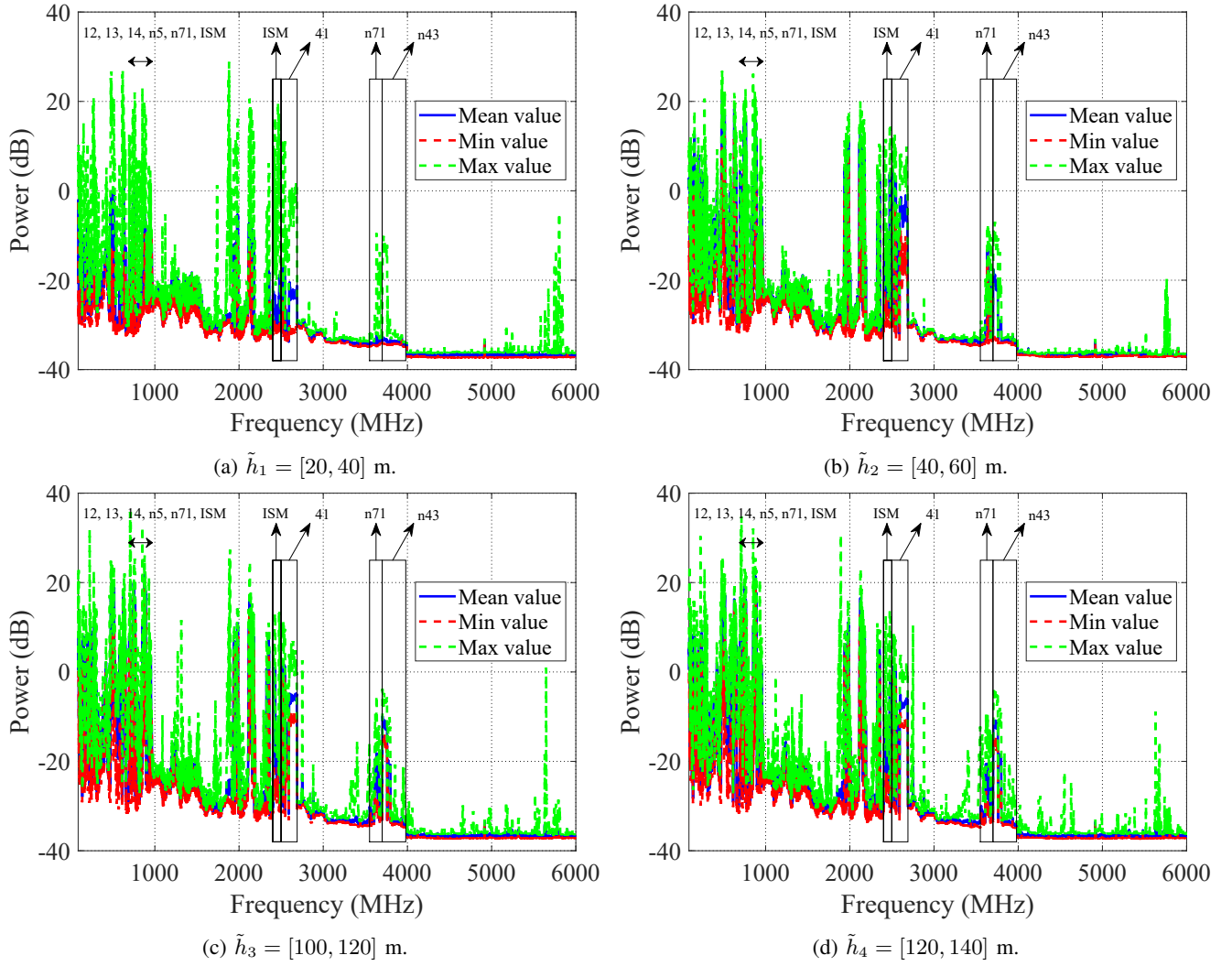


Fig. 2: Measured power versus the whole spectrum under consideration for urban environment.

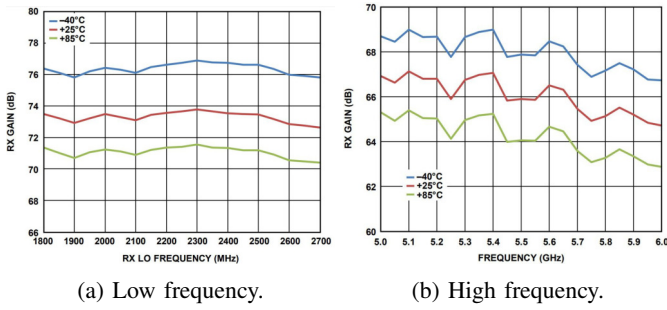


Fig. 3: Receiver gain versus the operating frequency for the Analog Devices AD9361 RF Agile Transceiver in USRP B205 mini: (a) low frequency, and (b) high frequency (taken from Analog Devices Technical Specification Sheets [19]).

be carried out to decouple the influence of USRP hardware impairments from spectrum measurements.

IV. PROBABILITY OF SPECTRUM OCCUPANCY

In this section, our goal is to evaluate the spectrum occupancy probability of various 4G and 5G cellular bands at

different altitudes. First, in Figs. 4a and 4b, we present the measured power of LTE band 12 in an urban environment for uplink and downlink (DL) channels, respectively, with respect to altitude in the y-axis. As can be seen clearly, some portions of the spectrum are underutilized and those regions may vary with altitude. Let $P(H_1, F_1)$ represent the measured power for a specific altitude H_1 and frequency F_1 . In order to calculate the probability of occupancy, we divide the spectrum of the band under consideration into frequency bins of width $\Delta f = 180$ KHz. We consider the spectrum to be occupied if the measured power for a given altitude and frequency surpasses a predetermined threshold; i.e., $P(H_1, F_1) > t$ where t denotes the threshold value. By averaging over the altitude, the probability of occupancy for a given frequency can be calculated as

$$\Pr(F_1) = \frac{1}{N} \sum_{i=1}^N [P(H_i, F_1)], \quad (1)$$

where N is the total number of altitudes under consideration and the Iverson bracket indicator function $[x \geq t]$ evaluates

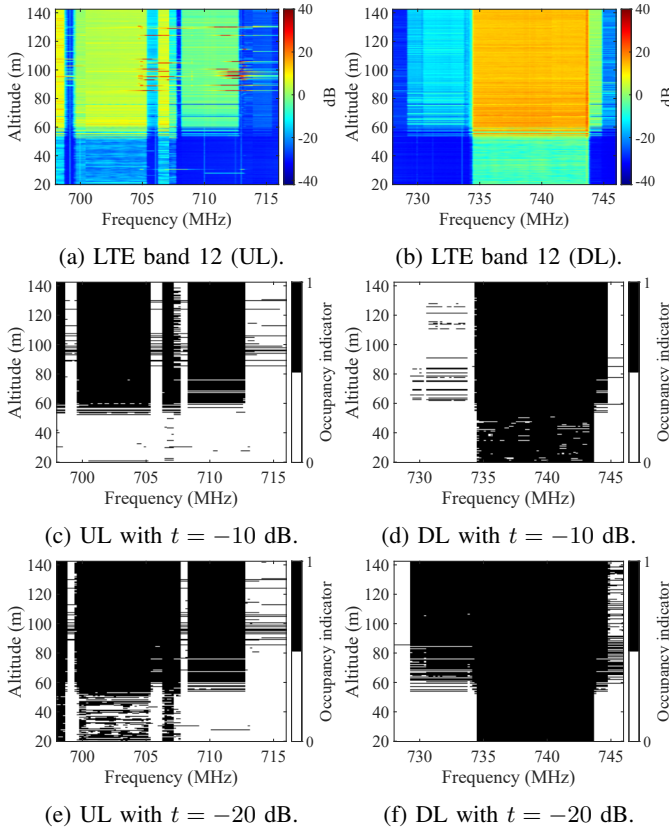


Fig. 4: Behaviour of LTE band 12 in urban environment in terms of (a) measured UL power, (b) measured DL power, (c) UL occupancy indicator with $t = -10$ dB, (d) DL occupancy indicator with $t = -10$ dB, (e) UL occupancy indicator with $t = -20$ dB, and (f) DL occupancy indicator with $t = -20$ dB. The black color in (c)-(f) indicates that the spectrum is occupied.

to 1 when $x \geq t$ and 0 otherwise. Throughout this paper, we consider two distinct threshold values; $t = \{-10, -20\}$ dB.

Figs. 4c and 4e respectively illustrate the occupancy of the UL LTE band 12 by assuming $t = -10$ dB and $t = -20$ dB. It is clear that a decrease in the threshold value leads to a higher occupancy of the spectrum, particularly at lower altitudes. Figs. 4d and 4f depict the occupancy of the DL LTE band 12 by assuming $t = -10$ dB and $t = -20$ dB, respectively. As it can be seen, the DL spectrum is more occupied compared to those of UL spectrum. For a high threshold (i.e., $t = -10$ dB), certain portions of the DL spectrum are occupied regardless of the altitude, whereas the UL spectrum remains practically unoccupied for altitudes below 60 m.

A. Probability of Occupancy for UL Channel

In this subsection, we study the probability of occupancy for UL bands under consideration. We set the threshold value as $t = -10$ dB and $t = -20$ dB in Fig. 5a and 5b, respectively. The error bars in these figures represent the variance in the occupancy probability across the bandwidth. As it can be observed, the probability of occupancy for urban environment is generally higher than rural ones at higher threshold (i.e., $t = -10$ dB). As the threshold value decreases, the probability

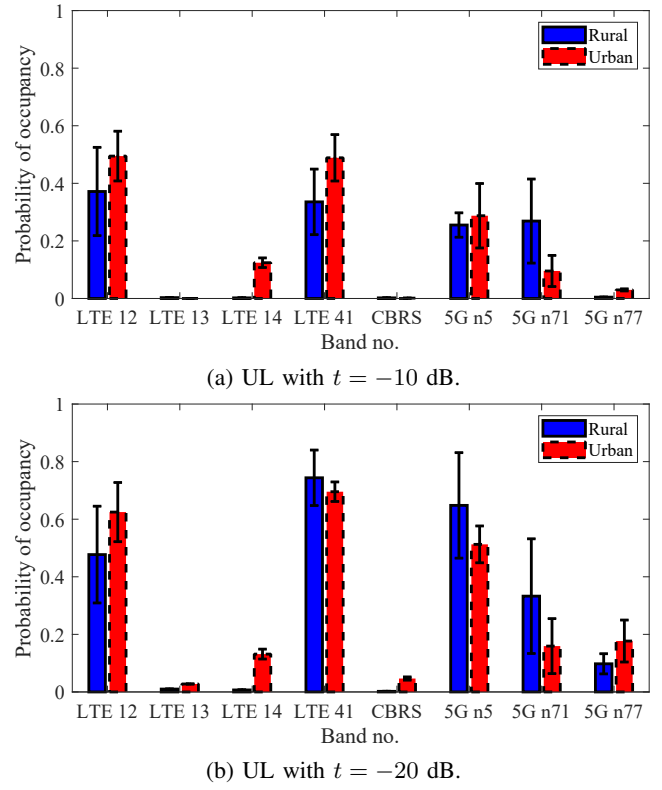


Fig. 5: Probability of occupancy for UL by considering threshold value of (a) $t = -10$ dB and (b) $t = -20$ dB.

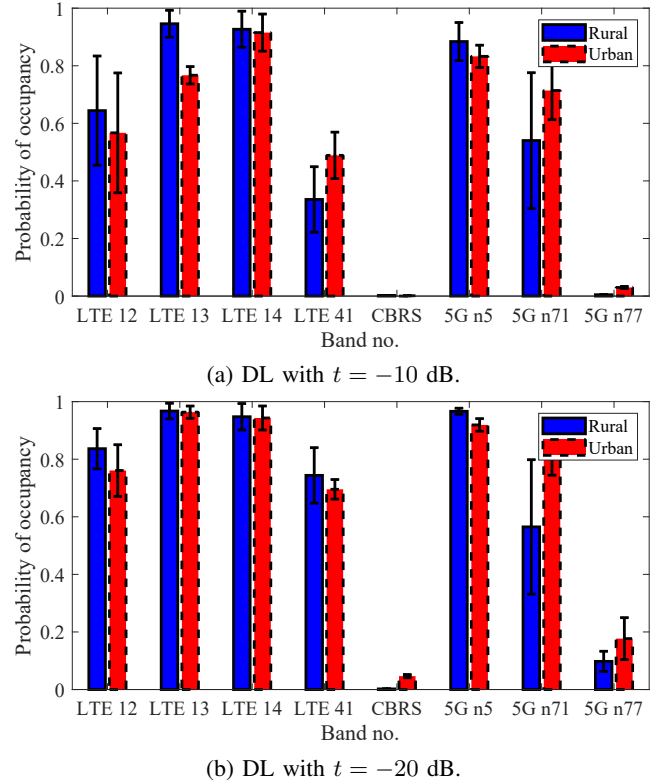


Fig. 6: Probability of occupancy for DL by considering threshold value of (a) $t = -10$ dB and (b) $t = -20$ dB.

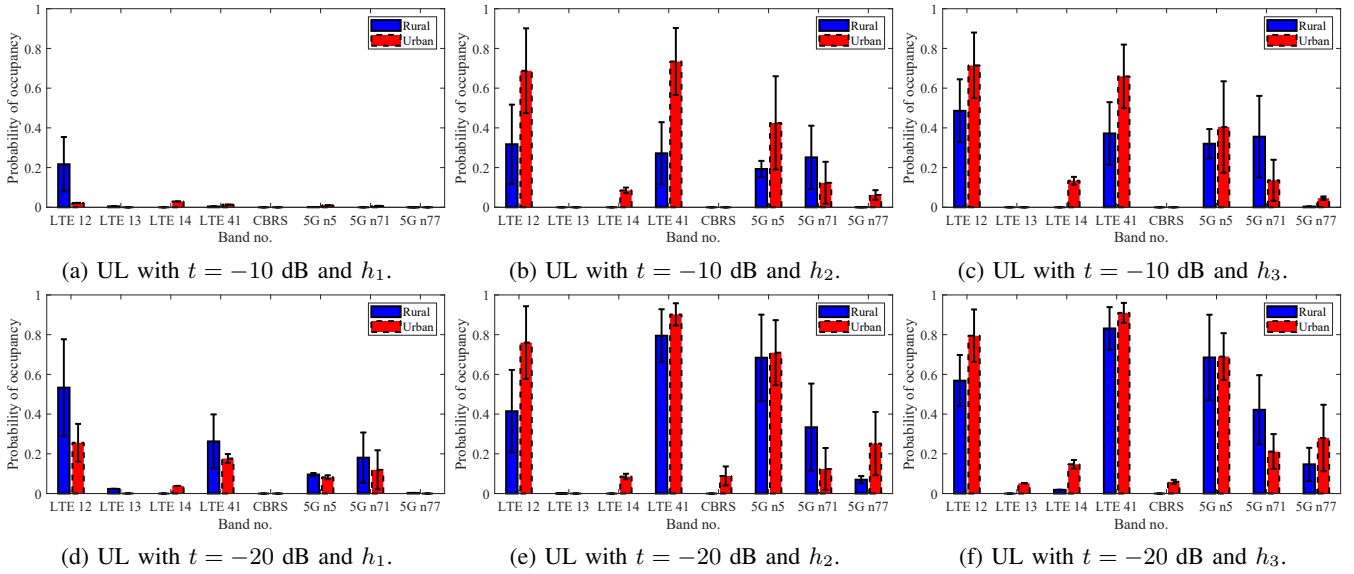


Fig. 7: Effect of altitude on UL spectrum occupancy by considering (a) $t = -10$ dB and h_1 , (b) $t = -10$ dB and h_2 , (c) $t = -10$ dB and h_3 , (d) $t = -20$ dB and h_1 , (e) $t = -20$ dB and h_2 , (f) $t = -20$ dB and h_3 .

of occupancy for rural environment surpasses that of urban environment for LTE 41 and 5G n5 bands. This behavior can be attributed to the specific characteristics of our rural experimental testbed, which incorporates an Ericsson 4G/5G radio access network (RAN) equipment located at the Lake Wheeler site. It is worth mentioning that LTE 41, 5G n77 and CBRS work in time-division duplexing (TDD) mode and includes both UL and DL transmissions, unlike other bands under consideration.

B. Probability of Occupancy for DL Channel

Figs. 6a and 6b illustrate the probability of occupancy for DL bands under consideration when $t = -10$ dB and $t = -20$ dB, respectively. As it can be seen, the probability of occupancy for DL bands are much higher than UL bands. The presence of a higher variance bar, such as in LTE 12, suggests that certain portions of the corresponding band experience greater utilization (cf. Fig. 4b). Note that CBRS and 5G n77 exhibit a significantly lower probability of occupancy.

V. EFFECT OF ALTITUDE ON SPECTRUM OCCUPANCY

In this section, we investigate the effect of altitude on the probability of occupancy. Specifically, we consider three distinct altitude ranges; i.e., (i) low altitude $h_1 = [20, 30]$ m, (ii) mid altitude $h_2 = [60, 70]$ m, and (iii) high altitude $h_3 = [120, 130]$ m. Consistent with previous scenarios, we maintain threshold values of $t = -10, -20$ dB for our analysis.

A. Uplink Channel

Fig. 7 illustrates the effect of altitude on UL spectrum occupancy for the considered frequency bands. As it can be seen, the occupancy probability increases as the altitude increases. This is due to the fact that at high altitudes, there is a higher probability of receiving signals from neighboring cells as the presence of obstacles decreases. Consequently, this leads to

an increased availability of line-of-sight (LoS) communication. For example, when considering a low altitude range and a high threshold value, only LTE 12 shows some occupancy, whereas the activity of the other bands becomes more noticeable at higher altitude ranges. As it can be seen from Figs. 7a and 7d, the probability of occupancy in the rural area surpasses that of the urban area at low altitudes due to the absence of obstacles and taller structures in the rural environment.

B. Downlink Channel

Fig. 8 illustrates the effect of altitude on DL spectrum occupancy for the frequency bands under consideration. In contrast to the UL scenario, LTE 12 is no longer the most active frequency band in the DL case. Notably, at high threshold value, the influence of altitude becomes more pronounced for LTE 41, 5G n77, and CBRS bands, which operate at higher frequencies compared to the other bands. This indicates that the presence of LoS signal is particularly crucial for higher frequency operations. Furthermore, it can be also seen that with increasing altitude, the probability of occupancy for the 5G bands in urban environments exceeds those of the rural areas. In the rural environment, it can be observed that the probability of occupancy for most of the considered bands remains constant for both threshold values at a given altitude.

VI. CONCLUSION

In this paper, we studied spectrum occupancy in various sub-6 GHz 4G, 5G, and CBRS bands using data collected by a Helikite flying over urban and rural environments. Both UL and DL spectrum occupancy were thoroughly investigated. Our findings revealed that the probability of occupancy generally tends to increase with higher altitudes, primarily due to a higher likelihood of LoS presence within the considered maximum altitude range. Furthermore, the DL frequency ranges exhibited higher levels of occupancy compared to

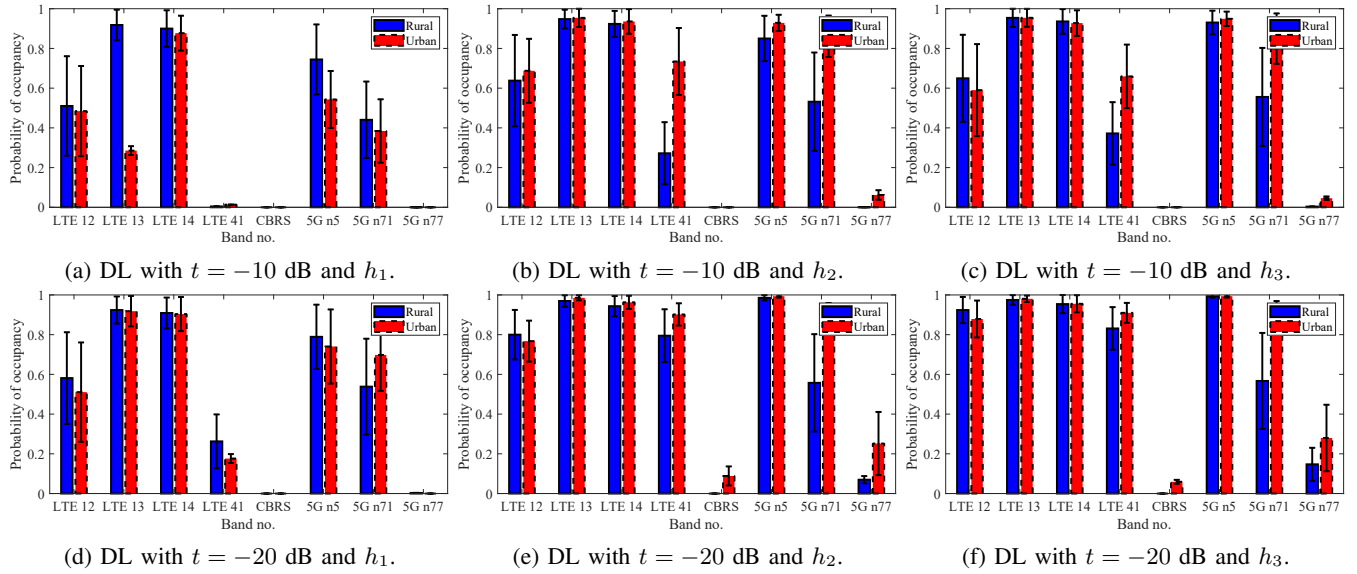


Fig. 8: Effect of altitude on DL spectrum occupancy by considering (a) $t = -10$ dB and h_1 , (b) $t = -20$ dB and h_1 , (c) $t = -10$ dB and h_2 , (d) $t = -20$ dB and h_2 , (e) $t = -10$ dB and h_3 , and (f) $t = -20$ dB and h_3 .

the UL ones in both environments. The critical role of LoS signals in higher frequency operations was also evident from our analysis. Moreover, we presented the variance in the occupancy probability across the bandwidth, highlighting the varying degrees of utilization within specific portions of the corresponding bands.

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