IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received September 11, 2016, accepted October 4, 2016, date of current version November 8, 2016.

Digital Object Identifier 10.1109/ACCESS.2016.2616113

Analysis of the FM Radio Spectrum for Secondary Licensing of Low-Power Short-Range Cognitive Internet of Things Devices

DEREK T. OTERMAT, (Student Member, IEEE), IVICA KOSTANIC, (Member, IEEE), AND CARLOS E. OTERO, (Senior Member, IEEE)
Electrical and Computer Engineering Department, Florida Institute of Technology, Melbourne, FL 32901, USA
Corresponding author: D. T. Otermat (dotermat2008@my.fit.edu)

ABSTRACT The analysis presented in this paper indicates that the FM radio spectrum is underutilized in the areas of the continental United States that have a population of 100 000 or less. These locations have vacant FM radio spectrum of at least 13 MHz with sufficient spectrum spacing between adjacent FM radio channels. The spectrum spacing provides the required bandwidth for data transmission and provides enough bandwidth to minimize interference introduced by neighboring predicted and unpredicted FM radio stations and other low-power short-range Internet of Thing (IoT) devices. To ensure that low-power short-range IoT devices maintain reliable communications vacant radio spectrum, such as the FM radio spectrum in these areas, will need to be used through cognitive radio.

INDEX TERMS Internet of things, cognitive radio, FM radio.

I. INTRODUCTION

The rapid growth of the Internet of Things (IoT) has ushered in a new class of low-power short-range wireless devices that require radio spectrum for the exchange of information. The rapid growth of IoT is placing an extreme demand on the radio spectrum. To overcome this demand, low-power short-range IoT devices need to embrace new and innovative technologies for the exchange of information. One such promising technology is Cognitive Radio (CR) [1]. CR enables a device to adjust its transmission parameters, such as frequency and transmit power, to capitalize on the conditions of the vacant radio spectrum. IoT devices that employ CR technologies, Cognitive IoT (CIoT) devices, would assume the role of a secondary user with respect to the primary license holder of the vacant spectrum. Secondary use, or secondary licensing, of vacant spectrum needs to be conducted in a manner that minimizes interference to the primary user.

This paper presents an analysis of the FM radio spectrum across the continental United States. The data are analyzed to determine which locations provide unallocated FM radio spectrum than can be used for the secondary licensing of low-power short-range CIoT devices. The analysis employs a novel six-step algorithm to determine which FM radio stations have protected coverage at a particular location. The accuracy of the six-step algorithm is validated by measurements of the FM radio spectrum occupancy at five select locations.

The preliminary research presented in [2] analyzed the FM radio spectrum at one location to determine if further research is warranted. This paper analyzes the FM radio spectrum at 195,280 locations across the continental United States. The four-step algorithm used in [2] was developed to be executed manually per location and is not adequate for execution on a large number of locations. Therefore, to accommodate a large scale analysis across the continental United States, a novel six-step algorithm was developed.

This paper is organized as follows: Section II provides a review of the literature and identifies how it fails to analyze the FM radio spectrum for low-power short-range CIoT devices; Section III describes the algorithm used to quantify the unallocated FM radio spectrum; Section IV presents the spectral measurements conducted in the FM radio spectrum that validate the algorithm; Section V showcases the maps that quantify the number of FM radio stations and unallocated FM radio spectrum and discusses the potential CIoT bit rates; Section VI concludes the paper.

II. LITERATURE REVIEW

With exception to [2], no research has been conducted on using the FM radio spectrum for secondary licensing of CIoT devices.

A. COGNITIVE IOT DEVICE RESEARCH

The author of [3] discusses the research directions for the IoT. The first research topic that the author addresses is the massive growth of IoT devices and proceeds to predict that at the current rate of smart device deployment, trillions of things will be on the Internet [3]. This rate of IoT device deployment will place an overwhelming demand on the radio spectrum. To counteract this, it is imperative that CR be implemented in IoT devices to ensure the reliable transmission of information. Furthermore, various portions of the spectrum, such as the FM radio spectrum, will need to be analyzed for the viability of secondary licensing through CR.

The authors of [4] compare the performance of three IoT deployment patterns when they are used with CR. The three widely used deployment patterns are Square Lattice (SL), Triangle Lattice (TL), and Hexagon Lattice (HL) [4]. The current growth trend of IoT devices is causing dense device distributions for deployment patterns [4]. Dense distributions are causing transmission conflicts and poor device energy efficiency [4]. To alleviate the dense distributions CR can be implemented in a spectrum band that can accommodate the growing number of IoT devices. The FM radio spectrum seems to be an excellent candidate.

The authors of [5] identify spectrum scarcity, interference, and coverage as major challenges that Machine to Machine (M2M) IoT devices are confronted with. Spectrum scarcity is caused by an increasing number of M2M IoT devices. If secondary licensing of IoT devices were permitted in vacant FM radio spectrum, the spectrum scarcity would be reduced. Interference between M2M IoT devices is related to the spectrum scarcity issue. The current licensing scheme is forcing M2M IoT devices to operate in congested unlicensed spectrum bands such as the Industrial, Scientific, and Medical (ISM) band. If secondary licensing were permitted, M2M IoT devices could transmit on the licensed spectrum bands on a non-interference basis, alleviating the interference. Depending on where the M2M IoT devices are physically located, access to unlicensed spectrum is not guaranteed which can limit the device's communications coverage. For example, in medical applications non-medical related IoT devices may be restricted from accessing the ISM band in medical facilities. Having access to vacant spectrum, such as vacant FM radio spectrum, would alleviate the dependence on the unlicensed ISM band and improve the devices coverage.

The authors of [6] discuss M2M IoT devices and their potential for forming a smart grid. In this capacity, M2M IoT devices could facilitate smart grids for Home Multimedia Distribution, Intelligent Transportation, Healthcare, and Smart Power applications [6]. Two key technical challenges for M2M IoT devices in smart grid applications are the massive number of M2M IoT devices and device interference [6]. The massive number of M2M IoT devices is a problem that is prevalent in all IoT applications. The massive number of M2M IoT devices leads to the issue of spectrum scarcity and can be mitigated via secondary licensing of vacant spectrum bands through CR. The challenge of interference amongst M2M IoT devices will be mitigated with the use of CR.

The authors of [3]–[6] substantiate the importance of employing CR in IoT and recognize that the most challenging issue for IoT is the increasing number of devices. To ensure IoT devices are able to maintain communications, CR technology must be employed to utilize vacant spectrum, such as vacant FM radio spectrum.

B. TV WHITE SPACE RESEARCH

One portion of the radio spectrum that has the attention of academia and industry is the former analog TV spectrum. The transition from analog to digital TV broadcasting has left much of the analog TV spectrum vacant. This vacant spectrum is termed TV White Space (TVWS). The success of secondary licensing in TVWS is crucial because it will set precedence and foster further research of underutilized areas of the radio spectrum, such as vacant FM radio spectrum. The authors of [7], [8] discuss the fundamental aspects of defining, using, and regulating TVWS and stress the importance of mitigating interference to the primary users of TVWS. The primary users of TVWS are Program Making and Special Event (PMSE) users e.g. wireless microphones [8]. To mitigate interference to PMSE users, two access control mechanisms are discussed; geolocation databases and spectrum sensing. White Space Devices (WSD) using TVWS send their respective geographic locations and device characteristics to a geolocation database [8]. Using this information, the geolocation database will reply back to the WSD with a list of permissible frequencies [8]. The second access control mechanism, spectrum sensing, is the ability of a WSD to autonomously detect the existence of a primary user using a detection algorithm [8]. Discussing these spectrum access control mechanisms is crucial because these methodologies can be used to facilitate and control access to vacant FM radio spectrum.

The literature review highlights the need for cognitive solutions that can help mitigate the issues caused by the rapid growth of low-power short-range IoT devices. The literature review also presents the precedence set by the TVWS research for using underutilized spectrum for CR. Therefore, there is a need to employ CR with IoT devices in vacant spectrum. Having low-power short-range CIoT devices use the vacant FM radio spectrum will enable efficient deployments of IoT devices and support the anticipated future growth of IoT.

III. FM RADIO SPECTRUM ANALYSIS ALGORITHM

The six-step iterative algorithm that calculates which FM radio stations have protected coverage in a particular area was developed adhering to the rules and regulations governed by the Federal Communications Commission (FCC) Title 47, Chapter 1, Subchapter C, Part 73, Subpart B – FM Broadcast Stations. The algorithm described in Fig. 1 is executed on a given coordinate referred to as the Coordinate Under Analysis (CUA). The algorithm consists of the following

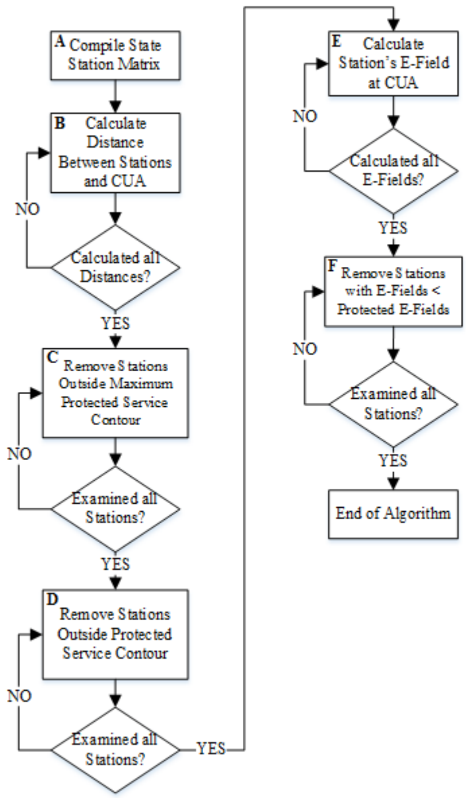

FIGURE 1. Flow diagram of the six-step algorithm used to determine which FM radio stations service a particular latitude and longitude coordinate.

six steps: (A) generate the state station file containing the stations located in the CUA's state and all neighboring states, (B) calculate the distance from each station in the state station file to the CUA, (C) remove the stations with distances to the CUA outside the maximum protected service contour, (D) remove the stations with distances to the CUA outside the protected service contour for each station class, (E) calculate each station's electric field strength at the CUA using a computational form of the F(50,50) field strength contour chart and each station's Effective Radiated Power (ERP) and Height Above Average Terrain (HAAT) [9], and (F) remove the stations with electric field strengths less than the protected electric field strength for each station class.

A. GENERATE STATE STATION FILE

The first step of the algorithm generates the state station file from the list obtained from the FCC that contains 37,589 FM radio stations that reside in the United States and the adjacent states in Mexico and Canada. The list was divided into forty-nine individual files representing the forty-eight continental states and Washington, D.C. Each state station file contains the FM radio stations for that respective state and the adjacent states, including those states in Mexico and Canada. For example, the California state station file contains FM radio stations residing in California, Oregon, Nevada, Arizona, Baja California (Mexico), and Sonora (Mexico).

The list of FM radio stations was divided into forty-nine state files for three reasons. First, the calculated FM radio station data were analyzed on a state-by-state basis. This approach mitigated time consuming re-computation of a single large data file versus smaller data files, in the event that unexpected results were observed. Second, executing the calculations on a state-by-state basis, in lieu of the entire United States at once, significantly reduced the computation processing time. The computation time was significantly reduced because the time required to perform the distance calculations between the CUA and the smaller number of FM radio stations in each of the forty-nine individual state files is significantly less than time required to perform the distance calculations between the CUA and all of the FM stations in one large file. Third, if any of the forty-nine station state files containing the calculated FM radio station data were to become corrupt, recovering data of a few small files, versus one large file, is less of an impact.

B. CALCULATE STATION DISTANCES TO CUA

The second step of the algorithm iteratively calculates the distance of each FM radio station in the state station file to the CUA using the Haversine equation set (1) [10].

$$\begin{aligned} lon_{\Delta} &= lon_2 - lon_1 \\ lat_{\Delta} &= lat_2 - lat_1 \\ a &= \sin(lat_{\Delta}/2)^2 + \cos(lat_1)\cos(lat_2)\sin(lon_{\Delta}/2)^2 \\ c &= 2a\tan 2(\sqrt{a}, \sqrt{1-a}) \\ d &= Rc \end{aligned} \tag{1}$$

In (1) the station's latitude and longitude are represented by lat_1 and lon_1, respectively and the latitude and longitude of the CUA are represented by lat_2 andlon_2, respectively. The radius of the Earth, R, is approximated as 6378.1 km.

C. REMOVE STATIONS OUTSIDE MAXIMUM PROTECTED SERVICE CONTOUR

The third step of the algorithm iteratively removes the FM radio stations with a distance to the CUA greater than 91.8 km [11]. No FM radio station, regardless of the station class, is guaranteed protected service outside this maximum protected service contour. As evident in Table I, 91.8 km corresponds to the protected service contour of class C stations.

D. REMOVE STATIONS OUTSIDE PROTECTED SERVICE CONTOUR

The fourth step of the algorithm iteratively uses the distance values computed in the second step of the algorithm to remove the FM radio stations with distances to the CUA greater than the values stated in Table I for each radio station class. For example, if a class C3 FM radio station has a distance of 42.1 km to the CUA, the station is removed. This evaluation is performed for the remaining FM radio stations. It is important to note class D FM radio stations are omitted during this step as there is no defined protected service contour for this class. Class D stations are evaluated during the last step of the algorithm.

TABLE 1. FM station classes and service contour [2].

Station Class	Maximum		Protected		Protected Contour [km]
	ERP [kW]	*HAAT [m]*	*dBu*	*mV/m*	
A	6.0	100.0	60.0	1.0	28.3
B1	25.0	100.0	57.0	0.7	44.7
B	50.0	150.0	54.0	0.5	65.1
C3	25.0	100.0	60.0	1.0	39.1
C2	50.0	150.0	60.0	1.0	52.2
C1	100.0	299.0	60.0	1.0	72.3
C0	100.0	450.0	60.0	1.0	83.4
C	100.0	600.0	60.0	1.0	91.8
L1	0.1	30.0	60.0	1.0	5.6
L2	0.01	30	60.0	1.0	3.2
D	0.25	N/A	60.0	1.0	N/A

E. CALCULATE FM RADIO STATIONS FIELD STRENGTH AT CUA

The fifth step of the algorithm iteratively calculates each FM radio station's electric field strength received at the CUA and compares it to the electric field strength values in Table I. For a specified distance, the electric field strength of a station is calculated using the F(50,50) field strength contour chart [12]. The F(50,50) contour chart provides field strengths occurring at 50% of the receivers 50% of the time [12]. Using the F(50,50) contour chart to determine the field strengths for this analysis is impractical therefore, the computational form of the F(50,50) provided by [9] is used. The model approximates the electrical field strength, received power, and median path loss [9]. To determine the electric field strength the following calculations are required.

a) The value of the path loss exponent n is calculated using a polynomial model of the fourth degree:

$$n = \sum_{i=0}^{4} \sum_{j=0}^{4} b_{ij} h^i d^j \tag{2}$$

Where the fourth degree polynomial coefficients b_{ij} are defined in [9] and h, in feet, and d, in miles, represent the antenna height and distance between the FM radio stations and the coordinate under analysis, respectively.

b) Once n has been calculated using (2), the path loss is calculated using:

$$L = 10n \log_{10}(d) + 20 \log_{10}(4\pi/\lambda) \text{ dB} \tag{3}$$

Where λ is the wavelength in meters.

c) After the path loss has been calculated using (3), the isotropic received power is calculated using:

$$P_{iso} = P_{rad} - L \text{ dBW} \tag{4}$$

Where P_{rad} is the FM radio station's ERP in dBW.

d) Lastly, the electric field strength is calculated using:

$$E = \pi/\lambda \sqrt{480 \times 10^{\frac{P_{iso}}{10}}} \text{ V/m} \tag{5}$$

After the electric field strength has been calculated it is converted to units of dBu for comparison against the electric field strength values, for each station class, in Table I.

F. REMOVE STATIONS WITH FIELD STRENGTHS LESS THAN PROTECTED FIELD STRENGTHS

The last step of the algorithm iteratively uses the electric field strengths computed in the previous step of the algorithm to remove the stations with electric field strengths less than the strengths stated in Table I for each radio station class. After all field strengths for each station has been evaluated, the stations that have not been removed during any steps in the algorithm have protected coverage at the CUA.

IV. FM RADIO SPECTRUM MEASUREMENTS

Prior to quantifying the unallocated FM radio spectrum across the continental United States, it is important to validate the algorithm presented in the preceding section. To validate the algorithm, measurements at five locations were conducted.

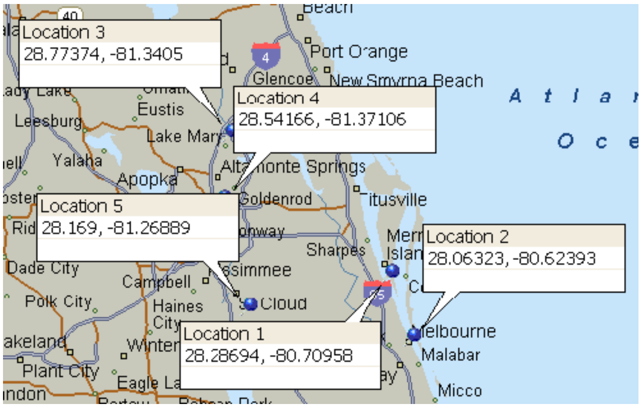

FIGURE 2. The latitude and longitude coordinates of the five locations where measurements of the FM radio spectrum were conducted.

A. MEASUREMENT LOCATIONS

The five measurement locations, presented in Fig. 2, were chosen to represent various population distributions. The first location is in Rockledge, Florida. Rockledge has a population of 24,926 [13]. The second location is the Florida Institute of Technology (FIT) Olin Engineering Complex, located in the Melbourne-Palm Bay, Florida area which has a population of 76,068 [13]. This location is also the location analyzed in [2] therefore, these measurements will verify that analysis. The third location is in Lake Mary, Florida which is a suburb of Orlando, Florida. Lake Mary has a population of 13,822 [13]. The fourth location is located in downtown Orlando. Orlando has a population of 238,300 [13]. The fifth location in a rural area outside of St. Cloud, Florida. St. Cloud has a population of 35,183 [13].

B. MEASUREMENT HARDWARE

The FM radio spectrum measurements were made using the Diamond D-130NJ antenna, reference Fig. 3, and

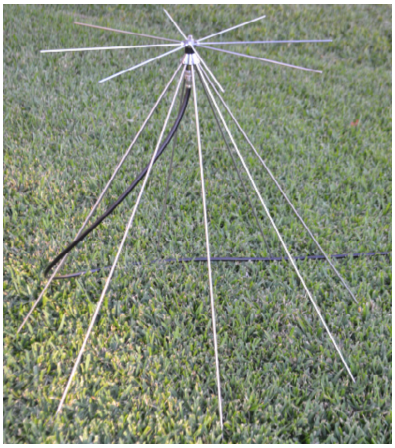

FIGURE 3. **The Diamond D-130NJ antenna is a wideband discone antenna that has a nominal gain of 2 dBi and an operating bandwidth of 25 MHz to 1300 MHz.**

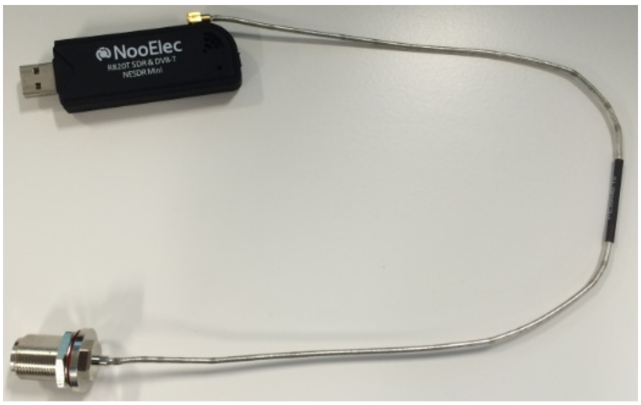

FIGURE 4. **The RTL-SDR is connected to the Pasternack PE-SR405FL RF cable, which is used to interface the LMR-400 RF cable to the MCX connector on the RTL-SDR.**

the NooElec Realtek Software Defined Radio (RTL-SDR), reference Fig. 4. The D-130NJ has a gain of 2 dBi and an operating bandwidth of 25 MHz to 1300 MHz. The RTL-SDR captured the FM radio spectrum measurements using MATLAB/Simulink [14]. The RTL-SDR interfaces with a Dell XPS M1330 laptop via the USB.

The RTL-SDR has a variable gain and a power offset that is a by-product of performing the Fast Fourier Transform (FFT) operation. The variable gain is set in MATLAB/Simulink. The power offset across the FM radio spectrum was determined by inputting a Radio Frequency (RF) signal, generated by a calibrated Keysight Signal Generator, into the RTL-SDR. The input power level and frequency were varied and measured with the RTL-SDR using MATLAB/Simulink. The averaged FFT power offset measurements yielded 42.34 dB.

To determine the actual Received Signal Level (RSL) of the measured FM radio signals (6) was used.

$$RSL_{FM} = RSL_{RTL-SDR} - 62.34 + 0.634 - 2 \text{ dBm} \tag{6}$$

In (6), the 62.34 value is the sum of the variable gain, which was set at 20 dB, and the FFT power offset of 42.34 dB. The 0.634 value is the sum of 0.284 and 0.35. These two values are the insertion losses of the LMR-400 and PE-SR405FL RF cables, respectively. The PE-SR405FL RF cable was used to interface the N-type connector on the LMR-400 RF cable to the Micro Coaxial (MCX) connector on the RTL-SDR. The last value, 2, is the gain of the D-130NJ antenna.

C. MEASUREMENT RESULTS

To compare the results obtained from the algorithm and measurements, graphs were created to showcase the predicted channels alongside the measured channels. It is important to note that the algorithm uses a computational form of the F(50,50) contour chart. The F(50,50) predicts field strengths occurring at 50% of the receivers 50% of the time [12]. Because the F(50,50) predicts signal strengths occurring at only 50% of the receivers, there is the other 50% of the receivers where the field strengths could statistically be lower or higher. This is because there is no way the F(50,50) contour chart can predict variations in terrains, buildings, or any other types of propagation obstacles. In addition, the F(50,50) contour chart cannot predict the location of the receiver e.g. inside or outside of a building, which has direct impacts on the received signal levels. Due to these limitations some differences between the predicted and measured received signal strength levels are inevitable. However, one needs to keep in mind that the purpose of these measurements is not the comparison of the received signal levels but the comparison in the actual FM radio station frequencies that were predicted and measured.

The list of 37,589 FM radio stations used in the execution of the algorithm has an associated status field for each station. The status field conveys the current status of each FM radio station e.g. the FM radio station is in the application process (abbreviated APP), has been granted a construction permit (abbreviated CP), or has been given permission to commence broadcasting (abbreviated Licensed). FM radio stations that have been designated status APP or CP will show up during the execution of the algorithm but will not be present during the measurements. This is because the station is not actually broadcasting on that respective frequency.

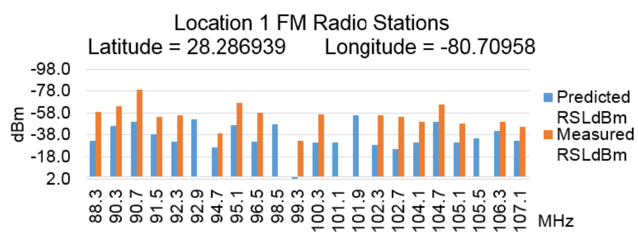

FIGURE 5. **The predicted and measured received signal level strengths of the FM radio spectrum at location 1.**

The measurement results for the first location are shown in Fig. 5. The algorithm for this location predicted 22 channels and the measurements confirmed 17 of the 22 channels. Of the 5 channels that were not detected frequencies 92.9 MHz, 101.9 MHz, and 105.5 MHz had statuses of CP, APP, and CP, respectively. The two other channel frequencies not detected were 98.5 MHz and 101.1 MHz. This could have been a result of antenna location, terrain, or other propagation factors. On the other hand, the measurements detected 6 FM radio stations that the algorithm did not predict. This is expected as locations outside, but near the fringe, of a FM radio station's protected service contour can be measured with a low signal strength.

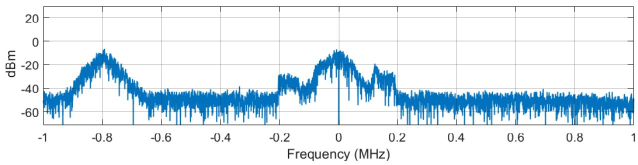

FIGURE 6. The MATLAB/Simulink spectrum measurement of FM radio channel 222, which corresponds to 92.3 MHz at location 1.

Fig. 6 is a MATLAB/Simulink spectrum analyzer output image of the measured FM radio spectrum at location 1. The spectrum measurements were made at baseband and span +/− 1 MHz around the center frequency, which corresponds to the measured FM radio station frequency. The frequency axis is in 200 kHz increments, which correspond to the FM radio station channel size. In Fig. 6 the center frequency corresponds to FM radio station frequency 92.3 MHz. 800 kHz below 92.3 MHz is a station with frequency 91.5 MHz. This correlates with the measured and predicted channels in Fig. 5.

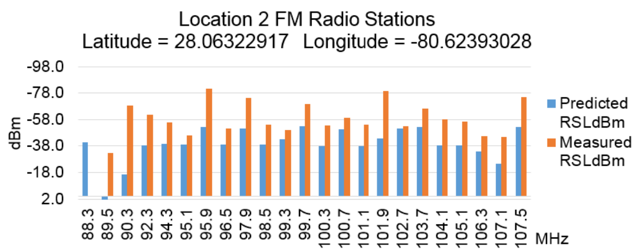

FIGURE 7. The predicted and measured received signal level strengths of the FM radio spectrum at location 2.

The measurement results for the second location are shown in Fig. 7. The algorithm for this location predicted 23 channels and the measurements confirmed 22 of the 23 channels. The channel not detected by the measurements had a frequency of 88.3 MHz, and is an educational station that may not have been broadcasting while these measurements were conducted. The measurements detected 4 FM radio stations that were not predicted by the algorithm.

This location is also the same location analyzed in [2], which predicted 24 channels while this paper's algorithm predicted 23 channels. The channel not predicted by this paper was channel 289, a low power station operating at 105.7 MHz. It was determined that this station was not predicted because it no longer exists. This was verified by the querying the station's facility identification number, 193757, in the FCC's FM Query Broadcast Station Search tool [15].

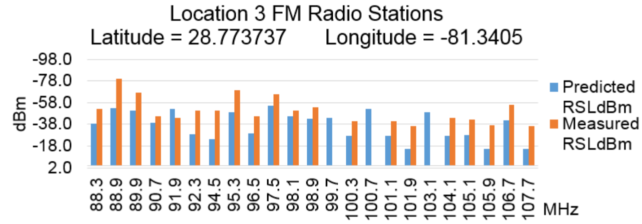

FIGURE 8. The predicted and measured received signal level strengths of the FM radio spectrum at location 3.

The measurement results for the third location are shown in Fig. 8. The algorithm for this location predicted 23 channels and the measurements confirmed 20 of the 23 channels. Of the 3 channels that were not detected frequencies 99.7 MHz and 100.7 MHz had statuses of APP. The one channel frequency not detected was 103.1 MHz. The measurements detected 7 FM radio stations that were not predicted by the algorithm.

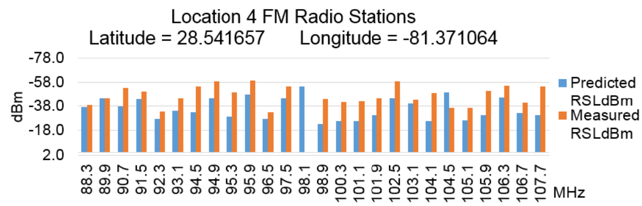

FIGURE 9. The predicted and measured received signal level strengths of the FM radio spectrum at location 4.

The measurement results for the fourth location are shown in Fig. 9. The algorithm for this location predicted 26 channels and the measurements confirmed 25 of the 26 channels. The one channel frequency not detected was 98.1 MHz. The measurements detected 3 FM radio stations that were not predicted by the algorithm.

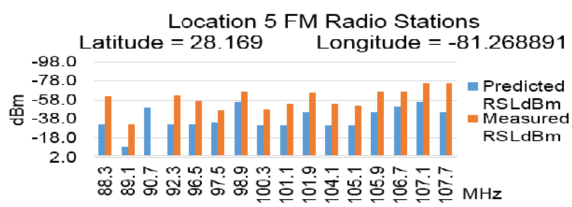

FIGURE 10. The predicted and measured received signal level strengths of the FM radio spectrum at location 5.

The measurement results for the fifth location are shown in Fig. 10. The algorithm for this location predicted 16 channels and the measurements confirmed 15 of the 16 channels. The one channel frequency not detected was 90.7 MHz. The measurements detected 4 FM radio stations that were not predicted by the algorithm.

The measurement results of the five locations provided a 94.1% average confidence level that the algorithm predicted the correct FM radio stations that provided service to those specific locations. This provides a high level of confidence that the algorithm is sufficient for estimating the FM radio station coverage across the continental United States.

V. UNITED STATES FM RADIO SPECTRUM ANALYSIS

With an algorithm that is validated by the measurements in the preceding section, FM radio maps can now be developed. These maps quantify the FM radio stations and unallocated FM radio spectrum across the continental United States. To achieve adequate granularity at the continental United States level, the FM radio data was averaged per county.

A. FM RADIO STATION PROTECTED COVERAGE MAP

To create a map that captures the FM radio station protected coverage across the continental United States, the algorithm was executed on a large matrix of coordinates. The United States Geological Survey provides a matrix that contains the coordinates of every human inhabited location in the United States [16]. The matrix of 195,280 coordinates was divided into 49 state station files, including Washington D.C., to facilitate the state-by-state analysis methodology that was previously discussed. The augmentation of the state-by-state analyses produced the FM radio station protected coverage map shown in Fig. 11. In order to identify locations across the continental United States that have underutilized FM radio spectrum that is suitable for secondary licensing of low-power short-range CIoT devices, data of 50 locations with populations ranging from less than 100,000, 100,000 to 1,000,000, and 1,000,000 and more are analyzed in Tables II, III, and IV, respectively.

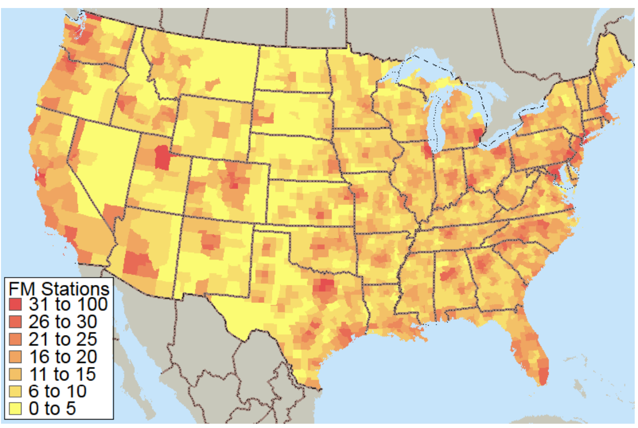

FIGURE 11. FM radio station protected coverage map of the continental United States.

It is important to note that algorithm predicts the FM radio stations that have protected coverage in a specific location. As observed in Section IV, measurements at all five locations measured additional stations that were not predicated by the algorithm. This is expected as locations outside, but near the fringe, of a station's service contour can be measured at a low signal strength but still be received and heard. The effects of these outlier stations will be important when discussing the amount of vacant FM radio spectrum that can be used for low-power short-range CIoT devices.

Tables II, III, and IV contain data relevant to both maps showcased in this paper. Table II contains FM radio statistics for 20 select locations that have populations less than 100,000 and are not a suburb of a major city. All locations in Table II have less than 22 stations with protected coverage and Scranton, Pennsylvania, has the most stations, 21.5. This equates to a 78.5% underutilization of the channel space by stations with protected coverage. The location in the preliminary analysis [2] had a population of 76,068 [13] and had a

TABLE 2. Statistics for populations less than 100,000.

City (State)	Population [13]	Protected Stations	$S_{Unallocated}$ [MHz]	S_{Vacant} [MHz] $\alpha=3$
Ruby (SC)	360	9.8	17.6	14.6
Mackinaw (MI)	806	19.6	15.7	12.7
New Haven (KY)	855	9.5	17.1	14.1
Crosslake (MN)	2,141	12.4	17.4	14.4
Bridgeport (WA)	2,409	10.2	17.7	14.7
Napoleon (OH)	8,749	11.1	17.0	14.0
Burley (ID)	10,345	7.8	18.4	15.4
Plainview (TX)	22,194	12.1	17.5	14.5
Richmond (KY)	31,364	12.9	16.7	13.7
Bozeman (MT)	37,280	16.8	16.5	13.5
Richland (WA)	48,058	17.6	16.1	13.1
Chicopee (MA)	55,298	15.3	14.6	11.6
Bismarck (ND)	61,727	18.0	16.2	13.2
Yuba City (CA)	64,925	15.7	14.8	11.8
Kalamazoo (MI)	74,262	20.1	15.0	12.0
Scranton (PA)	76,089	21.5	14.3	11.3
Duluth (MN)	86,265	12.1	17.3	14.3
Lakeland (FL)	97,422	20.2	12.8	9.8
Kenosha (SD)	99,218	16.5	14.7	11.7
Odessa (TX)	99,940	18.2	16.4	13.4

TABLE 3. Statistics for populations 100,000 to 1,000,000.

City (State)	Population [13]	Protected Stations	$S_{Unallocated}$ [MHz]	S_{Vacant} [MHz] $\alpha=6$
Green Bay (WI)	104,057	20.8	15.6	9.6
Savannah (GA)	136,286	26.3	14.3	8.3
Knoxville (TN)	178,874	20.3	14.7	8.7
Salt Lake City (UT)	186,440	39.2	9.6	3.6
Fort Wayne (IN)	253,691	17.7	15.7	9.7
St. Louis (MO)	319,294	27.8	10.4	4.4
New Orleans (LA)	343,829	24.3	13	7.0
Wichita (KS)	382,368	26.2	12.6	6.6
Miami (FL)	399,457	28.4	10.9	4.9
Atlanta (GA)	420,003	28.5	9.8	3.8
Las Vegas (NV)	583,756	25.2	10	4.0
Denver (CO)	600,158	26.3	11.3	5.3
Nashville (TN)	601,222	27.9	12.5	6.5
Washington (DC)	601,723	35.7	7.6	1.6
Seattle (WA)	608,660	28.4	10.5	4.5
Boston (MA)	617,594	30.4	9.6	3.6
Detroit (MI)	713,777	36.8	8.1	2.1
Austin (TX)	790,390	26.5	12.3	6.3
San Francisco (CA)	805,235	33.2	10.1	4.1
Jacksonville (FL)	821,784	25.5	12.7	6.7

TABLE 4. Statistics for populations greater than 1,000,000.

City (State)	Population [13]	Protected Stations	$S_{Unallocated}$ [MHz]	S_{Vacant} [MHz] α=8
Dallas (TX)	1,197,816	30.5	10.1	2.1
San Diego (CA)	1,307,402	25.1	12.9	4.9
San Antonio (TX)	1,327,407	24.7	12.4	4.4
Phoenix (AZ)	1,445,632	26.9	11.8	3.8
Philadelphia (PA)	1,526,006	31.9	8.4	0.4
Houston (TX)	2,099,451	27.5	10.8	2.8
Chicago (IL)	2,695,598	31.8	9.2	1.2
Los Angeles (CA)	3,792,621	29.8	10	2.0
New York (NY)	8,175,133	35.6	9.8	1.8

76% protected underutilization of the channel space. Based on this analysis smaller cities, towns, and unincorporated locations across the continental United States are expected to have protected underutilizations of the channel space greater than or equal to 75%.

Table III contains FM radio statistics for 21 select locations that have populations ranging from 100,000 to 1,000,000. All locations in Table III have between 20 and 40 stations with protected coverage, with exception to Ft. Wayne Indiana, The location with the most stations is Salt Lake City, Utah, 39.2 stations. This equates to a 60.8% protected underutilization of the channel space. The average number of stations for Table III is 27.8 which equates to a 72.2% underutilization of the channel space by stations with protected coverage. Based on the results of this analysis locations across the continental United States with populations ranging from 100,000 to 1,000,000 are expected to have protected underutilizations of the channel space less than or equal to 75%

Table IV contains FM radio statistics for the 9 locations across the continental United States with populations greater than 1,000,000 [13]. All locations in Table IV have between 24 and 36 stations with protected coverage. The average number of stations for Table IV is 29.3 which equates to a 70.7% underutilization of the channel space by stations with protected coverage.

B. UNALLOCATED FM RADIO SPECTRUM MAP

The FM radio spectrum ranges from 88 MHz to 108 MHz [17]. The spectrum range is divided into 100 channels and each channel is allocated 200 kHz of bandwidth for broadcast transmission [17]. However, FM radio stations that have been approved for High Definition (HD) broadcast transmission can utilize 400 kHz of bandwidth. Fig. 12 identifies the two 100 kHz sidebands that are used for HD transmission. The amount of unallocated FM radio spectrum, $S_{Unallocated}$, at a given location is calculated using (7).

$$S_{Unallocated} = 20 - \frac{x+y}{5} \text{ MHz} \tag{7}$$

Where x is the total number of FM radio stations and y is the subset of the total number approved for HD broadcasting. Fig. 13 shows the unallocated FM radio spectrum across the continental United States. Table II contains the FM radio statistics for 20 select locations that have populations less than 100,000 and are not a suburb of a major city. The unallocated FM radio spectrum in these locations range from 12.8 MHz to 18.4 MHz with an average of 16.2 MHz. Based on the results of this analysis the smaller cities, towns, and unincorporated locations across the continental United States are expected to have on average 15 MHz or more of unallocated FM radio spectrum.

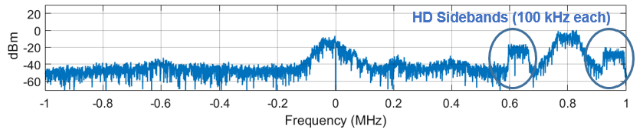

FIGURE 12. The MATLAB/Simulink spectrum measurement of a HD FM radio station at location 2.

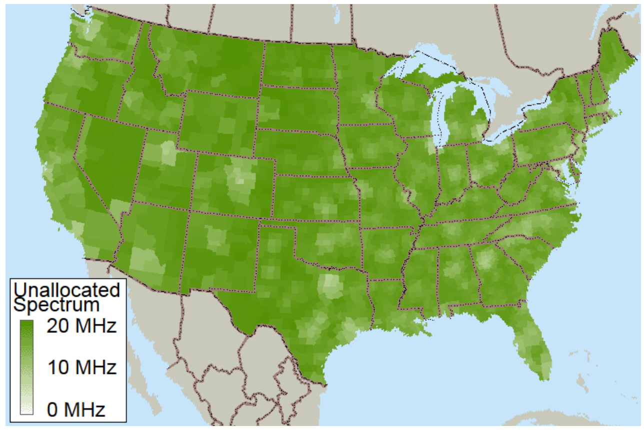

FIGURE 13. Unallocated FM radio spectrum map of the continental United States.

Table III contains FM radio statistics for 21 select locations that have populations ranging from 100,000 to 1,000,000. The unallocated FM radio spectrum in these locations range from 7.6 MHz to 15.7 MHz with an average of 11.5 MHz. Based on the results of this analysis locations across the continental United States with populations ranging from 100,000 to 1,000,000 are expected to have on average 15 MHz or less of unallocated FM radio spectrum.

Table IV contains the FM radio statistics for the 9 locations across the continental United States with populations greater than 1,000,000 [13]. The unallocated FM radio spectrum in these nine locations range from 8.4 MHz to 12.9 MHz with an average 10.6 MHz.

C. VACANT FM RADIO SPECTRUM

The FCC provisions minimum distance separations between stations per station class for the same channel and five pairs of adjacent channels [18]. The purpose of the minimum distance separation is to mitigate interference between stations and to account for the stations with signals that are received outside of their protected service contour. This was evident when all five locations in Section IV measured stations that were not predicted by the algorithm and were therefore, outside of their protected service contour. In order to obtain the minimum distance separations between stations there will be portions of the spectrum that purposely remain unallocated. The portions of unallocated spectrum will be spread across the 20 MHz of FM radio spectrum.

As evident in Tables II, III, and IV there exists a correlation between a locations population and the amount of unallocated FM radio spectrum. In addition, the number of stations with signals received outside of their protected service contour will also increase with the locations population. This is expected as the presence of more people increases demand for FM radio stations, particularly HD stations. The analysis indicated that locations with larger populations contain more stations with station class A and L1. The small protected coverage areas of A and L1 allow for the broadcasting of more stations to satisfy the market demand. Many of the largely populated locations in Tables III and IV will have much of the unallocated FM radio spectrum occupied by stations with signals received outside of their protected service contour. This can be understood in locations with large populations when tuning an FM radio and having a station on almost every channel. This situation is known as spectrum saturation.

To account for the spectrum used by the stations with signals received outside of their protected service contour, an unpredicted bandwidth α is calculated using (8).

$$\alpha = 0.2x' + 0.2y' \text{ MHz} \tag{8}$$

Where x' is the total number of unpredicted stations and y' is the subset of the total number of unpredicted stations that are approved for HD broadcasting. Unpredicted stations are defined as stations whose signals are received at locations outside of their protected service contour. The unpredicted bandwidth is proportional to a locations population because x' and y' both increase as the population increases. Section IV conducted measurements at locations with populations ranging from 13,822 to 238,300. This population range covers the range discussed in Table II and the lower populations of Table III. The measurements detected 7 stations that were not predicted by the algorithm. To be conservative, for the populations less than 100,000, x' and y' are set to 10 and 5, respectively. For this population range, the unpredicted bandwidth is 3 MHz. The next population range, 100,000 to 1,000,000, contains heavily populated locations. Based on the measurements and the results of this analysis, x' and y' are set to 20 and 10, respectively. For this population range, the unpredicted bandwidth is 6 MHz. The last locations are the 9 most populated locations across the continental United States [13]. These locations have populations greater than 1,000,000. These locations have high market demand for FM stations and HD stations, resulting in high volumes of spectrum congestion therefore, x' and y' are equal to 25 and 15, respectively. For this population range, the unpredicted bandwidth is 8 MHz.

The total amount of vacant FM radio spectrum in the three population ranges is calculated using (9).

$$S_{Vacant} = S_{Unallocated} - \alpha \text{ MHz} \tag{9}$$

Table II contains the amount of vacant FM radio spectrum for 20 select locations that have populations less than 100,000. The vacant FM radio spectrum in these locations range from 9.8 MHz to 15.4 MHz with an average of 13.2 MHz. Based on the results of this analysis the smaller cities, towns, and unincorporated locations across the continental United States are expected to have on average 13 MHz or more of vacant FM radio spectrum.

Table III contains FM radio statistics for 21 select locations that have populations ranging from 100,000 to 1,000,000. The vacant FM radio spectrum in these locations range from 3.6 MHz to 11.7 MHz with an average of 5.5 MHz. Based on the results of this analysis locations across the continental United States with populations ranging from 100,000 to 1,000,000 are expected to have on average 6 MHz or less of vacant FM radio spectrum.

Table IV contains the FM radio statistics for the 9 locations across the continental United States with populations greater than 1,000,000 [13]. The vacant FM radio spectrum in these 9 locations range from 0.4 MHz to 4.9 MHz with an average 2.7 MHz.

D. CIoT DEPLOYMENT BITRATES

Predicting the bitrates of a CIoT deployment is challenging because each deployment has unique design parameters such as receiver sensitivity, required bit error rate, etc. and an RF environment that varies greatly with each location. Therefore, the bitrates discussed in this section assume that the design engineer has adequately assessed the design parameters and RF environments to achieve the SNRs required to realize these bitrates with the respective modulation scheme.

Table V contains the bitrates for the locations in Tables II, III, and IV using modulation types, Quadrature Phase Shift Keying (QPSK) and 8-PSK. These two modulation types use the vacant FM radio spectrum multiplied by the bandwidth utilization factor β to generate the potential bitrates for CIoT deployments. The bandwidth utilization factor ranges between 0 and 1 and represents the percentage of bandwidth being used for data transmission. The bandwidth not being used for data transmission is used for guard bands, filtering, etc. For the purposes of this analysis the bandwidth utilizations of $\beta = 0.75$ and $\beta = 0.5$ are used.

The locations from Table II yield average bitrates of 19.8 Mbps, 29.7 Mbps, 13.2 Mbps, and 19.8 Mbps for QPSK and 8-PSK with $\beta = 0.75$ and QPSK and 8-PSK with $\beta = 0.5$, respectively.

The locations from Table III yield average bitrates of 8.3 Mbps, 12.5 Mbps, 5.5 Mbps, and 8.3 Mbps for QPSK and 8-PSK with $\beta = 0.75$ and QPSK and 8-PSK with $\beta = 0.5$, respectively.

The locations from Table IV yield average bitrates of 3.9 Mbps, 5.9 Mbps, 2.6 Mbps, and 3.9 Mbps for QPSK and 8-PSK with $\beta = 0.75$ and QPSK and 8-PSK with $\beta = 0.5$, respectively.

TABLE 5. Bitrates for locations in Tables II, II, and IV.

City (State)	S_{Vacant} [MHz]	Bitrate [Mbps]			
		β=0.75		β=0.50	
		QPSK	8-PSK	QPSK	8-PSK
Ruby (SC)	14.6	21.9	32.9	14.6	21.9
Mackinaw (MI)	12.7	19.1	28.6	12.7	19.1
New Haven (KY)	14.1	21.2	31.7	14.1	21.2
Crosslake (MN)	14.4	21.6	32.4	14.4	21.6
Bridgeport (WA)	14.7	22.1	33.1	14.7	22.1
Napoleon (OH)	14.0	21.0	31.5	14.0	21.0
Burley (ID)	15.4	23.1	34.7	15.4	23.1
Plainview (TX)	14.5	21.8	32.6	14.5	21.8
Richmond (KY)	13.7	20.6	30.8	13.7	20.6
Bozeman (MT)	13.5	20.3	30.4	13.5	20.3
Richland (WA)	13.1	19.7	29.5	13.1	19.7
Chicopee (MA)	11.6	17.4	26.1	11.6	17.4
Bismarck (ND)	13.2	19.8	29.7	13.2	19.8
Yuba City (CA)	11.8	17.7	26.6	11.8	17.7
Kalamazoo (MI)	12.0	18.0	27.0	12.0	18.0
Scranton (PA)	11.3	17.0	25.4	11.3	17.0
Duluth (MN)	14.3	21.5	32.2	14.3	21.5
Lakeland (FL)	9.8	14.7	22.1	9.8	14.7
Kenosha (SD)	11.7	17.6	26.3	11.7	17.6
Odessa (TX)	13.4	20.1	30.2	13.4	20.1
Green Bay (WI)	9.6	14.4	21.6	9.6	14.4
Savannah (GA)	8.3	12.5	18.7	8.3	12.5
Knoxville (TN)	8.7	13.1	19.6	8.7	13.1
Salt Lake City (UT)	3.6	5.4	8.1	3.6	5.4
Fort Wayne (IN)	9.7	14.6	21.8	9.7	14.6
St. Louis (MO)	4.4	6.6	9.9	4.4	6.6
New Orleans (LA)	7.0	10.5	15.8	7.0	10.5
Wichita (KS)	6.6	9.9	14.9	6.6	9.9
Miami (FL)	4.9	7.4	11.0	4.9	7.4
Atlanta (GA)	3.8	5.7	8.6	3.8	5.7
Las Vegas (NV)	4.0	6.0	9.0	4.0	6.0
Denver (CO)	5.3	8.0	11.9	5.3	8.0
Nashville (TN)	6.5	9.8	14.6	6.5	9.8
Washington (DC)	1.6	2.4	3.6	1.6	2.4
Seattle (WA)	4.5	6.8	10.1	4.5	6.8
Boston (MA)	3.6	5.4	8.1	3.6	5.4
Detroit (MI)	2.1	3.2	4.7	2.1	3.2
Austin (TX)	6.3	9.5	14.2	6.3	9.5
San Francisco (CA)	4.1	6.2	9.2	4.1	6.2
Jacksonville (FL)	6.7	10.1	15.1	6.7	10.1
Green Bay (WI)	9.6	7.7	11.5	5.1	7.7
Dallas (TX)	2.1	3.2	4.7	2.1	3.2
San Diego (CA)	4.9	7.4	11.0	4.9	7.4
San Antonio (TX)	4.4	6.6	9.9	4.4	6.6
Phoenix (AZ)	3.8	5.7	8.6	3.8	5.7
Philadelphia (PA)	0.4	0.6	0.9	0.4	0.6
Houston (TX)	2.8	4.2	6.3	2.8	4.2
Chicago (IL)	1.2	1.8	2.7	1.2	1.8
Los Angeles (CA)	2.0	3.0	4.5	2.0	3.0
New York (NY)	1.8	2.7	4.1	1.8	2.7

VI. CONCLUSION

The research presented in this paper developed an algorithm that determined the FM radio stations that have protected coverage at specific locations. The algorithm was validated by comparing the predicted values to the measured values at five select locations. The validated algorithm was executed on 195,280 locations to generate maps that showcase the FM radio station protected coverage and unallocated FM radio spectrum across the continental United States. Using data gathered during the measurements, the vacant FM radio spectrum was calculated by subtracting the number of stations with signals received outside of their protected service contour from the unallocated FM spectrum. The vacant FM radio spectrum was then used to determine the potential bitrates that can be reached at select locations across the continental United States.

The analysis indicated that of the three population groups, locations with a population less than 100,000, and were not located near a major heavily populated location, showed the most potential for secondary licensing of CIoT devices. To achieve the full potential of the vacant spectrum, CIoT devices must operate in a low-power short-range mode to facilitate frequency reuse amongst CIoT devices. Low-power short-range CIoT devices using frequency-reuse can obtain potential bitrates of approximately 30 Mbps. The analysis also indicated that locations with populations greater than 1,000,000 did not yield enough vacant spectrum to justify risking interference to other FM radio stations.

REFERENCES

[1] S. Haykin, "Cognitive radio: Brain-empowered wireless communications," *IEEE J. Sel. Areas Commun.*, vol. 23, no. 2, pp. 201–220, Feb. 2005.

[2] D. T. Otermat, C. E. Otero, and I. Kostanic, "Analysis of the FM radio spectrum for Internet of Things opportunistic access via cognitive radio," in *Proc. IEEE 2nd World Forum Internet Things (WF-IoT)*, Milan, Italy, Dec. 2015, pp. 166–171.

[3] J. A. Stankovic, "Research directions for the Internet of Things," *IEEE Internet Things J.*, vol. 1, no. 1, pp. 3–9, Feb. 2014.

[4] W. Li, C. Zhu, V. C. M. Leung, L. T. Yang, and Y. Ma, "Performance comparison of cognitive radio sensor networks for industrial IoT with different deployment patterns," *IEEE Syst. J.*, vol. PP, no. 99, pp. 1–11, 2015.

[5] A. Aijaz and A. H. Aghvami, "Cognitive machine-to-machine communications for Internet-of-Things: A protocol stack perspective," *IEEE Internet Things J.*, vol. 2, no. 2, pp. 103–112, Apr. 2015.

[6] Y. Zhang, R. Yu, M. Nekovee, Y. Liu, S. Xie, and S. Gjessing, "Cognitive machine-to-machine communications: Visions and potentials for the smart grid," *IEEE Netw.*, vol. 26, no. 3, pp. 6–13, May/Jun. 2012.

[7] W. Webb, "On using white space spectrum," *IEEE Commun. Mag.*, vol. 50, no. 8, pp. 145–151, Aug. 2012.

[8] M. Nekovee, T. Irnich, and J. Karlsson, "Worldwide trends in regulation of secondary access to white spaces using cognitive radio," *IEEE Wireless Commun.*, vol. 19, no. 4, pp. 32–40, Aug. 2012.

[9] C. Perez-Vega and J. M. Zamanillo, "Path-loss model for broadcasting applications and outdoor communication systems in the VHF and UHF bands," *IEEE Trans. Broadcast.*, vol. 48, no. 2, pp. 91–96, Jun. 2002.

[10] A. G. Ismaeel, "Effective technique for allocating servers to support cloud using GPS and GIS," in *Proc. Sci. Inf. Conf.*, London, U.K., Oct. 2013, pp. 934–939.

[11] *Station Classes*, document 47CFR1.C.73.210, Federal Communications Commission.

[12] *Prediction of Coverage*, document 47CFR1.C.73.313, Federal Communications Commission.

[13] United States Census Bureau. (Apr. 1, 2010). *2010 Census Interactive Population Search*, accessed on Apr. 1, 2016. [Online]. Available: http://www.census.gov/2010census/popmap/ipmtext.php?fl=12

[14] R. W. Stewart, K. W. Barlee, D. S. W. Atkinson, and L. H. Crockett, *Software Defined Radio Using MATLAB & Simulink and the RTL-SDR*. Glasgow, Scotland: Academic, 2015.

[15] Federal Communications Commission. (Dec. 10, 2015). *FM Query Broadcast Station Search | Federal Communications Commission*, accessed on Apr. 3, 2016. [Online]. Available: https://www.fcc.gov/media/radio/fm-query

[16] United States Geological Survey. (Feb. 12, 2016). *Domestic and Antarctic Names—State and Topical Gazetteer Download Files*, accessed on Apr. 4, 2016. [Online]. Available: http://geonames.usgs.gov/domestic/download_data.htm

[17] *Numerical Designation of FM Broadcast Channels*, document 47CFR1.C.73.201, Federal Communications Commission.

[18] *Minimum Distance Separation Between Stations*, document 47CFR1.C.73.207, Federal Communications Commission.

[19] *Definitions*, document 47CFR1.L.74.1201, Federal Communications Commission.
[20] *Power Limitations and Antenna Systems*, document 47CFR1.L.74.1235, Federal Communications Commission.
[21] MathWorks. *RTL-SDR Support From Matlab & Simulink*, accessed on May 28, 2016. [Online]. Available: http://www.mathworks.com/hardware-support/rtl-sdr.html

DEREK T. OTERMAT received master's and bachelor's degrees in electrical engineering from the Florida Institute of Technology and the University of Florida, respectively. He is currently pursuing a Ph.D. degree with the Department of Electrical and Computer Engineering, Florida Institute of Technology. His research interests include cognitive radio, internet of things, and wireless communication systems. He currently works as a Communication Systems Engineer at the Kennedy Space Center, Florida.

IVICA KOSTANIC joined the Electronics and Communication Engineering Department, Florida Tech, as an Associate Professor in 2003. He teaches mostly graduate level courses in areas of RF propagation, communication theory and wireless communication. He spent more than seven years working in wireless communication industry. He was a Research Engineer for Agilent Technologies, SAFCO Technologies and TEC Cellular. His research interest include broad range of topics in cellular, microwave, and satellite communications.

CARLOS E. OTERO is currently an Associate Professor of Electrical and Computer Engineering with Florida Tech. He was a Faculty Member with the College of Engineering, University of South Florida, Tampa, and the University of Virginia, Wise. He worked 11 years in private industry as a Computer Software Engineer for military computer systems, including satellite communications, command and control, wireless security, and unmanned aerial vehicle systems. His research interests are in computer systems, with particular emphasis on the design, performance evaluation, and optimization of embedded, wireless, and data-intensive systems. He has authored or co-authored one university textbook and over 70 scientific peer-reviewed publications in venues such as the IEEE Intelligent Systems, the IEEE Transactions in Antennas and Propagation, IEEE Systems Journal, the IEEE Transactions on Instrumentation and Measurement, the IEEE Transactions on Engineering Management, and the *E*xpert Systems and Applications.