Spectrum Analysis Using Semantic Models for Context

Vaishali Nagpure(✉), Stephanie Vaccaro, and Cynthia Hood

Illinois Institute of Technology, Chicago, IL 60616, USA
{vnagpure, svaccaro}@hawk.iit.edu, hood@iit.edu

Abstract. With the ever-increasing demand for spectrum to support wireless innovation, it is critical to understand the fine-grained characteristics of spectrum use in frequency, space and time to facilitate greater spectrum sharing. Contextual information is needed to analyze how the spectrum is being utilized and understand the drivers for spectrum use dynamics. Since human activity often drives spectrum use, understanding this activity can provide significant insight. Analysis of wideband spectrum is extremely time consuming as each band has unique characteristics, domain knowledge and usage drivers. Toward automated analysis, this paper proposes an approach to incorporate contextual information into the analysis utilizing semantic models to capture domain and human activity knowledge. This approach is illustrated through analysis of spectrum measurements of four frequencies licensed to the Chicago White Sox.

Keywords: Spectrum occupancy · Spectrum measurements · Semantic modeling · Land Mobile Radio

1 Introduction

Increased access to the radio frequency (RF) spectrum is critical to continued wireless innovation. Spectrum is an extremely valuable natural resource in high demand, yet there is limited understanding about how this resource is being used. Spectrum allocations and licenses provide information about who has the right to utilize the spectrum and how they may use it, but do not provide insight into actual usage. Spectrum measurements play a key role in understanding spectrum use providing information about spectrum utilization in space, frequency and time. In particular, spectrum occupancy measurement studies involve determining the percentage of time that a given frequency band or channel is utilized over a period of time in a given location. These studies can potentially inform spectrum policy and management decisions, and facilitate more efficient spectrum usage through sharing. It is clear that measurement efforts are critical, yet most spectrum measurement datasets appear to be used only by the group that collected them. This lack of sharing along with the expense and effort to collect your own measurements is an impediment to spectrum management research. Although there have been many different types of spectrum measurement campaigns and studies, the technical and regulatory communities struggle to extract the information they need from the existing studies and datasets.

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Given our long-term experience collecting spectrum measurements through the IIT Spectrum Observatory [1], we have witnessed first-hand many of the challenges associated with collecting, managing and sharing spectrum measurements. Spectrum measurements are highly complex spatiotemporal data sets that require very specialized domain knowledge to collect, analyze and interpret [2]. Wideband data (as collected at the IIT Spectrum Observatory) spans a large number of frequency bands and each frequency band has it's own unique domain knowledge including physical characteristics, potential transmitters, etc.

Analysis of wideband data begins with parsing the data into frequency bands based on how the spectrum has been allocated. The goal of this type of analysis is typically to determine who is using the spectrum (i.e. emitters) and how they are using it. Although there are bands that are well documented in terms of spectrum allocation (e.g. public safety), it is often challenging to go beyond high-level descriptions such as those found in [3] to determine how a particular band is being utilized in a given geographic area. It can be particularly difficult to get information on government transmitters and since large portions of the spectrum are allocated for either exclusive or shared government use, this is a significant void. In the United States, a subset of potential emitters can be found in the Federal Communication Commission (FCC) Licensee database [4], but the existence of a license in a particular area does not guarantee an active emitter.

One of the challenges of analyzing the data collected in these monitoring efforts is putting the measurements into proper context. Since analysis typically involves identifying both usual and unusual spectrum usage, this generally involves both understanding how the spectrum is used in the location being measured and identifying potential triggers for changes in usage. Frequently usage can be traced directly or indirectly to human activity. An understanding of the human activity that drives spectrum dynamics can facilitate deeper insights into spectrum usage.

To address these issues, our long-term research goal is to automate analysis of spectrum measurements. This paper describes an approach that utilizes semantic web-based models and tools for ingesting and utilizing domain and human activity information in machine-readable format. This information can provide the contextual information needed to analyze and understand how the spectrum is being utilized. This paper focuses on the analysis of frequency bands licensed to the Chicago White Sox, a professional baseball team that plays their home games at Guaranteed Rate Field. The main contribution of this paper is to lay the groundwork for automating spectrum analysis. This includes detailing the type of contextual information that is needed to analyze spectrum measurements, identifying machine readable sources for the contextual information, demonstrating how this information may be collected automatically, and using semantic web techniques to model domain knowledge and human activity.

The rest of the paper is organized as follows. Section 2 includes background information about the measurement system along with related work. The contextual information related to spectrum measurement and analysis is described in Sect. 3. Section 4 describes the statistical analysis of the measurements of the Chicago White Sox frequencies studied. The design and implementation of the semantic models is detailed in Sect. 5. The results are highlighted in Sect. 6 and conclusions and future work are discussed in Sect. 7.

2 Background and Related Work

2.1 Measurements

The IIT Spectrum Observatory (IITSO) has been monitoring the 30–6000 MHz radio spectrum of the city of Chicago since mid-2007 from its location on top of the 22 story Tower on IIT's Main campus on the south side of Chicago [1]. The IITSO uses energy detection sensing to capture measurements and has a resolution bandwidth of 3 kHz for all bands. This results in approximately 93 MB of data per day. This data has been used to provide a high-level view of the spectrum occupancy in Chicago [5], but there are limitations to wideband sensing.

In the Land Mobile Radio (LMR) bands where channel bandwidths are narrow (<30 kHz), short transmissions cannot be detected due to the high sweep time. To address this issue, an additional measurement system was deployed. This system measures a subset of the LMR bands utilizing a Tektronix RSA 306 spectrum analyzer. It enables capture of higher resolution data. The band plan and resolution bandwidth were configured as shown in Table 1. This results in approximately 16 GB of data per day.

Table 1. Band plan (Tektronix)

Band plan (MHz)	Resolution bandwidth
100–200	3 kHz
400–460	3 kHz
460–463	1 kHz
463–516	3 kHz
800–900	3 kHz

This paper focuses on the analysis of four frequency bands shown in Table 2. These frequencies have been licensed to the Chicago White Sox and the transmitter address specified in the FCC license database [4] corresponds with Guaranteed Rate Field. Guaranteed Rate Field is the home ballpark for the White Sox and is located approximately .4 miles away from the IIT Tower where the measurement systems are installed. The license database does not provide a description of usage, but this is available from RadioReference.com [6], a crowd sourced radio communications data provider. Radio Reference is utilized and maintained by amateur radio enthusiasts and provides a complete frequency database, trunked radio system information, along with FCC license data.

Table 2. Chicago White Sox frequencies studied

Frequency (MHz)	License	Description
461.2	WPLI617	Parking
462.05	WPXR683	Guest relations operations
464.675	WQDD864	Sportservice concessions
464.95	WPLL482	Medical, guest relations, premium seating

2.2 Related Work

A good survey of spectrum occupancy measurements is given in [7]. Spectrum studies have mainly taken place on the order of days [8, 9], weeks [10–12] months [13] and longer [5]. Globally, there have been a number of spectrum occupancy studies and spectrum surveys conducted over the last decade. Most of these studies are characterized by the fact that they typically collecting wideband data beginning at a few Hz and going up to a 3–5 GHz. These studies focused on spectrum occupancy and as a result have identified substantial opportunities for frequency reuse in many bands, particularly those currently assigned to legacy systems. Analyses have also shown occupancy trends over both short periods of time and seasonal variations occurring weekly and yearly [5].

Occupancy models are broadly classified as time-dimension models, frequency-dimension models, location-dimension models [14–16]. Given knowledge of a particular channel's behavior as described by a set of statistical models, prediction of channel occupancy is possible. These models are limited in their ability to characterize significant dynamics in how spectrum is used.

SpecInsight [12] is an intelligent wideband spectrum sensing and analysis system that learns the characteristics of the signals in each frequency band and adjusts the sensing parameters to maximize detection. SpecInsight classifies usage patterns based on frequency and time attributes and maintains statistics on the timing of pattern occurrences. A detailed overview for the conventional narrowband and wideband spectrum sensing approaches are given in [17] which tackles the trade-off between system performance and practical system implementations very well. In [18], semantic modeling is used to capture configuration, domain knowledge and other potentially relevant information in a way that it can be fused with measurements for analysis and in particular can provide labels for the spectrum data.

3 Contextual Information

The Cambridge English dictionary [19] defines context as "the situation within which something exists or happens, and that can help explain it." Context is necessary to understand how to explain the results of quantitative analysis of spectrum measurements. Spectrum use is a function of frequency, space and time. For a particular location, given how the spectrum is licensed and allocated and how it has been measured, are the results consistent with what is expected? For many bands including LMR, spectrum use is driven by human activity so it is possible to gain additional insight through this lens. Going beyond statistical characterizations to understand how the spectrum is used and when it might or might not be available for sharing is critical for spectrum sharing and dynamic spectrum access.

In this paper, we analyze spectrum measurements of four different frequencies collected at the IIT Tower over a one year period, January 2018–December 2018. We focus on the domain context which includes how the spectrum has been licensed and allocated for use, and the human activity context which includes the drivers of spectrum use. We know that organizational conventions and protocols typically govern how human activity drives spectrum use in the LMR bands. Context is usually included in the narrative part of the analysis. This research proposes to model the contextual information to shift it from being part of the narrative to correlating context with quantitative results with a long-term goal of doing this automatically. As a substantive step in this direction, the machine consumable sources for context information are identified and modeled.

3.1 Domain Context

The domain is considered to be any relevant information about the specific frequency band under study. This includes who the frequency has been licensed to as well as how the licensee allocates the frequency for use in the licensee organization. It also includes characterization and location of the transmitters as specified in the license. In the United States, the FCC licenses spectrum for commercial use. Figure 1 shows part of the FCC database entry for the 461.2 MHz spectrum that has been licensed to the Chicago White Sox. It should be noted that the 461.2 MHz frequency along with other 3 frequencies studied in this paper have been licensed to several entities in the Chicago area, so geographic sharing is already being done. Given the proximity of the IIT Tower to the White Sox ballpark, the spectrum measurements sensed at the IIT Tower are attributed to the White Sox use.

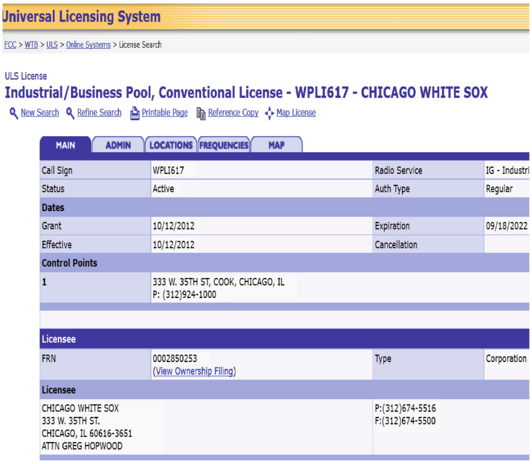
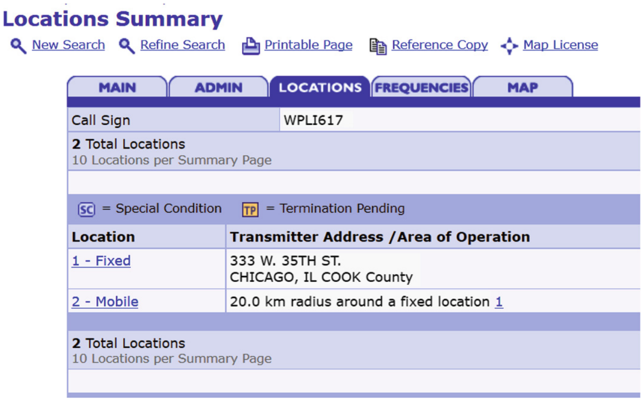


Fig. 1 FCC database entry for White Sox license for 461.2 MHz

Figure 2 shows another part of the database entry with the location of the transmitters. There is a fixed antenna that is used for mobile device communication. The antenna details provided in the license include the emission designator, a code that indicates the frequency bandwidth, modulation type and nature and information type. The emission designator for this antenna is 20K0F3E. Figure 3 shows the decoding of 20K0F3E to indicate a 20 kHz FM signal for analog voice.



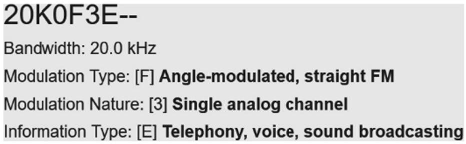
Locations Summary

New Search | Refine Search | Printable Page | Reference Copy | Map License

MAIN | ADMIN | LOCATIONS | FREQUENCIES | MAP

Call Sign	WPLI617
2 Total Locations 10 Locations per Summary Page	
SC = Special Condition	TP = Termination Pending
Location	**Transmitter Address /Area of Operation**
1 - Fixed	333 W. 35TH ST. CHICAGO, IL COOK County
2 - Mobile	20.0 km radius around a fixed location 1
2 Total Locations 10 Locations per Summary Page	

Fig. 2 White Sox 461.2 MHz Transmitter details



20K0F3E--

Bandwidth: 20.0 kHz

Modulation Type: [F] **Angle-modulated, straight FM**

Modulation Nature: [3] **Single analog channel**

Information Type: [E] **Telephony, voice, sound broadcasting**

Fig. 3 Emission designator details for 20K0F3E [20]

The FCC database can be used to determine what frequencies the White Sox have licensed, but it doesn't provide information on how these frequencies are being used. Additional information on usage can be obtained from RadioReference.com. RadioReference.com is a crowdsourced wiki that is maintained by radio enthusiasts, many of whom have experience in the field and bring that knowledge into the wiki. RadioReference provides valuable information on how frequencies are being used and the information is logically grouped by the function, organization or venue. For example, RadioReference provides information about how the various sports teams utilized the spectrum they've licensed. Figure 4 shows the RadioReference information about the Chicago White Sox frequencies [21]. There are 16 total frequencies included along with other information including a general description of the functions the frequencies are used for. Fifteen of the frequencies are active and one is deprecated. The report notes that the frequencies were confirmed to be active for the 2016 season and we cross-verified the information with the FCC database to ensure that the frequencies were indeed still active. There is always a concern about the reliability of the sources and correctness of the information gathered. This is an issue for further study, but not one that is unique to spectrum analysis.

Chicago White Sox

- CARMA Chicago 2010 White Sox frequency report

Conventional frequencies for Guaranteed Rate Field:

Note: these frequencies were confirmed still active during the 2016 season.

Frequency	Input	License	Type	Tone	Alpha Tag	Description	Mode	Tag
463.72500	468.72500	WPLL482	RM		CWS Security	Security & Safety		Security
461.20000	466.20000	WPLI617	RM		CWS Parking	Parking		Business
464.67500	469.67500	WQDD864	RM	223 DPL	CWS Concessn	Sportservice - Concessions		Business
462.05000	467.05000	WPXR683	RM		CWS GstRelations	Guest Relations		Business
464.28750			M	67.0 PL	CWS Ticketng	Ticketing		Business
464.81250			M	466 DPL	CWS Food	Food		Business
464.51250			M	226 DPL	CWS Food	Food		Business
464.75000	469.75000		RM	67.0 PL	CWS Sec old	Security - Main (old)		Deprecated
461.45000	466.45000	WQAU450	RM	67.0 PL	CWS Security	Former Security (expired 2014)		Security
464.55000			M	047 DPL	CWS Ops46455	Operations		Business
456.56250			M	051 DPL	CWS 456.5625	Food-Beverage service		Business
464.83750			M	051 DPL	CWS Janitor	Janitorial		Business
468.66250		WQDD864	M	223 DPL	CWS Concessn	Sportservice - Concessions		Business
463.72500	468.72500	WPLL482	RM		CWS Trades	Trades		Business
464.95000	469.95000	WPLL482	RM		CWS Medical	Medical		Business
464.95000	469.95000	WPLL482	RM		CWS PremSeating	Guest Relations / Premium Seating		Business

Fig. 4 Chicago White Sox frequency report from RadioReference.com

3.2 Human Activity Context

People drive the spectrum use in the LMR bands, including those frequencies licensed to the White Sox. More specifically, the White Sox spectral activity is centered around Guaranteed Rate Field. This is where the baseball games take place, but it also includes offices for day-to-day operations and space for special events. Special events may be public non-baseball events [22] or private events such as weddings [23]. The spectrum is used to support the functions necessary to support the people that come to Guaranteed Rate Field. The specific functions that correspond to the frequencies that we are studying include parking, concessions, guest relations and medical.

Although the White Sox organization operates year round. Baseball is seasonal, with the major league baseball season running from April to October. This means that we would expect much more human activity during the season, especially during game days. This activity at the ballpark includes seasonal workers along with fans who come to watch the games. During the 2018 season, the average attendance at White Sox home games was 20,110 [24].

There is a wealth of information available about each baseball game online. The schedules for each season are published well ahead of the season start. After each game, detailed information about the game including start time, end time, attendance, scoring and any delays is available at Baseball-Reference.com [24]. This study utilized [24] along with a ticket platform, SeatGeek [25]. SeatGeek has an Application Programming Interface (API) so it was easily queryable and reliably provided the planned game days and times. This information had to be verified with the game reports at Baseball-Reference.com to identify games that were rained out or delayed.

4 Statistical Analysis of Spectrum Data

One year of data was analyzed. The spectral occupancy was estimated based on the threshold method. Occupancy thresholds were determined by estimating the noise floor at each frequency. A frequency was considered to be occupied if the noise floor threshold was exceeded. The occupancy was first estimated on an hourly basis. The hourly occupancies were aggregated to provide daily occupancy estimates and then these were further aggregated to provide monthly and yearly estimates. The average occupancy of the four frequencies under study for all of 2018 is shown in Fig. 5.

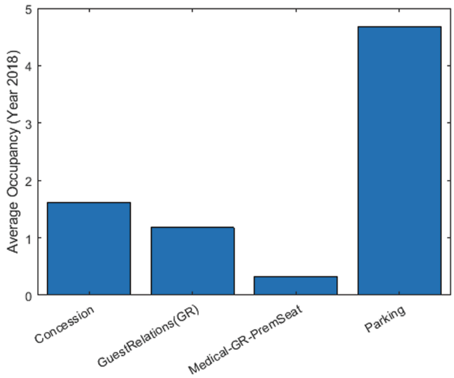


Fig. 5 Average occupancy for the year 2018

Figure 5 shows that there is activity on these frequencies, but they are not highly occupied. Thus there is potential for further sharing beyond the geographic sharing we mentioned earlier. The question is how and when the frequencies are being used.

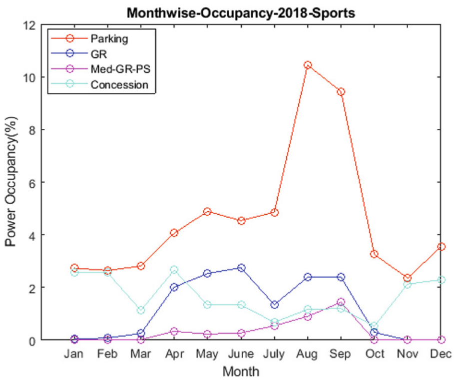


Fig. 6 Month wise occupancy

To get insight into this, we look at the monthly occupancy of each frequency. Figure 6 illustrates the seasonal trends that correspond to baseball season. Three of the four frequencies show increased occupancy during the baseball season. Clearly, further exploration is warranted. To do this, it is necessary to know when events (e.g. games) are taking place at the ballpark.

5 Semantic Models

Semantics can be used to model information in a machine-consumable way that enables reasoning. A key piece of a system utilizing semantics is the knowledge base. Figure 7 shows the current state of the knowledge base building blocks in our prototype application.

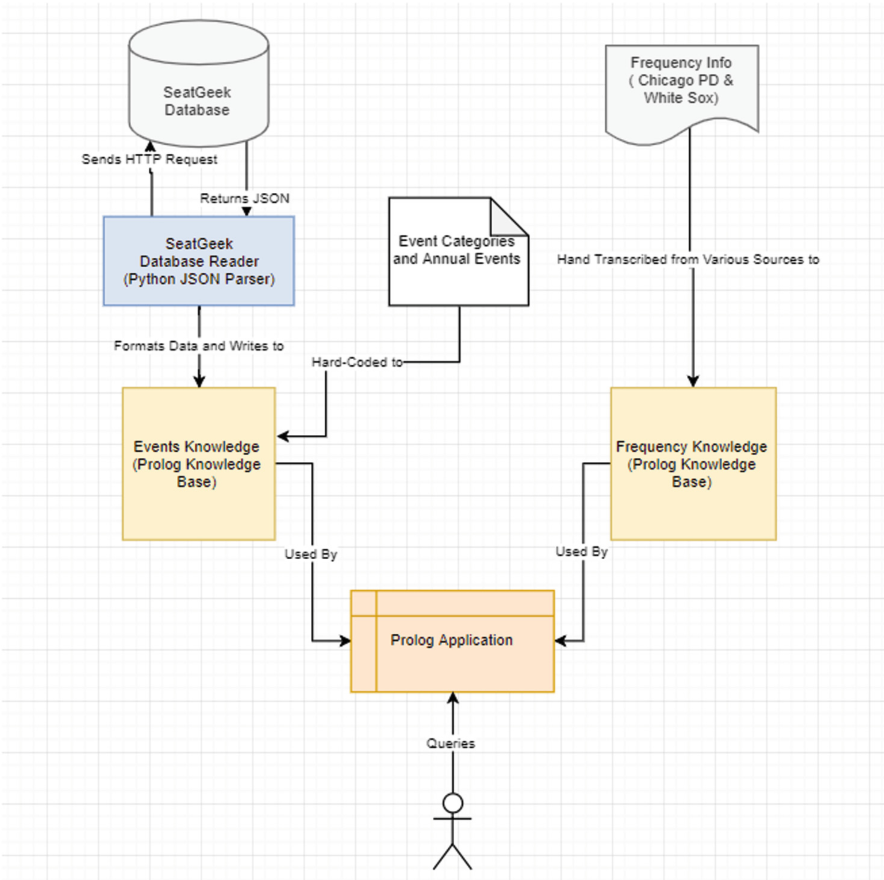


Fig. 7 Knowledge base building blocks

A prototype application was developed to match the frequency occupancy data gathered from our spectrum observatory with frequency specific knowledge and events going on in and around Chicago including White Sox games. In order to do this, Python's http database request abilities and Prolog's knowledge representation and reasoning capabilities were utilized.

Python is used to connect to and query SeatGeek's [25] event database via http request. In response to the query, a JSON file is returned which is then parsed and formatted into prolog readable text. Most of the application including the knowledge base is developed in Prolog. The Prolog knowledge base is split into two files, one for spectrum domain knowledge and one for event knowledge. The spectrum domain knowledge includes models and data for Chicago public safety frequencies, both zone and citywide, as well as White Sox specific frequencies utilized during White Sox games. The human activity domain knowledge captured in this prototype include the models and data for annual holidays, and events pulled from the SeatGeek database. These two knowledge bases are then queried using the main Prolog application.

The knowledge bases can be queried for two types of information: event by date information and frequency information as shown in Fig. 8. Using check Events (Month, Day, Year), a user can give a date in the form of month, day, and year and the knowledge base returns all events occurring on that specified date. Frequencies that might be associated with the event are also returned. In the example query shown in Fig. 8, the Chicago White Sox home game against the Detroit Tigers is identified and the associated White Sox frequencies are identified. Another event scheduled for the same day, Chicago Gourmet is also identified. The frequencies identified for this event include the Chicago Police Department channel for the Zone where this event is located (Zone 4) and the citywide channels used for events.

```
?- checkEvents('September',29,2019).
Got Events: [Detroit Tigers at Chicago White Sox,Chicago Gourmet - Chicago]

**********************************
Event Found: Detroit Tigers at Chicago White Sox
Event Type: outdoor
Time: 2:10pm

Check Channels:
Zones: zone_13
Citywide: citywide_5 | citywide_3 | citywide_1
----------------------------------
This is a White Sox Game.
The following frequencies are also in use:
----------------------------------
Frequency: 461.2
Channel Name: parking
Uses: [parking]
Frequency: 464.675
Channel Name: sportservice_concessions
Uses: [concessions]
Frequency: 462.05
Channel Name: guest_relations
Uses: [guest_relations]
Frequency: 464.95
Channel Name: medical
Uses: [medical]
Frequency: 464.95
Channel Name: guest_relations_premium_seating
Uses: [guest_relations,premium_seating]
**********************************
Event Found: Chicago Gourmet - Chicago
Event Type: outdoor
Time: 12:00pm

Check Channels:
Zones: zone_4
Citywide: citywide_5 | citywide_3 | citywide_1
**********************************
true.
```

Fig. 8 Example check events query to knowledge base

Using the command find Freq (INFO), the user can query for frequency information based on a given frequency, frequency name, or frequency usage. Example queries are shown in Fig. 9. The prototype returns all frequency information for a given match in the knowledge base. Using this prototype, we are able to associate human activity with the frequencies that might be impacted, thereby providing context to facilitate analysis of the actual measurements. This can be done with either a date or a frequency as a starting point.

```
?- findFreq(460.125).
Frequency: 460.125
Channel Name: citywide_1
Uses: [major accident,traffic,gangs,public housing,cta]
true.

?- findFreq('wanted flashes').
Frequency: 460.275
Channel Name: citywide_3
Use: [wanted flashes,maintenance,films,admin]
true.

?- findFreq(zone_5).
Frequency: 460.5
Channel Name: zone_5
Uses: [2,21]
true.

?- findFreq(parking).
Frequency: 461.2
Channel Name: parking
Uses: [parking]
true.
```

Fig. 9 Example find Freq queries to knowledge base

6 Results

The White Sox home games were extracted from the knowledge base describe above so the game days and non-game days could be compared. Figure 10 shows an example of gameday occupancy throughout the day and Fig. 10 shows an example of non-game day occupancy.

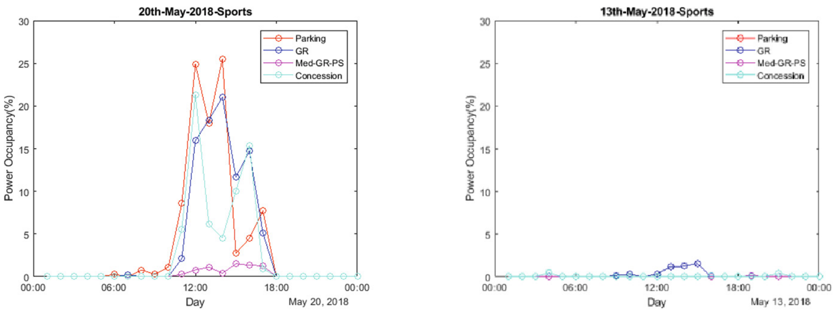


Fig. 10 Occupancy for home game day (left) and non-game day (right)

Figure 10 shows the occupancy of the four frequencies under study on a home gameday. The game details are as follows:

- Date: Saturday, May 20, 2018
- Start Time: 1:10 p.m. CST
- Attendance: 16,829
- Game Duration: 2:28 [24].

Comparison of Fig. 10 illustrates the occupancy increase during game time which is expected. Also, as expected the occupancy increases on the parking channel before the game starts and it is followed by increases on the other channels. This is an example of how human protocols drives spectrum occupancy. It is quite obvious that spectral activity around the parking function will start early as compared to the frequencies used for other functions which become more active once the fans enter the park. Figure 10 shows the non-game day occupancy charts for Sunday, 13th May 2018. There is little spectral activity on a non-gameday, weekend day. The maximum occupancy over the entire day is less than 2% for all four frequencies.

This study has shown that a significant portion of the occupancy on the four channels studied can be attributed to White Sox home game usage. Given the details of the game, the usage is reasonably predictable. We have also discovered that the usage cannot be completely attributed to White Sox games or even other public events. Further research is necessary to determine the patterns of both game-day and non-game day usage. It appears that there is significant opportunity to share this spectrum, particularly on non-game days. Out of four channels, we can see that Medical-Premium Seating-Guest Relations channel is the least utilized, having the highest availability for sharing.

7 Conclusion and Future Work

This paper describes the challenges of spectrum analysis and motivates the need for more in-depth analysis and fine-grained modeling for the purpose of spectrum sharing. Analysis requires a substantial amount of contextual information that includes domain knowledge along with information about human activities. Contextual information can be derived from a variety of different information sources and used to build semantic models that can be used to implement a knowledge base. The goal is to have machine-consumable information that can be used to build and populate semantic models that can be reasoned over.

This paper focuses on the White Sox channels used in Chicago. Semantic models were developed and coded in SWI-Prolog and Python to get detailed insights about events at Guaranteed Rate Field, especially White Sox home gamedays. Some data was pulled automatically through the SeatGeek API, whereas other data was manually entered from online sources. The goal is to automatically pull other relevant information and methods to do this are being investigated. These event (gameday) models allowed us to classify the data into gamedays and non-gamedays for analysis. This is an important step toward automating the analysis.

Ongoing work involves use of machine learning techniques for classifying the data to develop models and also to detect anomalies. As shown, even relatively straightforward cases like the ones we've explored in this paper are not simple and require significant information to get an accurate understanding of spectrum. Spectrum behavior is challenging to interpret and prediction of usage is driven by many factors such as planned and unplanned events, weather and human protocols. Further development of the semantic models is needed to capture the many different information sources as well as the correlations across time and frequency bands.

This research begins to lay the foundation for intelligent spectrum measurement and monitoring systems that reason over information from a variety of sources, analyze data and situations, and make decisions. The automatic generation of domain, activity and analysis-based metadata opens new avenues for more comprehensive and timely analysis of spectrum measurement data.

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