Outdoor Power Measurements of Wi-Fi Traffic on the University of Colorado Boulder Campus

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***Abstract*—Since the advent of mobile communication, the growth in demand for wireless communication devices and associated spectrum needs has been unstoppable. As a result, due to limited spectrum availability and historically inefficient management of assigned frequencies, spectrum sharing has steadily grown in importance and become a necessary solution to various capacity constraints. To support new developments in spectrum sharing, research in spectrum monitoring and spectrum utilization have become most valuable. GNU Radio offers a compelling opportunity to quickly develop and prototype new research in spectrum monitoring, sharing, and related radio frequency research that can support future deployments. GNU Radio's packaged capabilities combined with its compatibility with a multitude of Software Defined Radio (SDR) hardware OEMs allow spectrum sharing research to be conducted nimbly and rapidly. To improve spectrum sharing and management, this research used GNU Radio in conjunction with Ettus USRP SDRs to collect I/Q data across the CU Boulder campus in regular intervals over 4 weeks, to monitor changes in the power levels recorded across 1 indoor and 10 outdoor locations. The results show that a simple sensor consisting of an SDR and a Raspberry Pi is capable of tracking changes in Wi-Fi signal strengths measured in outdoor environments. With calibration and careful hardware design such a platform could also be used for broader spectrum monitoring applications.**

***Index Terms*—SDR, Wi-Fi, Spectrum Monitoring, GNURadio, Raspberry Pi**

I. Introduction

Wireless communications capabilities have increased exponentially since 2G in the 1990s with throughput growing from 10 kbps to 20 Gbps [1] while, at the same time, 13.1 billion wireless connected devices are expected by 2023 according to Cisco [2]. Cisco further estimates that on average by 2023 every person will carry 3.6 networked devices. Machine-to-Machine communication will see an even larger growth with its share among networked devices increasing from 33% to 50% [2], [3]. This relentless growth in devices requiring access to the radio frequency (RF) spectrum emphasizes the importance of efficient spectrum management. Well known are the inefficiencies caused by the traditional way of assigning spectrum based on exclusive use rights [4], leading to more governments and industries shifting their focus to unlicensed and shared spectrum.

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As a result, spectrum monitoring and utilization measurements have only gained in importance as tools to provide spectrum awareness in frequency, space, and time. Effective spectrum awareness not only makes it possible to assess the current spectrum state by identifying vacant and congested channels, but furthermore provides an important understanding of spectrum conditions, which assists the spectrum management process and can help solve interference problems [5], [6]. However, spectrum occupancy measurements are most often conducted using prohibitively expensive hardware such as highly sophisticated spectrum analyzers, hindering widespread spectrum monitoring research. This work demonstrates the potential advantages and downsides of low size, weight, power, and cost (SWaP-C) Software Defined Radio (SDR) alternatives to spectrum analyzers (SAs). Ettus B200-mini Universal Software Radio Peripherals (USRPs) are used to collect data on Wi-Fi channel 6 centered around 2.437 GHz in an outdoor environment in regular intervals across the University of Colorado campus over the course of 4 weeks. Section 2 reviews current monitoring solutions, followed by an outline of the proposed SDR-based approach in Section III, the discussion of results in Section IV, and concludes with a summary and potential for future work in Section V.

II. Related Work

To confirm compliance with established technical and operational rules, monitoring was in the past regularly conducted by national monitoring stations, such as the broadband spectrum survey in Denver, Colorado, which used a specialized vehicle for a large scale spectrum survey from 108 MHz to 19.7 GHz [7]. Without a standardized spectrum surveying framework formalized [6], more recent research conversely attempts to demonstrate the capabilities of less centralized spectrum sensing using a variety of spectrum analyzers instead of professional monitoring stations. Some more recent examples of spectrum measurements include: analyzing the 900 MHz GSM band in South Africa using an Aglient EXA N9010A spectrum analyzer [8]; using a Rhode & Schwarz (R&S) FSC3 spectrum analyzer to record traces of the 170-1000 MHz spectrum every 10 seconds for 7 days in India [9]; measuring utilization of the 80-2700 MHz band at the University of Hull, UK over the course of 12 hours using an Aiglent E4407B spectrum analyzer [10]; investigating the 801-965 MHz band during the busiest hours of the day in Samsun, Turkey using an RF Explorer 6G Combo spectrum analyzer [11]; recording occupancy in the 30-3000 MHz band over the course of 24 hours in Johor Bahru, Malaysia using an Agilent E4440A PSA high performance spectrum analyzer [12]; using a R&S FSP spectrum analyzer to measure the 300-3000 MHz band over the course of 20 days in Sharjah, UAE [13]; and many more. However, the quality of results gained from spectrum analyzer measurements largely depend on the hardware's appropriate configuration and data analysis method [10], which can raise the barriers to entry even further.

To make spectrum monitoring research more accessible, some recent research has taken steps to investigate the potential of using more affordable hardware, including low-cost SDRs such as RTL-SDRs and USB DVB-T dongles as enablers of more widely available spectrum monitoring research. Grönroos et al. for instance used a Raspberry Pi with a USB DVB-T dongle to measure the supported 110-1200 MHz band in 937 kHz intervals [14] while Fanan et al. used an RTL-SDR to measure spectrum occupancy of the UHF TV band [15]. Both are aware of the inherent downsides of using these low-cost SDRs such as a limited 8-bit resolution, high noise floor, USB noise, and RF leakage into the antenna port. Still, using such low-cost devices has some noticeable advantages including the ability to combine the results from multiple low-cost sensors [14].

In-between these two extremes, SDRs such as Ettus USRPs can provide more balanced results. While some models are still considerably lower in price, smaller in size, and offer increased flexibility compared to spectrum analyzers, they additionally provide improved performance compared to cheaper solutions, such as RTL-SDRs. Martian et al. for instance compared the performance of USRP B200 minis to a Tektronix RSA3308B Spectrum Analyzer, coming to the conclusion that the results obtained from the SDRs were very close to the reference spectrum analyzer [16]. However, when using SDRs it is very important to consider the trade-off between sensitivity and dynamic range [10]. Regardless of which method is chosen, research has highlighted that more studies of spectrum use are crucial for the continuing growth of wireless communication [17]. Therefore, to contribute to the growing availability of spectrum data, this research seeks to characterize the correlation in the change of spectrum utilization at 10 outdoor locations on the University of Colorado at Boulder campus in frequency and time using USRP B200-mini SDRs controlled by Raspberry Pis and scheduled by GNU Radio. Various statistics of power measurements converted from I/Q data recordings are used to measure outdoor activity in Wi-Fi channel 6 with center frequency at 2.437 GHz.

III. Methodology

A simple sensor systems consisting of a data collection host (DCH) in the form of a single board computer (SBC) and a SDR as its data collection sensor (DCS), connected to the DCH via a USB 3 connection, is used to measure outdoor power levels. A USB 3 connection is necessary to provide sufficient power to the DCS and to enable high-speed data transfer between the subsystems. The DCS consists of an Ettus B200 mini-i USRP SDR [18], with industrial enclosure, and a VERT2450 Dual Band omni-directional antenna with 3 dBi gain [19], vertical polarization, and supporting the frequencies from 2.4 to 2.48 GHz and 4.9 to 5.9GHz. The industrial enclosure provides improved shielding and increases the operating temperature range, which can be particularly useful for outdoor data collections under sunny and hot summer conditions.

The DCH consists of a Raspberry Pi 4 Model-b single board computer with 8 GB of RAM powered by a 5.2V Anker Portable Power Bank and operates via a 32GB SanDisk Ultra MicroSD card hosting a 32-bit Raspberry Pi OS, version 10 (buster), dated 2021-05-07. To ensure the DCH cannot self-contaminate the data collection, Wi-Fi and Bluetooth capabilities are disabled in the OS using rfkill. The code used to collect the power measurement samples consists of a GNU Radio (v3.7.13.4) flowgraph in Python which is automated and scheduled by systemd services. The USRP B200 series has a bit-depth of 12 bits, but delivers data from the SDR to the DCH in a 16-bit signed integer format, which is then converted at the host into a 64-bit complex format. Each 64-bit complex sample consists of one 32-bit in phase and one 32-bit quadrature sample. Additionally, to maintain consistent timestamps on the collected I/Q data recordings, the DCH is configured to connect to the National Institute of Standards and Technology (NIST) Network Time Protocol (NTP) server. Figure 1 illustrates the data collection components and data flow.

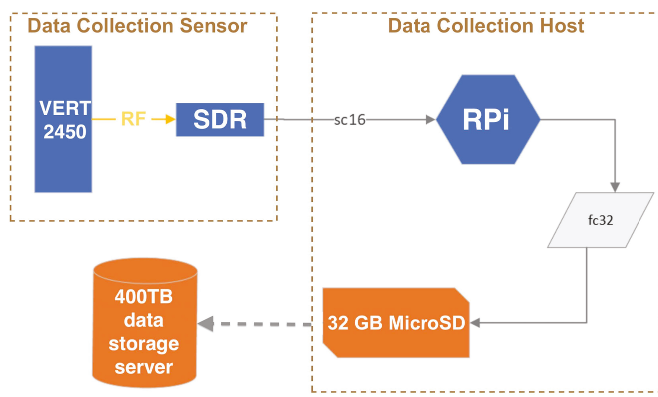

Fig. 1. Data collection setup components and data flow.

The primary objective of the data collection is to record Wi-Fi Channel 6 outdoor activity on the University of Colorado Boulder campus over a four-week data collection period that coincides with an increase in student population. Specifically, the month of August sees a low population summer session (Weeks 1 & 2) followed by student population increases due to Orientation and Fall move-in (Week 3), and finally full student body presence due to the first week of classes for the Fall semester (Week 4). This progressive increase in campus activity is ideal to attempt to determine changes in outdoor

Wi-Fi activity using simple SDRs and to potentially determine any correlation with the expected increase in campus activity.

To record power measurements at these 11 locations, the sensor system collects I/Q data from the 22 MHz wide Wi-Fi Channel 6, centered at 2.437 GHz. Due to the highly variable signal strength at these locations, using a relatively high gain setting could result in saturation across many locations. Instead the system is configured to use a lower gain setting to ensure none of the samples are saturated or clipped. In order to capture complete Wi-Fi signals within channel 6, the SDR is configured to record a bandwidth of 20 MHz with a centre frequency at 2.437 GHz.

Figure 2 shows the 11 data collection locations, which were chosen for a variety of reasons. Location 1 is a less frequented exit and entry point to the campus and only has slightly increased foot traffic during the semester. Location 2 is located inside the engineering center near a Wi-Fi access point and used as a verification checkpoint as it should show consistently higher power levels compared to other locations. Locations 3 and 8 are two of the major foot traffic intersections on campus that connect dormitories and major buildings. Location 4 is located at an intersection between dormitories and a parking lot. Location 5 is next to the Biosciences building, the stadium, and a path leading to the recreation center. Location 6 is in the main lobe of an access point in front of the main library. Location 7 and 10 cover the entrance to two of the campus' main dining locations. Finally, both location 9 and 11 are in somewhat quieter areas of the campus in front of an administrative building and on a large field at the corner of the main campus.

At these 11 locations, the data collection is conducted on a strict schedule. The GNU Radio Python flowgraph is configured to run and collect data once every minute as long as the DCS and DCH are connected. To pause the data collection, DCS and DCH can simply be disconnected and reconnected to resume. At each of the 11 locations, the sensor is positioned as close as possible to the same position every time data is recorded. Five 1-second long I/Q Data files are recorded at each location, resulting in 100 million I/Q samples or 160 MB of data. In total approximately 100 recordings or 16 GB of data are recorded every day for a period of 4 weeks. Table I details the approximate time at which samples are collected at each location. For the duration of the data collection, I/Q data recordings are temporarily stored on the DCH' SD card. After the conclusion of a single data collection cycle, the data are transferred from the DCH via Ethernet to a permanent storage location using rsync and finally removed from the DCH.

Once the data have been transferred to the server for permanent storage, a Python script is executed to calculate relevant time domain statistics, including average, maximum and median power. Since USRPs are not calibrated devices and no calibration was available at this frequency and gain setting at the time of data collection, relative power measurements are used by converting the I/Q values to dBFS (see Equation 1). Each value is labeled with its location number, which is then used to calculate a single average, maximum, or median value for each location for each day. These final location values are then used to plot the data, calculate correlation coefficients for each location and day of the week, and to investigate the data for trends.

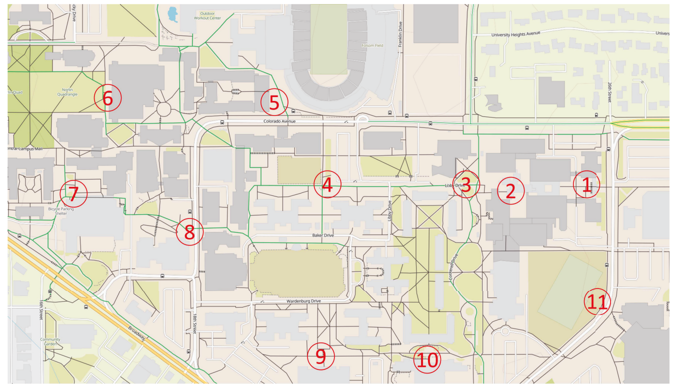

Fig. 2. Map of Data Collection Points.

TABLE I
DATA COLLECTION PROCEDURE TIMES

Site No.	**Description**		
	Site Name	*Location/Context*	*Time*
1	DLC Courtyard	Engineering classrooms	11:00-11:05
2	Engineering Center	Lobby	11:08-11:13
3	Math Roundabout	Classrooms, foot traffic	11:15-11:20
4	Libby Drive	Dormitory, foot traffic	11:23-11:28
5	Stadium	Classrooms, offices	11:31-11:36
6	Norlin Main Entry	Campus library	11:41-11:46
7	UMC Courtyard	Dining, student center	11:49-11:54
8	18th Street	Bus stop, car garage	11:57-12:02
9	Regent, N. Entry	Admin offices	12:07-12:12
10	C4C, N. Entry	Popular dining hall	12:15-12:20
11	Business Field	Open field near road	12:24-12:29

$$dBFS = 20 \cdot \log_{10}\left(\sqrt{\frac{1}{N}\sum_{n=1}^{N}|x(n)-\mu|^2}\right) \tag{1}$$

IV. RESULTS

Raw data [1] was collected over the course of 28 days following as strict a schedule as possible. On rare occasions the sensors had to be placed a few meters away from the regular location, which largely did not affect the data in the outdoor locations. Additionally, the engineering center was unfortunately closed on August 27 and 28, making it impossible to collect data at the usual location, resulting in lower recorded power levels. Figures 3 and 4 show the change in average relative power and maximum relative power respectively across the 4-week period. As expected, both average and maximum power levels at location 2 begin to increase noticeably as the engineering center was frequented more with students moving onto campus. The maximum recorded values

[1]Raw data and code can be found on the CU Boulder GitHub Repository for the WiFi Channel 6 survey, available at: https://github.com/UCBoulder/rfs-v1

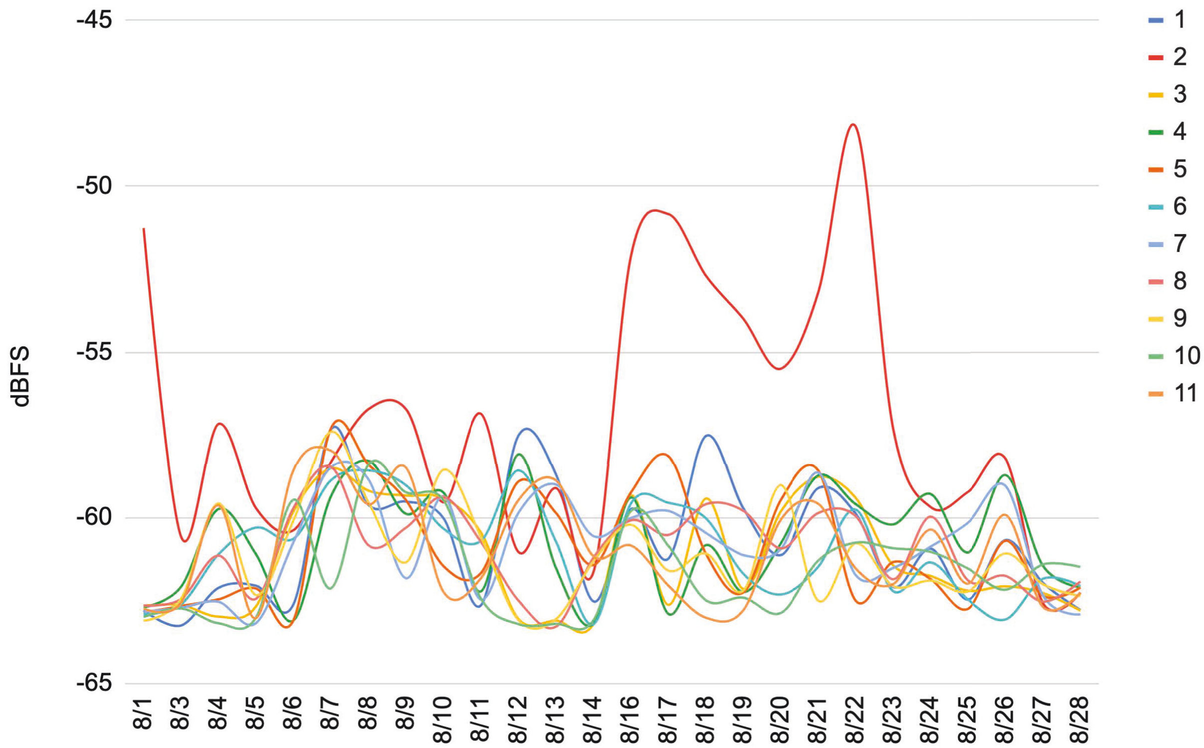

Fig. 3. Average power for each location over the first 4 weeks of August 2022

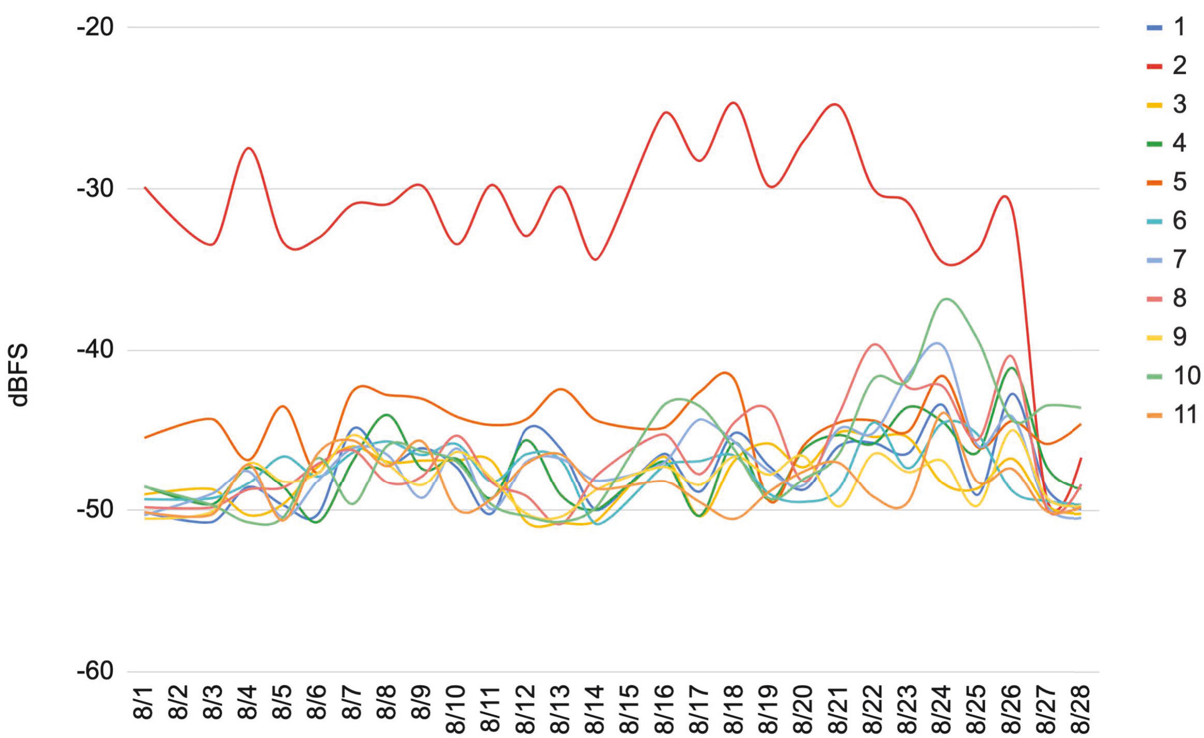

Fig. 4. Maximum power for each location over the first 4 weeks of August 2022

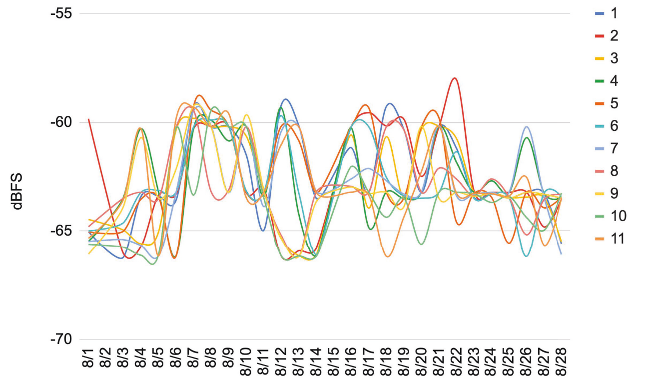

Fig. 5. Median power for each location over the first 4 weeks of August 2022

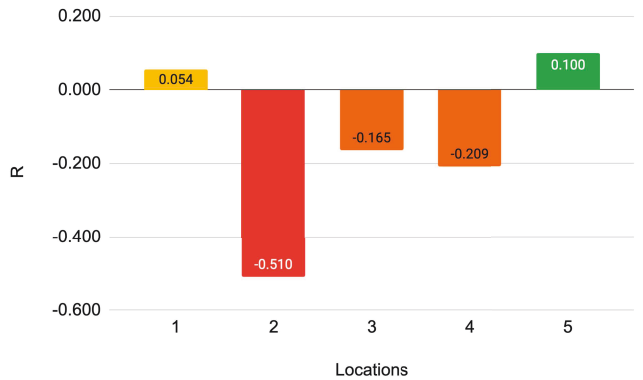

Fig. 6. Correlation of location and day of the week

	1	2	3	4	5	6	7	8	9	10	11
1	1	0.3	0.5	0.6	0.7	0.7	0.7	0.4	0.2	0.1	0.4
2	0.3	1	0.4	0.1	0.2	0.2	0.1	0.4	0.1	0.1	-0.1
3	0.5	0.4	1	0.4	0.4	0.5	0.4	0.8	0.6	0.6	0.3
4	0.6	0.1	0.4	1	0.5	0.4	0.5	0.2	0.3	0.3	0.4
5	0.7	0.2	0.4	0.5	1	0.6	0.7	0.3	0.3	0.2	0.5
6	0.7	0.2	0.5	0.4	0.6	1	0.3	0.4	0.3	0.4	0.4
7	0.7	0.1	0.4	0.5	0.7	0.3	1	0.4	0.3	0.3	0.6
8	0.4	0.4	0.8	0.2	0.3	0.4	0.4	1	0.7	0.5	0.2
9	0.2	0.1	0.6	0.3	0.3	0.3	0.3	0.7	1	0.3	0.4
10	0.1	0.1	0.6	0.3	0.2	0.4	0.3	0.5	0.3	1	0.2
11	0.4	-0.1	0.3	0.4	0.5	0.4	0.6	0.2	0.4	0.2	1

Fig. 7. Correlation Matrix

especially, are consistently higher inside the engineering center. The maximum values at location 6, the main University library, also show noticeably increased levels once classes were in session. Filtering the data for median power levels and thereby removing noise shows fairly consistent energy levels within a range of 5 dB at all locations, slightly fluctuating across different days.

While the data does not show the expected upward trend over the course of August, this could be attributed to the short duration of the data collection. A more frequent and longer term data collection at each location might be able to show a more noticeable trend. Still, even without a clear trend visible in the data, correlating each location with other locations and the day of the week, numbered from 1 to 7, showed a number of conclusive results. Location 2, the engineering center, shows a moderate negative correlation with the increasing day of the week. This could indicate, as would be expected, that more students are present in the engineering center during the week than on the weekend. A similar, but slightly weaker correlation can also be observed at location 10, the entrance to the C4C dining hall. Since not all students dining at the C4C live on campus, the amount of students dining on campus diminishes towards the end of the week, but to a lesser degree than general presence on campus, since some students might live close enough to campus to still rely on its dining hall.

Locations 5, 7, and 11 show a weak positive correlation. These locations include the outside of the stadium, which is part of a path to the campus' recreation center, the outside of the main dining hall, which is in front of a large open space, and the business field, a large open field. Many of these locations are either used for recreational purposes, which might occur more regularly on weekends, or in front of large open spaces that might have more activities planned on weekends, contributing to an increased correlation with weekends. Locations 3, 4, and 6 show a weak negative correlation, indicating less activity towards the weekend. These locations include the roundabout in front of the engineering center, the entrance to dormitories, and the main campus library's entrance. A common factor among these locations is that heavy foot traffic can be observed in these locations during the week as they belong to the main routes across campus.

Locations 1, 8, and 9 only show very weak either positive or negative correlation. Both Locations 1, the outside of the Discovery Learning Center, and Location 9, in front of administrative offices, are located in areas with generally little foot traffic. Conversely, Location 8 is located at a major crossing of foot traffic and bus stops on campus that has consistent foot traffic across the entire week. Due to the constant lack or the constant presence of traffic at these locations, the amount of energy recorded at these locations cannot be correlated with a time of the week.

Finally, correlating the energy at different locations with each other resulted in a generally, from weak to strong, positive correlations across the month of August with some exceptions. As expected, the change in power follows a general presence of students on campus. Students are not concentrated in a single location, meaning that energy increases or decreases across most locations. Interesting correlation coefficients include location 2, the engineering center, and location 11, the business field with a weak negative correlation. While this is only a weak correlation, it could be explained with the fact that fewer students will be outside during lunch hours than inside as they have lunch in the dining halls or the engineering center cafeteria. Additionally, the engineering center, which shows a consistently higher energy content, is only weakly correlated to most other locations since it has mostly consistent activity during the week. Very strong positive correlation can be found between locations 3 and 8, the engineering roundabout and the crossing from the University's main dining hall towards Farrand Field crossing 18th Street near a bus stop. Both locations have very dense foot traffic when classes are in session.

V. Conclusion

In this work, I/Q data was collected across the CU Boulder campus in 11 mostly outdoor locations during the same time of the day for 28 days. While the data does not show a clear positive energy trend on Wi-Fi channel 6 corresponding with increased campus activity, expected correlation could be established across days of the week and various locations. The results highlight the untapped potential of using SDRs, such as Ettus B200-minis, for monitoring and spectrum utilization measurements, which can enable longer term spectrum measurements in more diverse locations thanks to their comparatively low size, weight, power, and cost (SWaP-C). The growing emphasis on dynamic spectrum sharing in shared bands will increase the appeal of sensors with low SWaP-C for a variety of users and applications, including the monitoring the coexistence between active and passive users.

Future research can benchmark the use of low-cost SDRs for monitoring against data simultaneously collected by a reference spectrum analyzer to further emphasize advantages and disadvantages of using low SWaP-C sensors. Additionally, the limited range of observations can be addressed by expanding the observation window to cover complete 24 hour cycles as well as different seasons in order to identify diurnal and semester patterns. The SDR's host can furthermore be used to calculate and store only relevant statistics, reducing or potentially removing the need for data backhaul and permitting deployment in a larger variety of locations, achieving a wider spatial sampling coverage. Finally, a reduction in processing time on the host can be achieved by switching the code base to directly use the UHD Python API rather than GNU Radio, as well as developing custom FPGA images for deployment on USRPs.

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