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A Survey on Spectrum Occupancy Measurement for Cognitive Radio

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Abstract In order to support the ever growing demand of wireless communication systems and wireless local area network based 802.11 devices, the regulators are developing techniques to overcome the permanent scarcity of radio resources. Spectrum sensing in cognitive radio (CR) is considered as a key technology which estimates the availability of the licensed spectrum band for additional usages. The underutilized licensed band can be exploited among the secondary users provided that they would not cause any interference to the primary user. So, evaluation of spectrum occupancy is the main approach towards the successful deployment of CR. This paper studies the various spectrum occupancy models used in diverse locations by research campaigns worldwide. The detail analyses of the empirical results in different scenarios of measurement have been compared. The purpose of this survey is to evaluate up to what percentage the whole spectrum band is occupied by different services.

Keywords WLAN · Cognitive radio · Spectrum sensing · Spectrum occupancy

1 Introduction

An efficient utilization of spectrum is necessary to alleviate the spectrum scarcity issue which arises due to traditional fixed frequency allocation policy. On the other side, the rapid growth of the applications of wireless communication and devices demand for more spectra. The conflicts between spectrum scarcity issues and underutilization led Federal Communication Commission (FCC) to develop CR which allows the unlicensed users to

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access the licensed band in an opportunistic manner [1]. CR senses the spectrum availability, learns from the spectrum and changes its parameters according to the surroundings [2]. To make the CR deployment successful in near future, spectrum occupancy measurement is very essential. It predicts the PU activity on the different licensed bands allocated for different services. An effective quantitative measurement is essential to provide a detailed structure of the current spectrum usage and to identify the suitable and potential candidate bands for future CR access.

Experiments have been conducted in various locations such as US, Europe, New Zealand, South Africa, China, Singapore, Vietnam etc. covering the wide frequency range in order to evaluate the suitable bands for the secondary usage in context of CR. Most of the observations were conducted in US and hence assess the American spectrum regulations and monitoring. National Telecommunications and Information Administration (NTIA) has performed first larger spectrum occupancy measurement [3]. Spectrum occupancy percentage varies with the location, time, space and the band of operation. Moreover, the spectrum usage in the nearby country also affect the occupancy statistics [4]. These research activities involve survey on Television (TV) band, cellular band, Ultra-high frequency (UHF) band, and many more assigned to different services. Based on the derived solutions from these studies conducted in diverse locations and scenarios, CR should undertake the various possibilities and challenges of technological aspects before successful deployment.

In this paper, we summarize the spectrum occupancy measurements conducted by different campaigns in different locations and frequency bands meant for different services. Furthermore, we also compare the different measurement setups along with the empirical results. Hence, this paper will be helpful in developing more ideas regarding the measurement techniques and proposing new methods.

This paper is structured as follows. Section 2 highlights the various challenges, and discusses the technological aspects in spectrum measurement policy. Section 3 describes the past studies made by different campaigns worldwide very briefly. Section 4 describes some of the important factors that influences spectrum occupancy and finally, the paper is concluded in Sect. 5.

2 Spectrum Measurements Policies and Challenges

The main objective of the spectrum measurement policy is to evaluate the availability of the channels which remain vacant both temporarily and permanently in time and frequency domain. Figure 1 shows the basic spectrum occupancy measurement model adopted worldwide. Most of the measurement campaigns are performed outdoor at a high point so as to get the accurate estimation of the licensed user activity in various spectrum bands. Also, the indoor measurement is considered in some of the places in order to find the effect of shadowing, path loss on the spectrum occupancy. These measurements provide an extensive idea about the presence of the PU on the licensed band in practical environment scenario. This measurement procedures involve the challenges and technological aspect while spectrum monitoring.

2.1 Measurement Scenario

The characteristics of the spectrum occupancy show considerable variations depending on the locations and on the time of observations. It is mostly due to the wireless channel

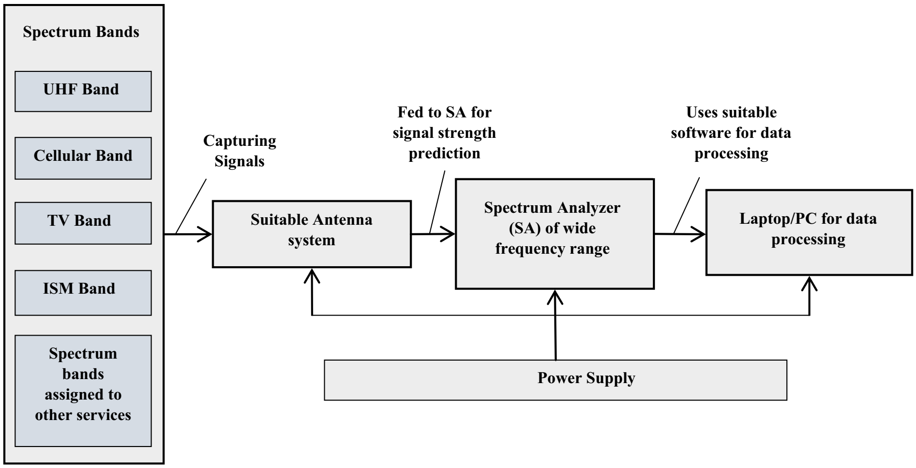

Fig. 1 Basic model of spectrum occupancy measurement

effect, propagation path and also diversity effect on the received signal, and hence, results different channel availability. Apart from the location, duration of the measurement has also a large effect on the constancy of occupancy in a particular channel. Long term measurement provides the detail channel statistics as it gives the more accurate and potential bands to be reused by the CR devices. This system includes taking sufficient amount of data spanning several days, months or years which involve different times in working days such as noon, evening, night, weekend, holidays and also special events [5–8]. Shortest measurements are mainly preferred in rural areas and less population density areas [9–17].

Secondly, consistencies of channel occupancy statistics also depend on the frequency band under observation. This variation is mainly due to the types of service assigned to that band. For example, cellular Global system for mobile (GSM) band and TV broadcast band are always highly occupied and show less variation in channel occupancy while the spectrum above 1 GHz is always lightly used and shows more variation of occupancy depending on the location and duration of measurement. Again, the uplink cellular band shows the lower PU activity on the channel as compared to downlink band because of the low transmission power from the mobile users.

2.2 Spectrum Sensing

The continuous measurement system enables the CR device to scan multiple numbers of bands with sufficient sensitivity and efficiency by rotating or switching the antenna. Again, the CR device can't perform both transmission or reception and sensing operation simultaneously. Additionally, efficiency in the cognitive radio networks (CRNs) can be maximized by minimizing the energy consumption during sensing and data transmission. So, it is desirable to develop an optimized spectrum sensing model to minimize both time and energy consumption ensuring the maximum throughput [18].

In the literature, lots of spectrum sensing techniques are available, such as energy detection [19], matched filter [19], cyclostationary [20], blind spectrum sensing [21] etc. Out of these techniques, energy detection method is simple, low cost and easy to implement [19]. Hence, all the measurement systems use energy detection method which compares the received signal energy with the decision threshold value. If the energy of the received signal is equal to or more than the threshold, PU is active on the channel. If the energy of the received signal is less than the threshold, then the channel is suitable for secondary usage. Hence, selection of decision threshold is a major challenge for the accurate detection of channel occupancy. This can be evaluated considering different parameters such as the average noise floor [14] or the minimum value of signal level [12] or the false alarm probability [9]. In [22], another method called Transmission Encapsulation based on the Connected Component Labeling (TECCL) was proposed to calculate this threshold value. But, energy detector is not suitable for the detection of spread spectrum and cyclostationary property based PU signal. Provided with these limitations, the spectrum occupancy model can be developed in such a way to meet these following challenges.

- Investigating the spectrum bands which are permanently occupied for the long time both spatially and temporally.
- Developing spectrum sensing strategies and algorithms for the bands which are vacant most of the time in order to allow the CR devices for secondary access.
- Discovering the moderately occupied spectrum bands and their channel occupancy statistics over different time period.

2.3 Technological Aspects

Different spectrum measurement campaigns follow different methodologies for spectrum occupancy evaluation. There are various setting parameters required to be considered in the measurement setup. These are mainly the antenna selection for the investigated band, sweep time, resolution bandwidth, noise floor etc. The antenna used must perceive the bands assigned to different services. The selection of measurement bandwidth is also a challenging issue. The lower measurement bandwidth results in a longer sampling measurement time. On the other hand, the higher measurement bandwidth produce widely ineffectively separated signals that are very difficult to distinguishable. Wider band signal is divided into a number of narrow bandwidth signals to get the high measurement accuracy. There are various trade off exist between the spectrum analyzer and the detection accuracy. A smaller resolution bandwidth lowers down the noise floor, hence clear visualization of signal level. Higher frequency resolution results long sweep time. Also, the noise floor must be considered very carefully to avoid excess error possibilities on the measurement.

3 Spectrum Measurement Survey

An extensive measurement survey has been performed by different measurement campaigns worldwide covering a wide frequency range, specific licensed band, unlicensed band considering the different time period and scenarios. The motivation of these studies is only to allow the operation of CR device in unused/underutilized spectrum. This section describes some of the campaigns performed their observation in TV band and ISM band. It also describes the short-term and long-term measurement monitored in different locations throughout the world.

3.1 ISM Band

A measurement campaign has been conducted in eight different locations in Oulu and nearby Oulu each with approximately 1 week of continuous observation [22]. A novel method called transmission encapsulation based on the connected component labeling (TECCL) was proposed to minimize the significant changes in the false alarm probability which mainly affect the detection of PU activity in the desired channel. The measurement setup consisted of Fluke networks PC card sensor mounted into IBM think pad T42 PCMCIA slot which can directly calculate the duty cycle. Threshold was decided 20 dB above the noise floor. Among the eight areas, the crowded area was observed twice in 2 months apart so as to get the spectrum utilization in two different times, the rural area was monitored for 5 days due to presence of less number of users and the other areas were measured approximately for 7–8 days. From these studies, it was investigated that 2.45 ISM band was very less occupied and the average duty cycle in Oulu is only 0–3 %. Mostly, all the measurements consist of single wideband Omni directional antenna or 2–3 antennas to attend different frequency bands or different areas. But the spatial dimension has a greater effect on the spectrum occupancy. To illustrate this, distributed and directional spectrum occupancy metrics was presented to investigate in ISM band ranging from 2400 to 2485 MHZ over 5 working days from 8 a.m. to 4 p.m. through continuous observation [23]. This measurement system consisted of two measuring devices each controlling by three directional antennas receiving the signals from the same office area but from opposite direction. The threshold value was decided 15 dB above the noise floor. The three antennas from the same device show different power level though having almost same shape. Recently, mostly WLANs use this 2400–2483.5 MHz ISM band for their operations. There are also lots of devices such as microwave oven, RF identification devices, licensed fixed wireless access (FWA) system, Bluetooth devices etc. share this same band making this limited bandwidth more congested. Hence, to investigate the occupancy of different services, monitoring was conducted in three different types of location in Cambridge over a week [24] covering the private sector (internet cafe around the Cambridge where the interference signal was generated from microwave oven), public sector (both primary and secondary school in Birmingham, hospital and Heathrow airport) and in the city center location (city center in London and Glasgow). Hence, these locations affect the WLAN signal differently depending on the interfering devices. Here, authors used a data analysis method to separate WLAN emission from other devices' leakage signal. The measurement system included right hand circular antenna covering the frequency range from 2400 to 2483.5 MHZ with 30 MHz guard band on either side. The activity plot was observed for each type of signal in these three different types of locations using different thresholds value. Due to the variation of monitoring location and interfering devices these three sectors showed different value of activity. The activity in Private sector, public sector and the city center location was found to be 5, 30 and 4 %, respectively.

3.2 TV Broadcasting Band

Recently TV white space (TVWS) has attracted much more attentions of the CR researchers to exploit its available frequency band among the unlicensed users so as to provide an extensive platform to solve the spectrum scarcity issues. This motivated the author to investigate the exact spectrum availability in United Kingdom (UK) in a realistic manner and to show the effect of location and transmission power on the variation of

TVWS occupancy [25]. The digital TV standard DVB-T (Digital Video Broadcasting Terrestrial) in UK uses 8 MHz wide frequency bands with the entire UHF range is 256 MHz, out of which only 240 MHz frequency band can be accessed by the cognitive users. Again, the CR users should maintain the minimum "keep out distance" D_{CR} to avoid the interference to the TV receiver which is given by [25]

$$D_{CR} \geq \left(\gamma_{th} \frac{P_{CR}}{P_{TV}}\right)^{\frac{1}{\alpha}} D_{Tv} \tag{1}$$

where, P_{CR} and P_{TV} were both transmit power of the CR transmitter and TV transmitter respectively. D_{Tv} was the maximum coverage area of the TV transmitter. α and γ_{th} were path loss exponent and sensitivity threshold of a TV receiver respectively. Let d and D_i be the location of CR and location of TV, respectively, where the CR can use the TV frequency if $|d - D_i| \geq D_j'$. Here, D_j' was given by $D_j' = \left[1 + \left(\gamma_{th} \frac{P_{CR}}{P_{TV}'}\right)^{1/\alpha} D_{TV}'\right]$.

To explore the occupancy of both cellular and TV bands, authors evaluated its occupancy in Malaysia, where the measurements were conducted for 24 h in College of Information Technology (COIT), University Tenaga Nasional (UNITEN) and Selangor by employing two types of antennas namely tri-band dipole and discone antennas for 2G/3G cellular bands and UHF/VHF TV bands, respectively [26]. Advantest U3741 spectrum analyzer having the frequency range of 9 kHz–3 GHz with noise level −135 dBm was used to measure the received power. Then the average noise floor was calculated for each 500 MHz band starting from 0 to 3000 MHz frequency band. Accordingly, the threshold is set 6 dB above the average noise floor. It has been observed that the average duty cycle of the GSM 900 and UHF TV band were more than the GSM 1800 and VHF TV band, respectively. Average duty cycles of all these bands are summarized in Table 1.

IP-based broadband wireless protocol has been proposed to enlighten the various applications in different bands in TVWS frequencies in US 2009 [27]. This paper also discussed about the IEEE 802.16e standard and its adaptation to TVWS. If the unlicensed device works near the TV spectrum band, it may cause interference to the TV receiver. The operation of the secondary user and its effect on the TV receiver was illustrated in [28].

3.3 Long Term Measurements

The main objective of the long term study is to find the more accurate potential model for spectrum occupancy after observing the signal statistics in different times and also in working days, holidays, special events, weekend etc. So, these studies will give a detailed

Table 1 Average occupancy statistics in different bands [26]

Different services	Frequency ranges (MHz)	Average duty cycle (%)
GSM 900	880–960	35.51
GSM 1800	1710–1880	9.59
3G	1885–2200	26.08
VHF TV	174–230	10.92
UHF TV	470–798	13.36

occupancy model of the investigated bands. In order to identify the permanent underutilized band ranges from 300 to 4900 MHz, a measurement campaign was conducted in Bristol, UK over 6 months (19th May 2010–18th October) making a continuous studies [5]. To capture the signal two wideband discone antennas covering the frequency bandwidth from 300 MHz to 1 GHz and from 1 to 4.9 GHz were used both in the indoor and outdoor of Merchant Venturers Building, Bristol, UK. The output of the antennas were connected to spectrum analyzer through RF cables, and to compensate the losses preamplifier was used with gain 28 and 12 dB for outdoor and indoor, respectively. Smaller value of resolution bandwidth about 300 kHz was decided to lower down the noise floor. Channel activity showed less activity in the overnight and at the weekend and peak at around noon in working days. After these long term studies it was found that the broadcast TV band (470–862 MHz) and cellular band GSM 900//1800 MHz were always occupied whereas the spectrum above 2.5 GHz was mostly vacant. Channel occupancy was also varied depending on the spectrum region. Cellular band showed highly variation with standard deviation 20–30 % whereas bands below 800 MHz had very less variation.

New Zealand spectrum measurement campaign conducted spectrum measurement in the frequency bandwidth 806–2750 MHz over 12 weeks of period in outdoor and indoor location in urban Auckland, New Zealand [6]. The measurement equipment consisted of a dipole antenna covering the frequency range 806–1000 MHz and a discone antenna covering the bandwidth 1000–2750 MHz, both were connected to a Rohde & Schwarz ESVN40 spectrum analyzer which was set for the resolution bandwidth 15 or 120 or 250 kHz depending on the condition. The spectrum utilization was evaluated by deciding the threshold 5 dB above the mean noise floor. The received signal strength in the outdoor environment was about 5–25 dB greater than the signal strength measured in indoor environment. From the spectrum occupancy measurement studies it has been investigated that the cellular downlink band was heavily occupied i.e. 64.15 and 50.05 % for outdoor and indoor scenario, respectively. The overall average occupancy of outdoor and indoor location was 6.21 and 5.72 %, respectively.

Another long term study was performed in two locations Ho Chi Minh City and Long An province which is a rural area in Vietnam for 4 months starting from October 2010 to February 2011 over the frequency range 20–3000 MHz [7]. The equipment consisted of a set of antennas namely HE016, HE309, HE314A1, HF214 and HF902 connected to EM550 digital wideband receiver via switch matrix. The detailed antenna characteristics are discussed in this paper. The server was also installed with R&SARGUS monitoring software. The threshold was chosen 3 dB above the average noise floor. It was obvious that the range below 1 GHz was heavily occupied while the spectrum between 2 and 3 GHz was lightly occupied. From all the bands of service, TV broadcasting band (470–806 MHz) was heavily occupied about 58 %, and the average occupancy in Ho Chi Minh City was found to be 13.74 % which was 1.46 and 1.15 % more than Long an province and New York, respectively.

Then to evaluate the spectral activity in Chicago, the Illinois Institute of technology (IIT) measurement campaign monitored the spectrum range from 30 to 6000 MHz spanning 3 years starting from July 2007 [8]. This paper also illustrated the noticeable effect in 609–806 MHz range due to transition of TV band from analog to digital in 2009. Here, the equipment consisted of three directional antennas connected to a pre-selector and a Rohde & Schwarz FSP-38 spectrum analyzer, and a computer which was controlling the entire operation. Here, the threshold varied between 5 and 10 dB above the average noise floor in order to give accurate spectrum occupancy result. Average occupancy over this entire band was found to be 18, 15 and 14 % for the year 2008, 2009 and 2010, respectively.

3.4 Short Term Measurements

3.4.1 Spain Measurement Campaign

The spectrum occupancy in urban Barcelona, Spain was evaluated in the frequency range 75 MHz to 3 GHz in outdoor environment which was carried out by Radio Communications Group of the Technical University of Catalonia (Universitat Politècnica de Catalunya) [9]. The measurement equipment was composed of a broadband discone antenna AOR DN753 covering the desired frequency range, and its output was connected to the Anritsu spectrum master MS2721B spectrum analyzer of frequency range from 9 kHz to 7100 MHz through 10 m low loss coaxial cable RG-58A/U. The entire frequency band was divided into six consecutive 500 MHz band and each band was measured for continuous 48 h. The threshold was set to make the false alarm probability to 1 %. The spectrum below 1 GHz was heavily occupied whereas the frequency range between 1 and 3 GHZ was mostly vacant. The overall average duty cycle in this desired frequency band was observed 22.57 %. To extend this measurement and to predict the spectrum occupancy level discussed in [9] more accurate measurements were performed for 24 h continuous study over different realistic rich diversity of scenarios in the city of Barcelona, Spain [29] which includes high points to provide line of sight path, indoor environments when the CR users were mobile users inside the building and outdoor locations at the ground level in open areas and in between the buildings when the CR users were moving down the street in the urban environment. The measurement setup included two broadband discone-type antennas of frequency range from 75 to 7075 MHz same as [9], a Single-Pole Double-Throw (SPDT) switch for selecting the desired antenna. Additionally, to improve the overall sensitivity and to nullify the out-of-band signal a low noise amplifier and several filters were employed respectively. The threshold was calculated as per [9]. The average duty cycle of indoor scenario was less than the outdoor environment due to presence of radio propagation blockage which results lower signal strength. It was obvious that the average spectrum occupancy was more below 1 GHz band. Furthermore, the author developed an extensive method to evaluate the duty cycle model for both analogical and digital TV band measured in any geographical location which was given by

$$DC = Q\left(\frac{Q^{-1}\left(P_{fa}\right)\sigma_{\eta} - SNR}{\sigma_{s}}\right) \tag{2}$$

where SNR represents the average Signal to Noise ratio in decibels while P_{fa}, σ_{η}, and σ_s represent the false alarm probability, standard deviation of the noise power and signal, respectively. Here, due to the consideration of practical scenario the overall average duty cycle is less than that of [9] which was only 12.10 %. Then the effect of various methodology aspects on spectrum activity was highlighted in [30]. The spectrum occupancy results can be evaluated accurately by considering several factors into account.

3.4.2 South Africa Measurement Campaign

The spectrum measurement system was designed in more populated density area at Hatfield area of Pretoria, South Africa for UHF (470–854 MHz), GSM 900 MHz downlink (935–960 MHz) and GSM 1800 downlink (1805–1880 MHz) by observing continuously for 6 weeks [10]. The received data was processed by the hardware and software used in this monitoring system. Figures 2 and 3 represent the hardware and software component used by this campaign.

The resolution bandwidths of UHF, GSM 900 and GSM 1800 were set 2000, 100 and 100 kHz, respectively. A new method was proposed namely maximum normal fit (MNF) to evaluate the threshold value and the accuracy was compared with recursive one-sided

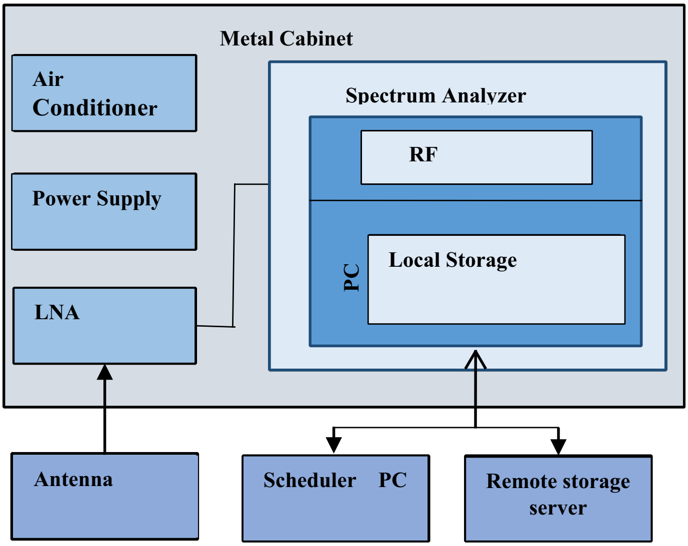

Fig. 2 Hardware component functional block diagram [10]

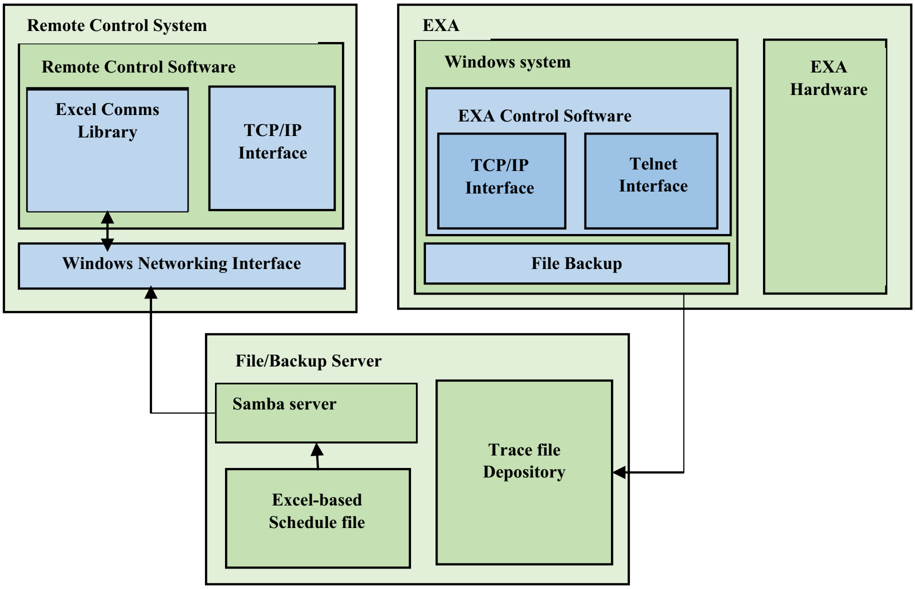

Fig. 3 Software system block diagram [10]

hypothesis test (ROHT) method. So, MNF method outperformed the ROHT method for reducing the occupancy error. Among these three bands GSM downlink band showed the highest occupancy about 92 %.

3.4.3 Beijing Measurement Campaign

In Beijing [11], the spectrum usage pattern was found out by continuous 24 h observation over the frequency range from 450 to 2700 MHz. The measurement equipment consisted of an Omni-directional BOGER DA-5000 broadband antenna covering the frequency band 70 MHz–3 GHz. An Agilent N9030A Spectrum Analyzer with frequency measurement capacity 3 Hz–3.6 GHz was used to receive the signal from an antenna and it has the capability to detect the lower value signal i.e. from −154 dBm to higher signal value 30 dBm. The resolution bandwidths were set 15, 100 and 200 kHz depending on the measured frequency bandwidth. The threshold was taken 5 dB above the noise floor. The cellular GSM 900 MHz band showed the highest average spectrum occupancy i.e. 45.52 % and the overall average spectrum occupancy rate was found to be 13.5 %.

3.4.4 Europe Measurement Campaign

Measurements were carried out in three different locations of two countries named Czech Republic and France during the year 2008 and 2009, respectively for the frequency bandwidth 400 MHz–3 GHz [12]. Three sets of measurements were taken in three regions namely, in the suburb of the city of Brno in the Czech Republic in July 2008, in suburb of Paris and in the city of Paris in February and December 2009, respectively. The received signal was captured by highly directive wideband log periodical antenna with 60^0 half power beam width at 3 GHz. So the antenna was rotated 6 times to analyze the relevant area continuously for 24 h. Then the signal was fed to the Rohde & Schwarz FSP and Tektronix RSA3408A spectrum analyzer setting two resolution bandwidths 3 and 55 kHz for Czech Republic and France, respectively. The entire frequency band was divided into 20 MHz sub bands. The threshold value was chosen 7 dB above the average noise floor. Region 2 showed the highest occupancy 47.9 % in GSM 900 MHz band whereas region1 showed the minimum occupancy 0.2 % in ISM band. The average occupancies in these three different regions were 6.5, 10.7 and 7.7 % respectively. The lower spectrum utilization in Czech Republic indicated the existence of other wireless system in that investigated band.

3.4.5 China Measurement Campaign

A detailed occupancy studies along with the spectral and spatial correlation measurement between the channels belonging to the same service but different locations were carried out in four locations concurrently in Guangdong province of China covering the frequency range from 20 MHz to 3 GHz [13]. The objective was to find out the channel statistics for both urban and suburban area. The data was collected continuously for 1 week from four different locations, out of these, two were downtown area and other two were suburban areas. The measurement equipment consisted of a R&S EM550 super heterodyne VHF/UHF Digital Wideband Receiver. EM550 is a super heterodyne receiver covering the frequency bandwidth 20 MHz to 3.6 GHz. The resolution bandwidth was

0.2 MHz. Here, the channel state was represented as binary sequence 0 and 1 denoting idle and busy respectively and was obtained by comparing the received signal with the threshold which was 3 dB higher than the minimum signal value of the channel over the entire duration of observation. The Spectral and spatial correlation were investigated for GSM 900 uplink and GSM 900 downlink frequency band. The small value of spectral correlation indicated that some of the channels in this band were permanently idle and some were busy, while the higher spatial correlation value represented that the spectrum utilization were highly correlated irrespective of type of location. It was obvious TV channel and GSM 900 MHz frequency band were predicted to be highly occupied.

3.4.6 Netherland Measurement Campaign

Recently 2.36–2.4 GHz band was drawing much more attention of the CR researchers after the FCC noticed to make this band used for body sensor network. To present the practical utilization, the authors conducted spectrum measurement in the Eindhoven area, in the Netherlands [14], where this band was currently allocated for land mobile and amateur radio services. The measurement set up consisted of 2.4 GHz receiving antenna which was then connected to Rohde & Schwarz ZVL6 spectrum analyzer with resolution bandwidth 30 kHz. Data was processed in laptop connected to the spectrum analyzer through Ethernet cable. The whole bandwidth was observed for 2 days with 12 h observation per each day (9 a.m.–9 p.m. and 9 p.m.–9 a.m.). The threshold was decided 10 dB above the noise floor. Complementary cumulative distribution function (CCDF) of the received power and cumulative distribution function (CDF) of average occupancy were analyzed for different narrow band signals considering 2362.48, 2376, 2386.83, and 2400.05 MHz as center frequencies. Out of these, the signal centered at 2386.83 and 2376 MHz experienced highest occupancy and highest average idleness in the wireless medium i.e. 16.7 and 99.9 %, respectively. Hence, this bandwidth can be utilized for wireless health care services.

3.4.7 Chicago Measurement Campaign

The Chicago spectrum measurement campaign performed long-term studies in the entire bandwidth from 30 to 3000 MHZ in November 2005 [15]. The aim of these studies was to identify the underutilized spectrum band which can be accessed by the secondary users dynamically. This paper also provided sufficient information in developing proper spectrum sharing algorithm. The investigation was conducted in urban area with highly deployed wireless users. The measurement equipment used here were an omnidirectional antenna for the frequency below 1 GHz and a small log periodic array for frequency greater than 1 GHz, both was connected to SSC-designed high linearity pre-selector composed of filters, RF switches and preamplifier at their base. The purpose of using pre-selector was to increase the measurement sensitivity and dynamic range. The output of the antenna was fed to 3 GHZ spectrum analyzer. From the spectrum occupancy plot, it has been observed that the frequency bandwidth from 54 to 88 MHz was heavily occupied with average duty cycle 70.9 % whereas the spectral range from 2300 to 2360 MHz showed lower spectral occupancy <20 %. The overall spectrum occupancy has been found to be 17.4 and 13.1 % more than the New York's aggregate occupancy result.

3.4.8 Germany Measurement Campaign

An extensive measurement campaign has been conducted in the city of Aachen, Germany in the frequency bandwidth 20 MHz–3 GHz [16]. The main aim of this research was to investigate the signal statistics both in the outdoor and indoor scenario measuring continuously over 7 days. It was obvious that the desired band in outdoor scenario was highly occupied than the indoor scenario. For this wide band of measurement two different antennas were used, namely AOR DA-5000 larger and AOR DA 5000JA smaller discone antennas for the frequency range 20 MHz to 1.52 GHz and 1.5–3 GHz respectively. Another random antenna was also used which can cover up to 10 GHz. The received signals from antennas were fed to an Agilent E4440A spectrum analyzer with setting 200 kHz resolution bandwidth. The maximum, minimum and average PSD were analyzed over the entire investigated band. The threshold was chosen 3 dB higher than the average noise floor. Very high spectrum occupancy nearly about 100 % was observed in outdoor scenario due to the presence of direct-line of sight propagation while indoor measurement showed lower occupancy about 32 %. Hence, spectrum statistics was highly affected by the location and decision threshold. Furthermore, the authors discussed more details about the Amplitude probability distribution (APD) to gather more information about the potential bands for secondary usage. In addition to this, with the previous measurement setup, several adaptive spectrum sensing techniques with detailed outage probability were discussed in [31] as the performance metrics of these techniques.

3.4.9 Singapore Measurement Campaign

Another study on spectrum occupancy has been performed in Singapore to identify the potential candidate bands for secondary utilization in context of CR [4]. The whole frequency band ranging from 80 MHz to 5850 MHz was evaluated for 24 h measurement over 12 weekday period. Unlike other countries, the occupancy pattern in Singapore is also affected by the signal statistics of the nearby countries. The measurement system consisted of a BiConiLog antenna of model 3149 made by ETS-Lindgren covering the frequency range of 80 MHz to 6 MHz and connected to 750 W AC power supply. The antenna output was fed to the Agilent E4407B which can operate in the frequency range 9 kHz to 40 GHz able to measure the range from -150 to 30 dBm. This antenna was connected to rotator to achieve the Omni-directional effect. The overall spectrum was divided into more 60 MHz frequency bands, and each band was observed for continuous 24 h. The resolution bandwidth was set at 10 kHz. The threshold was chosen 6 dBm above the minimum received power level. From the results, it was seen that the band 490–614 MHz was heavily occupied with average duty cycle 52.35 % while all the bands from 2400 to 2700 MHz, from 3400 to 4200 MHz and from 5755 to 5875 MHz remained unused. The average occupancy of whole band was found to be 4.54 %. Hence, most of the bands allocated for different services can be used dynamically to get the CR deployed successfully in Singapore.

3.4.10 UK Measurement Campaign

An extensive 12 days measurement campaign was conducted in University of Hull (UK) for the 180–2700 MHz frequency band [17]. The measurement setup consisted of Bilog Antenna CBL 6143 covering the frequency range from 30 to 3000 MHz, which was

Table 2 Summary statistics of short-term measurement campaigns

Location	Investigated frequency range	Duration of observation	RBW	Threshold setting	Occupancy (%)
Spain [9, 29]					
Outdoor	75 MHz–3 GHz	48 h	10 kHz	P_{fa} is 1 %	22.57
		24 h			12.10
Indoor					
South Africa [10]	470–854 MHz	6 weeks	2 MHz	Based on total gain and received signal	20
	936–960 MHz		100 kHz		92
	1805–1880 MHz		100 kHz		40
Beijing [11]	450–2700 MHz	24 h	15/100/200 kHz	5 dB above noise floor	13.5
Europe [12]					
Czech Republic	400–3000 MHz	24 h	3 kHz	7 dB above noise floor	6.5
Suburban Paris			55 kHz		10.7
Paris			55 kHz		7.7
The Netherlands [14]	2.36–2.4 GHz	12 h each day for 2 days	30 kHz	10 dB above noise floor	16.7
Chicago [15]	30–3000 MHz	2 days		Varies	17.4
Germany [16]	20–3000 MHz	7 days	200 kHz	3 dB above noise floor	32
Singapore [4]	80–5850 MHz	12 weekdays	10 kHz	6 dB above noise floor	4.54
UK [17]	180–2700 MHz	12 days	30 kHz	5 dB above noise floor	11.02

connected to an Agilent E4407B spectrum analyzer for predicting the signal strength. The entire frequency range was divided into several blocks where each block was attended in 24 h interval. The resolution bandwidth was set 30 kHz. Threshold was considered 5 dB above the noise floor which varies for each block. GSM 900 MHz downlink band showed the highest average spectrum occupancy of 32.91 % whereas 2500–2700 MHz band was completely vacant. However, the average spectrum occupancy for the whole frequency range was 11.02 %.

The summary of average spectrum occupancy is presented in Table 2. It also highlights the effect of the diverse locations and scenarios on the spectrum resources availability. Hence, it provides most reliable platform for deploying CR successfully in near future.

4 Scope of Further Research

Accurate spectrum occupancy evaluation gives exact information regarding the spectrum usage pattern in a particular band. This would reduce any unnecessary delay to the SUs, improve the system throughput, and also the most important is it would avoid interference to the PU. In the measurement system, there are some important factors which greatly influence the spectrum occupancy statistics. Selection of these factors are really a challenging issues for achieving the final decision about the spectrum occupancy of a particular band.

4.1 Huge Data Set

Either it may be a short-term or long-term measurement system, the spectrum analyzer collects huge data set over a long period in the desired frequency band. Different spectrum analyzers have different sweep/trace points as per their manufacturing guide. Storing and processing such large volume of data is really a big challenge to the researchers who always intend to obtain the exact statistics of spectrum occupancy.

4.2 Frequency Range of Measurement

The measurement campaign conducted in the wide range of frequency band usually gives more realistic idea about the spectrum utilization over different bands allotted for different services. It has been observed from literature studies that ISM band is very lightly occupied and the main advantage is that there is no such differentiation between PU and SU in this band. So, this band can be thought as to be adopted for different devices and services operating in this high frequency band.

4.3 Threshold

As, most of the detection techniques employ energy detection method due to its low complexity and ease to implement, the selection of proper threshold plays a vital role in selecting accurate spectrum holes. Most of the techniques discussed in the literature have considered the threshold based on the false alarm probability or some dB above the noise floor. But in the single threshold based detection technique, minimization of false alarm probability leads to maximization of missed detection probability, which produces sensing error, and this may cause serious harmful interference to the PU. Hence, threshold should be selected such that it balances between false alarm probability and missed detection probability, thereby reduces the sensing error.

4.4 Less Utilized Band

Spectrum measurement studies showing the less utilized spectrum band cannot be considered as the final spectrum occupancy statistics to assess that band. The lower occupancy is may be due to the low power transmission from the PU, which cannot be identified by the receiver. Hence, long term studies over different population densities in different geographic regions of measurement provide a realistic idea about the actual statistics of the spectrum usage in these less utilized bands.

4.5 Presence of Malicious Users

Another important factor which influences the spectrum occupancy is the presence of malicious users in the band of measurement. These users send similar type of PU signal and try to make illusions to the receivers such that secondary receivers identify the malicious user as PU. Thus, spectrum occupancy increases which reduces the spectrum access probability. So, presence of malicious users need to be identified and their effects have to be mitigated while conducting the spectrum occupancy measurement in a particular band.

4.6 Prediction Models

There are several spectrum occupancy prediction models discussed in the literature. Some of them are based on artificial neural network (ANN) models [32, 33] and some are based on hidden Markov model (HMM) [34]. The accuracy of these prediction models is mainly depends on the efficiency of the algorithms used to train that specific model. So, by selecting suitable algorithm with less complexity one can design a better prediction model with higher accuracy.

4.7 Historical Data Set

The usage of historical data set in the prediction model not only improves the spectrum occupancy prediction accuracy but also minimizes the extra energy consumption made by the SUs during the spectrum sensing. This process is mainly effective when the PU shows a periodical behavior in its licensed band.

4.8 PU Traffic

Though accuracy in spectrum occupancy evaluation is the primary concern in CR, certain factors such as energy consumption or any disruption to the PUs have also the same importance. So, inclusion of PU traffic in the spectrum occupancy prediction model would provide accurate estimation of PU activity in the desired band which ultimately avoids unusual interference to the PU.

4.9 Cooperative Receivers

In the practical wireless environment, the received signal at the receiver often suffers from multipath effect, fading or any wireless impairments through its propagation path. These diverse effects degrade the signal strength at the receiver. Also, the single receiver which present in the shadowing region of large obstacles may cause hidden terminal problem. This effect can be minimized by using multiple CR receivers situated at different geographic regions. They receive the signal cooperatively from the licensed user. So, the cooperative receivers provide more accurate spectrum occupancy result as compared to the single receiver.

The literature studies show that still there are significant amount of licensed band available for the application of CR. Specially, the ISM band is almost vacant in most of the places. So, our future studies include better understanding of the different parameters that influences spectrum occupancy in less utilized spectrum band. This would help in identifying most suitable spectrum bands for future application of CR devices that operating in this high frequency band. Altogether, some factors need to be considered before obtaining a final decision about the spectrum occupancy of a particular band.

5 Conclusion

In this paper, we made a survey on past studies carried out by different campaigns in various diverse locations and scenarios. The results show that most of the bands are vacant at the date which can be utilized for the secondary usage. The overall occupancy statistics is very low worldwide, hence shows a step ahead towards the successful deployment of CR in near future. Also, we have discussed some of the future challenges which need to be taken care while evaluating the spectrum occupancy. This would surely help the researchers to propose new methodologies and prediction models for spectrum occupancy measurement. Further, we plan to observe the spectrum occupancy statistics in 5 GHz band which is now becoming more popular for its flexibility to support WLAN service based on IEEE 802.11 as part of our future work. This enables the CR devices to operate in this band with very less interference.

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