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Spectrum Usage Monitoring and Airtime Utilization: Insights from a Practical Case Study

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***Abstract*—This paper introduces an innovative spectrum monitoring setup and a new performance metric, airtime utilization, which quantifies the extent of spectrum usage. Our design offers a *protocol-independent* solution for detailed spectrum analysis across frequency, time, and power dimensions, which is essential for effective spectrum management. The presented experimental spectrum monitor is cost-effective for large-scale deployment. Extensive measurements in the 3.1 to 3.7 GHz frequency range are reported to demonstrate the practical application of our setup. The airtime utilization metric is explored through various case studies, showing its impact on understanding spectrum dynamics at different times of day, across weekdays and weekends, as well as long-term statistics over 26 weeks. It is observed that a large portion of the spectrum from 3.18 to 3.4 GHz is underutilized, presenting an opportunity to share the spectrum. The paper emphasizes the importance of dynamic and responsive spectrum allocation strategies to optimize the use of this vital global resource. We also discuss the potential for expanding our network of distributed stand-alone spectrum monitoring systems to enhance real-time, comprehensive oversight of spectrum usage.**

***Index Terms*—Airtime utilization, dynamic spectrum sharing, spectrum monitoring.**

I. Introduction

THE relentless expansion of wireless communication technologies has led to a surge in demand for radio frequency spectrum, driven by the proliferation of mobile devices, the expansion of internet services, and the emergence of next-generation technologies like the Internet of Things (IoT) and sixth-generation (6G) networks, see [1]. The finite nature of spectrum resources necessitates efficient management to accommodate these burgeoning demands. Regulatory bodies, such as the Federal Communications Commission (FCC) in the United States, alongside international agencies, have increasingly focused on strategies of innovative spectrum sharing to optimize spectrum utilization, e.g., see [2]. Effective spectrum usage monitoring, through advanced techniques such as dynamic spectrum access and real-time usage analytics, could significantly enhance spectrum efficiency. This approach not only helps in identifying underutilized bands but also in implementing real-time adjustments to spectrum allocation, thereby ensuring more adaptive and optimal use of this valuable resource [3].

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A. Spectrum Sharing in the 3-GHz Bands

In recent years, the FCC has orchestrated significant auctions, notably Auction 105 [4] and Auction 110 [5], aimed at reallocating spectrum traditionally designated for federal use to support burgeoning commercial wireless services. Auction 105 focused on the 3.55–3.7 GHz band, introducing the Citizens Broadband Radio Service (CBRS) framework, which provided 22,631 Priority Access Licenses to enhance fifth-generation (5G) deployment across the United States [4]. This auction highlighted a novel approach to spectrum sharing between federal incumbents, licensed commercial users, and general authorized access commercial users, integrating a three-tiered access system to manage interference and optimize band use. Following Auction 105, Auction 110 targeted America's Mid-Band Initiative Team (AMBIT) band from 3.45–3.55 GHz, offering 100 MHz of mid-band spectrum crucial for flexible use including advanced 5G services [5]. The auction format and the strategic division of licenses were designed to accommodate a wide array of applications, from enhanced mobile broadband to critical IoT connectivity, marking a significant shift towards more dynamic spectrum management practices.

The 3.1–3.45 GHz band has traditionally been used in the United States by the Department of Defense (DoD), Department of Homeland Security (DHS), and other Federal Agencies for radar and military applications. The MOBILE NOW Act and studies by the National Telecommunications and Information Administration (NTIA) have explored the feasibility of sharing this band with commercial users [6]. The National Spectrum Strategy published by the U.S. White House in Nov. 2023 indicated the lower 3 GHz band (3.1-3.45 GHz) is considered for non-government use in the near term, and dynamic spectrum sharing will be explored in this band [7]. The DoD Chief Information Officer (CIO) has acknowledged the potential for shared federal and nonfederal use but indicated that the DoD cannot fully vacate the segment without significant operational impacts [8].

B. Spectrum Monitoring

These strategic auctions underline the FCC's commitment to facilitating more efficient use of spectrum, balancing the need for national defense and public service applications with commercial aspirations. The introduction of such flexible-use spectrum necessitates the development of sophisticated monitoring systems capable of real-time analysis to prevent interference and ensure the reliability of both existing and new

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services. A U.S. Presidential Memorandum in 2013 discussed monitoring spectrum usage in real-time across the country to discover opportunities for more efficient spectrum sharing [9].

Spectrum monitoring can significantly improve spectrum utilization at multiple levels. At the foundational level, the spectrum monitoring data are used to identify unutilized or underutilized spectrum, aiding regulators in developing technical policies and enabling spectrum license owners to optimize their network planning. Beyond this, spectrum occupation data can be leveraged by spectrum coordinators in shared and unlicensed bands to improve efficiency. Notable examples include the Environmental Sensing Capability (ESC) and Spectrum Access System (SAS) in the 3.5 GHz shared CBRS band, as well as the Automated Frequency Coordination (AFC) system in the 6 GHz unlicensed band. Looking ahead, spectrum monitoring could play a transformative role in next-generation dynamic spectrum sharing (DSS) systems, enabling near real-time or real-time spectrum coordination. Finally, integrating the spectrum monitoring capabilities into the "sensing" aspect of Integrated Sensing and Communications (ISAC) offers a revolutionary opportunity to advance spectrum efficiency. By harnessing a vast network of base stations and mobile devices to generate geographical heatmaps of spectrum utilization, this approach has the potential to elevate spectrum efficiency to unprecedented levels. Our study focuses on the initial stage of spectrum monitoring: providing experimental references for regulators and operators. Additionally, our study also lays the groundwork for the next generation of DSS systems.

The dynamic nature of spectrum utilization, the ever-changing policies, and the reliance on geolocation necessitate real-time monitoring and reporting of spectrum activities. While recent experimental campaigns have sporadically reported their findings, there is a clear need for more consistent and thorough monitoring efforts, with an emphasis on long-term observation to better understand trends and changes over time [10]–[15]. Engiz *et al.* conducted extensive spectrum measurements in Samsun City, Turkey at 115 locations using energy detection and average spectrum occupancy techniques, revealing significant variations in spectrum utilization by location and service [10]. In [11], Chennamsetty *et al.* examine the activity of long-term evolution (LTE) and new radio (NR) frequency bands in Andhra Pradesh and Telangana, India, revealing significant urban-rural variations in spectrum occupancy, with urban areas showing high occupancy due to dense user presence, while rural areas have higher fourth-generation (4G) but lower 5G occupancy due to limited deployment, highlighting the need for efficient spectrum management and allocation for future network deployments. In another study [12], Chandhar *et al.* analyze the spectrum activity of various 4G LTE frequency bands in Chennai, India, showing significant variation in activity levels within a small geographical area. In [13], Maeng *et al.* overview the NSF Aerial Experimentation and Research Platform for Advanced Wireless (AERPAW) platform as an aerial spectrum monitoring testbed, presenting observations on spectrum occupancy variations by altitude, environment, transmission type, and technology. In [14], spectrum occupancy measurements from 2018 to 2019 near San Diego, Norfolk, San Francisco, and Astoria showed that areas near military sites had higher 3.45-3.65 GHz band occupancy. Regions with less military activity demonstrated significant underutilization, highlighting opportunities for dynamic spectrum sharing. More recently, a long-term spectrum monitoring campaign for the 3.1-3.7 GHz band in Louisville, Colorado, was reported in [15], providing detailed insights into spectrum occupancy, with implications for improving spectrum sharing and informing regulatory and business decisions.

C. Main Contributions

The current landscape of spectrum monitoring systems is constrained by several critical shortcomings. Traditional spectrum monitoring methods—such as the use of laboratory-grade spectrum analyzers (e.g., [10]) or mobile drive-testing campaigns (e.g., [13])—are often constrained by high capital and operational costs, limited scalability, and labor-intensive deployment. As a result, rural and remote areas often remain under-monitored due to the prohibitive expense of traditional equipment and the logistical challenges of installation. Additionally, these systems typically provide only periodic snapshots of spectrum usage (e.g., [11] and [12]), resulting in considerable data gaps that can overlook important trends such as unexpected spikes in signal activity or unauthorized usage. Moreover, the inability to support fast data processing further diminishes their utility in managing the dynamic nature of spectrum allocation, where decisions must be made quickly to adjust to changing conditions. To address these deficiencies, our proposed system leverages advanced algorithms and cost-effective sensor networks to achieve continuous (24×7), fast-tracking monitoring across diverse and extensive geographic regions without the prohibitive costs associated with traditional methods. This paper not only advances the technical understanding of spectrum dynamics but also contributes significantly to the ongoing discussion on spectrum policy and management. Our spectrum monitoring work focuses on the 3-GHz mid-band in the U.S.; however, the presented methodology is adaptable to other bands, including millimeter-wave bands, once they become congested. The main contributions of this study are as follows:

- Innovative Spectrum Monitoring System: We introduce a cost-effective, robust, and scalable spectrum monitoring system that provides detailed data across frequency, time, and power dimensions, essential for effective spectrum management.
- Airtime Utilization Metric: We propose the "airtime utilization" metric, which quantifies the extent of spectrum usage more accurately than traditional methods, facilitating nuanced policy and operational decisions.
- Extensive Spectrum Measurements: The paper details comprehensive measurements across the 3.1 to 3.7 GHz frequency range, illustrating the practical application of our setup in real-world environments.
- Long-term Data Collection and Analysis: Our ongoing data collection campaign, running from late January 2024 to the present, provides unique insights into both short-term and long-term behavior of spectrum usage, supporting dynamic spectrum allocation strategies.

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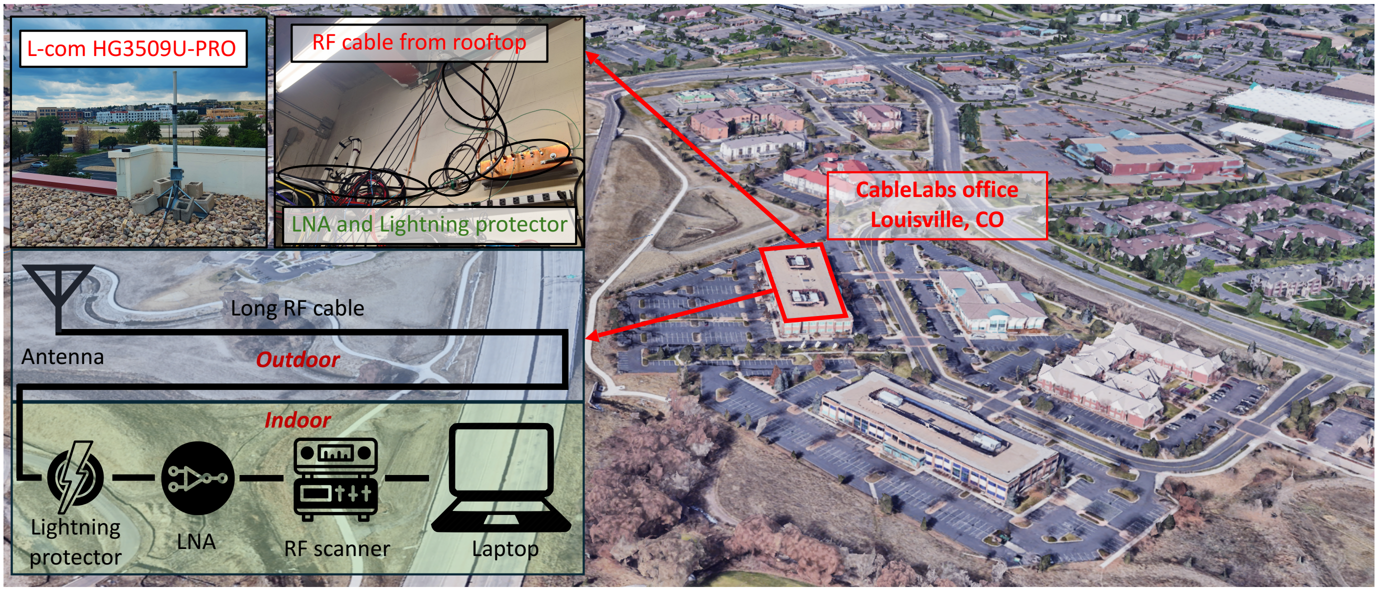

Fig. 1. Overview of the spectrum measurement setup at CableLabs office in Louisville, Colorado, USA.

The remainder of this paper is organized as follows. Section II details the spectrum monitoring system requirements and design, including a comprehensive description of the experimental setup and calibration processes used at the CableLabs office. Section III defines the airtime utilization and presents results and discussions, offering insights into trends in spectrum usage. Section IV discusses the role of distributed spectrum monitoring systems in enhancing spectrum management and dynamic spectrum sharing using cloud-based analytics and ISAC technologies. The paper concludes in Section V, which summarizes key findings and outlines future research directions and potential enhancements to the spectrum monitoring framework.

II. Spectrum Monitoring System Requirement and Design

Fig. 1 shows the experimental setup situated on the roof of our office building in Louisville, Colorado, USA. The locale is characterized as suburban, and the antenna is mounted at an elevation of approximately 10 m above ground. The experiment setup includes several key components for proper functioning and accurate data collection. The primary device is the radio frequency (RF) scanner, a Signal Hound®BB60C, chosen for its high reliability, sensitivity, and affordability. The noise floor is approximately -154 dBm/Hz near 3.5 GHz with a 15 dB noise figure. The noise floor is also determined by a configurable reference level at the Signal Hound. The noise floor is approximately 60 dB below the reference level. An LMR-600 coaxial cable connects the various components, known for its low loss over long distances. The cable length is 75 ft which has a loss of 3.75 dB. The antenna used in the setup is the L-com®HG3509U-PRO, a vertical-polarized 3.5 GHz omni-directional antenna with 9 dBi maximum gain, designed for all-weather operation, ensuring wide coverage and reliable signal reception. An L-com®AL6-NFNFBW-9 lightning protector (LP) is incorporated to safeguard the equipment from potential lightning strikes, thereby enhancing the resilience of our system against severe weather conditions. An optional low-noise amplifier (LNA), the Mini-Circuits®ZX60-63GLN+, can be included to enhance signal strength. The LNA gain is approximately 27.8 dB at 3.5 GHz. Data processing and analysis are performed using a laptop. For system characterization purposes, a matched load is employed at the end of the RF scanner to evaluate its noise floor. A CW tone created by a signal generator and a spectrum analyzer are used to estimate LNA gain, LP loss, and cable loss at multiple frequencies between 3 and 4 GHz.

Frequency 3.1 to 3.7 GHz with a 10 kHz resolution bandwidth (RBW) is used in spectrum monitoring, which covers the 3.1–3.45 GHz band being considered for mobile networks, AMBIT band (3.45–3.55 GHz), and CBRS band (3.55–3.7 GHz). The selection of a 10 kHz RBW represents a careful balance between managing data size and preserving meaningful information for this study. Some narrow-band signals were observed with bandwidth ranging from 30-50 kHz. Narrowband-IoT (NB-IoT) has a bandwidth of 200 kHz. In LTE and 5G, physical resource block (PRB) blanking is an effective interference mitigation technique, with PRB bandwidth of 180 or 360 kHz in low- and mid-band. By using a 10 kHz RBW, the data can effectively resolve narrow-band signals, it also offers valuable insights for informing PRB blanking decisions.

To facilitate 24×7 uninterrupted data collection, a -72 dBm/RBW power threshold is applied. Only signals above the power threshold are recorded. The - 72 dBm/RBW power threshold at the RF scanner is equivalent to -105 dBm/RBW or -72 dBm/20MHz (i.e., new power (dBm) = initial power (dBm) + $10\log_{10}$(new bandwidth/initial bandwidth) $\approx$ -105 dBm + 33 dB = -72 dBm) in the air, which is the power detection (PD) threshold employed in the IEEE 802.11 Clear Channel Assessment (CCA) technique, also known as listen-

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before-talk (LBT), that indicates a channel is available for transmission. An alternative power threshold is -89 dBm/MHz as used in the CBRS ESC networks, which is 4 dB lower than the -72 dBm/20MHz CCA threshold. Frequency, Unix timestamp, and power of signals are recorded in a Parquet format. The sweep time is configured to 10 sweeps/second, but it only achieves 4 to 5 sweeps per second due to the limitation of Fast-Fourier Transform (FFT) size, number of frequency points, and data transfer rate to the laptop via USB. The data size is 2 to 3 GB per day depending on the activities monitored in the frequency range. Note that it is a tradeoff between the data size and power threshold, a lower power threshold improves sensitivity but significantly increases data size. A comparison of data size without and with different power thresholds is provided in [15]. In addressing the need for monitoring across various frequency ranges, it is important to note the modular design of our equipment. Both the Signal Hound device and the antenna can be substituted with alternatives suitable for higher frequencies, thereby enhancing the flexibility and adaptability of our monitoring approach. This capability allows for seamless adjustments to meet diverse operational requirements.

Fig. 2 depicts the received power measurements across the frequency range of 3.1 GHz to 3.7 GHz, collected over 24 hours from May 6-7, 2024. To optimize storage, only power levels above –72 dBm were retained. The recorded power spans from –72 to –60 dBm. The power is stronger from 3.1 to 3.18 GHz and near 3.45 GHz, likely due to radar and aviation links nearby. Notably, in certain frequency segments, such as from 3.18 to 3.4 GHz, power levels fall below the –72 dBm threshold, as indicated by the white spaces where no data was recorded. At our measurement location, the spectrum condition is relatively clean allowing a terrestrial link to operate, suggesting the 3.18-3.4 GHz is suitable for potential sharing. Sparse signals in the CBRS band (3.55-3.7 GHz) are probably attributed to the proximity (∼13 miles) of a Federal quiet zone, and the corresponding incumbent protection rules do not allow active CBRS radiation in the area. In the time domain, the spectrum utilization is active in the daytime and inactive in the evening, e.g., from 8 PM to 8 AM.

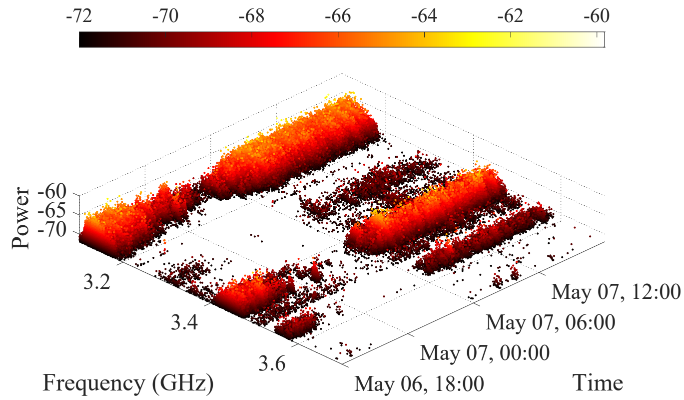

Fig. 2. Three-dimensional scatter plot showing the variation in received power across the frequency range of 3.1–3.7 GHz, over the course of May 6 and May 7, 2024. White regions indicate frequency segments where no signals were recorded due to power levels falling below the –72 dBm threshold, which was applied to optimize storage.

III. Airtime Utilization

To extract meaningful information from massive amounts of data, two concepts are defined: channel occupancy and airtime utilization. The entire span is divided into 5-MHz channels because 5 or 10 MHz will likely be the granularity for mobile network channel allocation. A comparison of choosing difference channel bandwidth was presented in [15]. A 5-MHz channel inside a second is identified as "occupied" if at least one data point is above the power threshold indicating the channel is considered unavailable for transmission in CCA.

Airtime utilization quantifies the proportion of time that a communication channel or frequency band is actively transmitting data, expressed as a percentage of the total available time. In this paper, "airtime utilization per hour" is defined as the ratio of the total number of "occupied" seconds to 3600 seconds. Adjustments to key parameters—such as channel bandwidth, power threshold, and measurement interval—can significantly impact airtime utilization metrics. For instance, increasing the power threshold imposes stricter criteria, thereby reducing airtime utilization since only stronger signals will qualify. Additionally, the measurement interval has to include multiple sweeps. Extending the measurement interval from one second to ten seconds may smooth out brief signal fluctuations, generalizing airtime activity and potentially overlooking short-duration bursts, thus altering the utilization rate. Decreasing the channel bandwidth provides a more focused analysis of a smaller frequency range, which may be necessary for applications such as NB-IoT with 200 kHz bandwidth. These adjustments should be carefully aligned with specific research goals, as they critically affect the sensitivity and specificity of network performance evaluations.

Moreover, selecting appropriate values for these parameters is not only a technical decision but also a strategic one, affecting the accuracy and reliability of spectrum monitoring. For example, by selecting a narrower channel bandwidth, we can detect finer granularity in spectrum usage, which is crucial for densely populated spectral environments where interference and overlapping transmissions are common. This approach allows for more precise identification of underutilized channels, which could be reallocated or dynamically shared among multiple users, enhancing spectrum efficiency. Similarly, the choice of power threshold and measurement interval must balance between sensitivity to fleeting signals and stability against noise, reflecting a strategic prioritization of either catching brief, significant transmissions or ensuring consistent data over time. These decisions are instrumental in shaping the policies for spectrum management, as they directly influence the outcomes of spectrum monitoring and ultimately the formulation of more informed, data-driven regulatory frameworks. In essence, airtime utilization focuses on the "when" and "how often" aspects of spectrum usage, providing a time-based analysis that complements the "how strong" insight offered by power measurements. Unlike traditional spectrum occupancy metrics such as duty cycle, which often summarize activity based on instantaneous or averaged power

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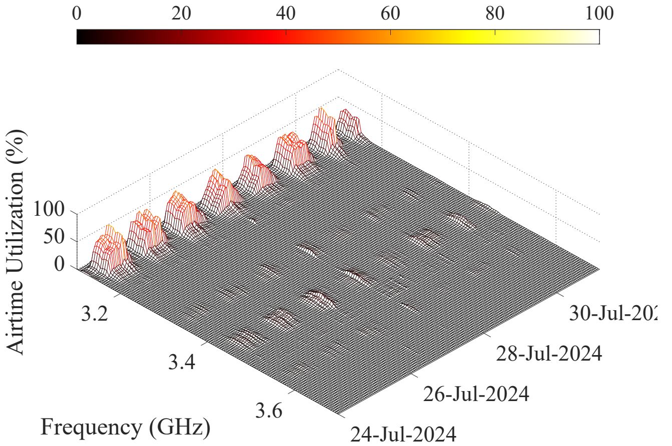

Fig. 3. Airtime utilization across various frequency bands from 3.1 GHz 3.7 GHz during the week of July 24 (Wednesday) to July 31, 2024. The color bar represents the level of airtime utilization ranging from 0% to 100%, with brighter colors (white, yellow) indicating higher utilization and darker colors (red, black) indicating lower utilization.

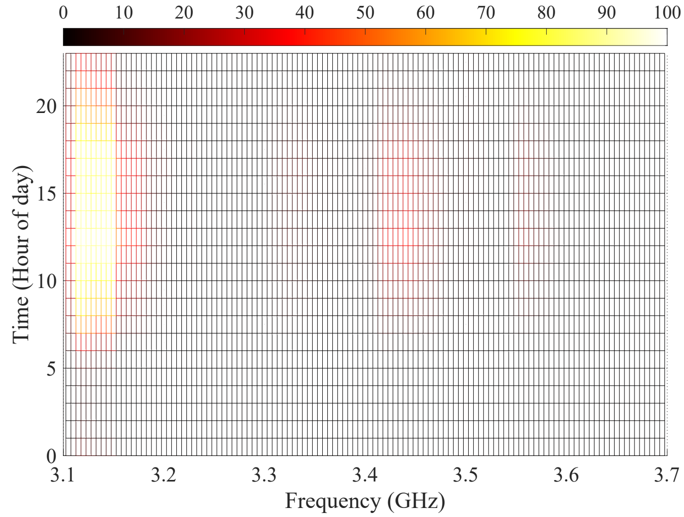

Fig. 4. Airtime utilization across frequency range of 3.1-3.7 GHz versus time of day, the median value over the measurement period from January 21 to July 31, 2024.

levels, the proposed airtime utilization metric captures the temporal intensity of spectrum use. It quantifies the proportion of time that a frequency band is actively transmitting above a calibrated threshold over a defined interval, thus offering finer temporal resolution and better reflecting channel availability over time. This makes it particularly valuable for dynamic spectrum sharing strategies and regulatory insights.

In the rest of this section, we present the airtime utilization in both the short-term and long-term. The short-term statistics demonstrate spectrum usage within a week that compares weekday with weekend, as well as compares daytime with evening usage. The long-term study presents spectrum usage over 26 weeks. Again, the frequency was from 3.1–3.7 GHz. The threshold value for airtime utilization was set at -72 dBm per 10 kHz resolution bandwidth at the RF scanner, equivalent to -72 dBm/20MHz in the air. Measurements commenced on January 21, 2024, and data collection has been continuous, with temporary interruptions only for regular maintenance.

Fig. 3 illustrates the airtime utilization for the week of July 24 to July 31, 2024. The x-axis represents the frequency range under consideration, the y-axis denotes the date and time with a resolution of one hour, and the z-axis indicates the airtime utilization for a given time and frequency. The color bar represents the level of airtime utilization ranging from 0% to 100%, with brighter colors (white, yellow) indicating higher utilization and darker colors (red, black) indicating lower utilization. Over multiple days, distinct peaks and troughs in utilization are observable, suggesting non-uniform demand across this frequency band. Certain sub-bands (i.e., 3.1-3.18 GHz) reach utilization levels nearing or exceeding 50%, indicating areas of intense usage, while others maintain consistently lower utilization, potentially signaling underutilized spectrum resources. This uneven distribution across both frequency and time underscores the importance of dynamic spectrum management to alleviate congestion in high-demand sub-bands and to optimize usage across the full spectrum. The temporal component further suggests fluctuating demand likely due to diurnal or weekly patterns, reinforcing the need for adaptive allocation strategies that respond to real-time usage metrics. For example, it can be observed that the activity during weekdays is higher compared to weekends, e.g., July 27 and 28, 2024.

Fig. 4 presents the airtime utilization versus the time of day for the entire measurement period, from January 21 to July 31, 2024. For each hour of the day, the median airtime utilization was calculated over all measured data to assess long-term trends. The x-axis represents the frequency range, the y-axis represents the time of day, and the color bar indicates the level of airtime utilization. As observed, the frequency range of 3.1–3.18 GHz shows higher activity compared to other portions, with higher utilization levels indicated by the yellow and orange colors. In contrast, the other frequency bands show significant activity primarily during daytime hours, from approximately 8:00 AM to 8:00 PM, with peaks around 10:00 AM to 3:00 PM. Specifically, the frequency range of 3.4–3.45 GHz exhibits noticeable activity during these hours, although their utilization levels are generally lower than those of the 3.1–3.18 GHz range, as shown by the brighter color shades. Given the location and considered threshold value, this pattern suggests that while the 3.1–3.18 GHz band is heavily utilized and possibly allocated for critical or continuous communication services, the other bands are likely used for activities that peak during regular business hours.

Fig. 5 illustrates the airtime utilization over a period of 26 weeks, from January 21 to July 31, 2024. The x-axis represents the frequency range, the y-axis denotes the weeks, and the z-axis indicates the percentage of airtime utilization averaging over the week. The week number corresponds to the week of the year starting from January 1, 2024. As observed, certain frequency bands exhibit consistent patterns of utilization across the weeks. The airtime utilization for the frequency range of 3.1–3.12 GHz is always higher than the rest of the bands, with spikes in weeks 12 and 13, where utilization exceeds 80%. The frequency range of 3.4–3.5 GHz shows

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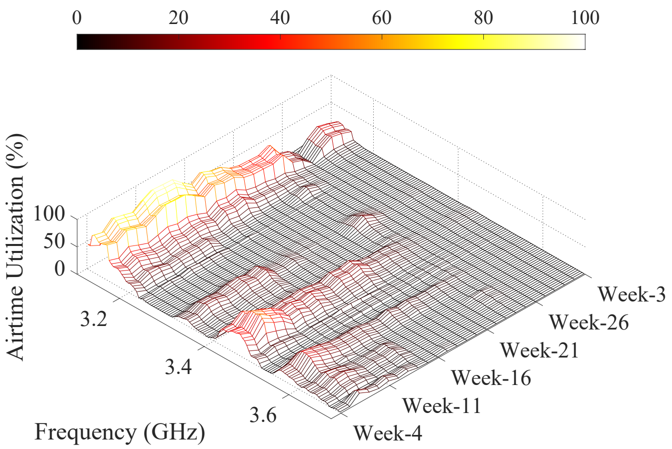

Fig. 5. Airtime utilization across different frequency bands (3.1 GHz to 3.7 GHz) over a 26-week period in 2024. Note that "Week-4" is from Jan. 21 to 27.

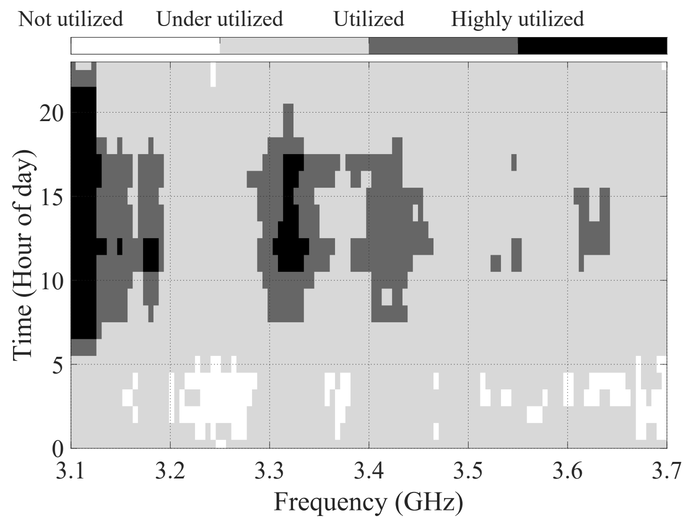

Fig. 6. Heatmap of maximum airtime utilization for frequency band from 3.1 GHz to 3.7 GHz over the period from June 1 to June 30, 2024, illustrating levels of airtime utilization: highly utilized (black, (50%, 100%]), moderately utilized (dark gray, (20%, 50%]), underutilized (light gray, (0%, 20%]), and not utilized (white, 0%).

notable peaks in utilization, with the highest levels observed in week 6. The peak occurred in the frequency range of 3.435 to 3.445 GHz, indicating utilization levels approaching 50%. Other frequency ranges, such as 3.3–3.4 GHz and 3.6–3.7 GHz, also show some increases in utilization during some specific weeks, though they generally maintain lower levels compared to the 3.4–3.5 GHz range. The visualization highlights temporal trends in spectrum usage, showing how certain frequency bands experience higher demand during specific periods. To quantitatively summarize long-term occupancy across the entire band, we computed the average weekly airtime utilization over the 26-week measurement period. This analysis revealed an overall mean airtime utilization of 8% with a variance of 32 ($\%^2$), indicating relatively low average usage but substantial week-to-week variability in spectrum activity. This information is crucial for understanding long-term patterns in airtime utilization and for planning the efficient allocation of frequency resources. The consistent peaks during specific weeks suggest regular or scheduled activities that heavily utilize these frequency bands, providing insights into the behavior of spectrum usage over time.

Fig. 6 illustrates a heatmap representing the maximum airtime utilization for frequency bands in the 3.1–3.7 GHz range over the period from June 1 to June 30, 2024. Note that using the maximum airtime utilization represents a conservative approach. The utilization levels are categorized as black for highly utilized (airtime utilization higher than 50%), dark gray for moderately utilized (airtime utilization between (20%–50%]), light gray for underutilized frequencies (airtime utilization between (0%–20%]), and white for not utilized frequencies, i.e., airtime utilization equal to 0%. Fig. 6 reveals that the frequency range between 3.1 GHz and 3.125 GHz is heavily utilized, particularly from 7 AM to 10 PM, indicating consistent demand during these hours. In contrast, the bands around 3.3 GHz to 3.45 GHz generally show intermittent utilization, with less consistency and lower overall usage compared to the first region. Notably, the frequency bands between these highly utilized regions, specifically around 3.2 GHz to 3.3 GHz and above 3.45 GHz, remain largely underutilized. In addition, there are some portions of the frequencies that the airtime utilization is zero during off-peak hours, particularly from midnight to 5 AM. This visualization is crucial for understanding spectrum occupancy patterns and can inform more efficient spectrum management and planning strategies.

IV. Large-Scale Spectrum Monitoring Network

One spectrum monitoring kit evaluates channel occupancy and availability for a commercial link at a specific location. However, this isolated evaluation is inadequate to conclusively demonstrate that a channel can be shared with an incumbent user without causing harmful interference.

Distributed stand-alone spectrum monitoring systems are crucial for achieving real-time, comprehensive oversight of spectrum usage across diverse geographic regions. While these systems operate independently, they are interconnected to form a robust framework for continuous spectrum observation. Monitoring systems at multiple locations may establish a geographic heatmap of spectrum usage, which could better assist decision-making of spectrum allocation for regulations and operators, as well as assist dynamic spectrum sharing technique design. This architecture enables localized detection of spectrum occupancy, interference issues, and underutilized spectrum, thereby facilitating dynamic spectrum access. This setup not only enhances the granularity and accuracy of the spectrum data but also significantly reduces latency in decision-making processes related to spectrum allocation. Such systems are essential for implementing regulatory strategies, especially in environments where spectrum utilization varies significantly across different areas. By providing detailed and localized data, distributed stand-alone spectrum monitoring supports more nuanced and responsive spectrum management policies, optimizing the utilization of valuable spectrum resources.

We are actively encouraging organizations to host the monitoring kit and share data. Multiple organizations have already participated at various locations across the United States, including Louisville, Colorado; Philadelphia, Pennsylvania; Louisville, Kentucky; Washington, D.C.; Anchorage, Alaska; Santa Clara, California, etc. The data collected from various locations will be uploaded to a cloud-based server, enabling centralized storage and accessibility. This data will then be automatically analyzed through a user-friendly interface that can be customized according to specific user demands. This system ensures efficient data management and facilitates easy retrieval and analysis of information, enhancing the effectiveness of monitoring across different sites. Once the cloud-based data analytics platform design is mature, we will report in future publications along with spectrum usage data from various locations.

At CableLabs, we are exploring the potential to establish a large-scale spectrum monitoring network that would serve as a collaborative platform for researchers, developers, and industry stakeholders. This platform would allow the real-world experimentation and validation of advanced wireless services, dynamic spectrum-sharing techniques, and other innovations in a controlled yet realistic environment. Such a platform at CableLabs would enhance our current spectrum monitoring efforts by providing diverse data from various deployments and usage scenarios, further accelerating the practical application of our research findings in spectrum management.

Integrated sensing and communication is of interest in both academia and industry. Many Standard Development Organizations (SDOs) have started the study on ISAC including the International Telecommunication Union (ITU), 3GPP, and IEEE 802.11 Working Groups. One of the potential use cases for ISAC is spectrum sharing. Base stations (BSs), access points (APs), or user devices could integrate spectrum occupation sensing capability that forms a much denser sensing network than the distributed spectrum monitoring systems mentioned above. ISAC could enable both (near) real-time spectrum coordination and long-term statistics collection. The frequency-time-power-based sensing requirements (Section II) and CCA power detection threshold-based airtime utilization (Section III) could be considered in the future ISAC spectrum sensing and sharing framework.

V. Conclusions

In conclusion, this study underscores the critical role of innovative spectrum measurement techniques and the introduction of the "airtime utilization" metric in refining spectrum management strategies. Our findings from extensive measurements across the 3.1 to 3.7 GHz frequency range reveal significant insights into spectrum dynamics, demonstrating the efficacy of our setup in real-world applications. The results highlight the potential for more efficient spectrum utilization through advanced monitoring and analysis tools. Our observations for this specific geolocation reveal that daytime activity is notably higher than evening, and weekdays activity is slightly higher than weekends, with peak utilization occurring in the 3.4–3.5 GHz range on specific days, and consistently high utilization in the 3.1–3.18 GHz band throughout the 26 weeks observation time. The 3.18–3.4 GHz is not utilized or underutilized, which could be considered for sharing with commercial users. While our study provides significant insights into spectrum usage and airtime utilization within the 3.1 to 3.7 GHz range at a suburban location, we acknowledge that these findings are inherently limited by the geographical and environmental specificity of the data source. The spectrum dynamics observed at our single suburban site may not fully represent those in urban or rural settings, where different patterns of usage and interference might prevail. Furthermore, factors such as population density, the presence of industrial or commercial facilities, and regional regulatory policies can all influence spectrum utilization differently. Future research will focus on expanding our measurement framework to various locations and broader spectra, and integrating more granular and longer-term data analytics to further enhance the precision of spectrum allocation and policy-making. These efforts aim to deepen our understanding of spectrum dynamics through advanced statistical methods such as variance analysis and confidence intervals, providing robust substantiation of our findings. We are committed to supporting further research in this area and recognize the importance of making our dataset accessible to the wider research community upon request. Interested parties are encouraged to contact the CableLabs team directly. By enhancing the scope and accessibility of our research, we strive to facilitate more informed and adaptive spectrum management practices that dynamically respond to evolving technological demands and usage patterns.

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