Spectrum Occupancy Evaluations at 2.35-2.50 GHz ISM Band in a Hospital Environment

Muhammad Hasnain Virk
Centre for Wireless
Communications (CWC)
University of Oulu, Finland
mvirk@ee.oulu.fi

Risto Vuohtoniemi
Centre for Wireless
Communications (CWC)
University of Oulu, Finland
rv@ee.oulu.fi

Matti Hämäläinen
Centre for Wireless
Communications (CWC)
University of Oulu, Finland
matti.hamalainen@ee.oulu.fi

Juha-Pekka Mäkelä
Centre for Wireless
Communications(CWC)
University of Oulu, Finland
juha.makela@ee.oulu.fi

Jari Iinatti
Centre for Wireless
Communications (CWC)
University of Oulu, Finland
jari.iinatti@ee.oulu.fi

ABSTRACT

In this paper we describe an overhauled, robust approach for spectrum occupancy evaluations (SOE) at industrial, scientific and medical (ISM) band in a hospital environment for interference free, dynamic spectrum access (DSA). A novel bandwidth and center frequency estimation algorithm is presented in order to distinguish among various coexisting systems. Different results are inferred by processing data obtained from a day long measurement campaign including channel occupancies, frequency band occupancy, and spectrum resource occupancies.

Keywords

Spectrum occupancy measurements, Interference modeling, Frequency band occupancy, Spectrum resource occupancy, WBAN, ISM band, Dynamic spectrum access, Interference analysis, Co-existence.

1. INTRODUCTION

Radio frequency spectrum is a scarce resource and the dynamic nature of spectrum not only imposes certain limitations, but also creates many challenges for system designers. Modern concepts to cope with this problem involve DSA/cognitive radio (CR) solutions where secondary users opportunistically look for and then subsequently utilize the whitespaces available [1]. ISM band is an unregulated, unlicensed frequency band where many conventional communication technologies share the frequency resource, try to coexist and operate together harmoniously, e.g., wireless local area network (WLAN), Bluetooth (BT), ZigBee, Cordless phones, etc. The IEEE 802.15.6 (2012) based wireless body area network (WBAN) devices are running contenders for resources as one of the three standard physical layers (PHY), Narrowband (NB) PHY apart from medical implant communication service (MICS) and wireless medical telemetry service (WMTS) bands, operates in ISM band worldwide [2]. In pursuit of providing broadband access to resource hungry user applications, ISM band is of special interest to be exploited for aggressive resource reuse. Also, on the other hand, it is important for WBANs or any other system operating in ISM band to detect, identify and adapt in response to the potential interferers. Several studies have shown that before indulging into actual complicacies of dynamic/runtime spectrum sensing and adaptive spectrum reuse strategies, it is helpful to gather statistical information relating to the systems and devices utilizing the band under observation [3]. These statistical evaluations are called as spectrum occupancy measurements which generally represent the utilization of a channel, band or spectrum resource over a period of time. Dynamic spectrum access networks and wireless spectrum reutilization policies rely on accurate, robust spectrum utilization statistics obtained from above mentioned spectrum occupancy evaluations or surveys.

This paper is organized into four sections. Section 1 comprises introduction. Section 2 sheds light upon previous related research work as well as the motivation for this work. Section 3 discusses the contribution of this paper to the existing literature, measurement equipment, measurement parameters and resulting plots. Section 4 summarizes the paper and discusses future prospects.

2. BACKGROUND AND MOTIVATION

Medical information communication technology (ICT) is one of the most interesting and challenging research areas for both industry and academia. As described earlier, there are several conventional wireless communication technologies that may appear to be competing for bandwidth resources in a hospital environment. In addition to that, there are a few non-communication systems which can also cause interference to the communication systems, e.g., microwave ovens, microwave diathermy, and microwave ablation etc. Wireless sensor networks (WSNs) involving communication techniques, e.g., IEEE 802.15.6 (WBAN), IEEE 802.15.4 (ZigBee) and IEEE 802.15.1 (BT) have been exten-

BODYNETS 2014, September 29-October 01, London, Great Britain

DOI 10.4108/icst.bodynets.2014.256965

sively studied for health care systems. Especially ZigBee, BT Smart based WSNs are rapidly being deployed in hospitals and strategies regarding Internet of Things (IoT) are being unrolled. All this will add up to significantly increase the electromagnetic clutter in hospital environments and hence interference will cause major threats. In this respect, it is important to evaluate the shared spectrum and calculate duty cycles, i.e., occupancies of various interferers. In order to undertake such evaluations, spectrum occupancy measurement campaigns or surveys come into picture. Generally, spectrum occupancy measurements involve collection of measurement data, processing the measured data for occupancy assessment and development of models to characterize spectrum occupancy [4, 5]. The international telecommunication union radio communication sector (ITU-R) guidelines for spectrum occupancy measurements are elaborated in a special handbook [6] and also in two short reports [7] and [8]. There is substantial amount of literature available regarding spectrum occupancy measurements, e.g., [3–5] and [9–14]. Stochastic modeling of spectrum occupancy is also extensively studied in [15–19]. Spectrum occupancy measurements usually involve:

a) Spectrum sensing, utilizing an antenna coupled with a band pass filter and a spectrum analyzer.

b) Sample collection and saving the records in some disk drive.

c) Processing and analysis of saved data in order to calculate occupancies.

Spectrum occupancy measurements handbook published by ITU-R suggests to divide the sample space, i.e., one full record of the band (sweep) into channels of the expected system which is utilizing the spectrum resource. Then, each channel is searched for number of samples above a predefined noise threshold. If more than 50% of the samples in the channel are above noise threshold, channel is marked as occupied. In this way, individual channel occupancies (CO) are calculated for all the channels. There are two more metrics which can also be calculated, frequency band occupancy (FBO) and spectrum resource occupancy (SRO). FBO provides statistical information about how much the whole frequency band is used, independent of a particular system. SRO is a system specific metric, which gives information about the utilization of resources available to a specific system [6].

From cognitive radio point of view, it is important to determine not only the duty cycle, i.e., occupancies but also the characteristics of the signals from various interferers, e.g., modulation type and order, single carrier or multicarrier, hopping sequence, chip rates, center frequency and bandwidth estimates etc. The cognitive radio should have the capability to blindly identify interference and try to mitigate its effects. The method adopted for this article regarding spectrum sensing is energy detection (ED) based. There are various other spectrum sensing mechanisms as well such as cyclostationary features method, wavelet decomposition, and matched filtering [20]. All of these on their part reveal certain aspects or features of the signals, but they scale high in order of complexity as compared to energy detection. ED is simple and fast but notoriously coarse. It only considers magnitude and loses phase part of the signal, therefore fails to dig out various features of the signals, e.g., cyclostationarity would have enabled us to distinguish between single carrier and multicarrier systems. We chose to stick with ED in order to exploit its simplicity and easy processing, but on the other hand we also wanted to avoid underestimation or over estimation. So we had to come up with a re-engineered approach to calculate duty cycles more efficiently, and separate the interfering systems on the basis of center frequency and bandwidth estimates.

3. MEASUREMENT CAMPAIGN

A day long spectrum occupancy evaluation campaign was undertaken at Oulu University Hospital. Such evaluations or campaigns are highly dependent upon the location of measurement equipment. In our case, it was placed near the reception area.

3.1 Measurement Equipment and Parameters

Measurements were carried out using high performance spectrum analyzer (SA) Agilent E4446A [21] connected to a computer. Instrument Control Toolbox was used to connect MATLAB directly to the spectrum analyzer enabling control over SA and direct measurement results analysis. The spectrum analyzer was connected with a 1 m length cable to an omnidirectional, wideband antenna ARA CMA-118/A [22]. The setup used in measurements is shown in Figure 1.

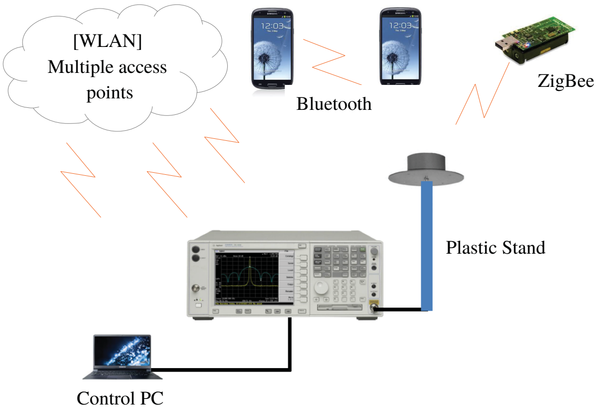

Figure 1: The Measurement Setup

Before the measurement campaign, signal levels were measured and dynamic range of the spectrum analyzer was optimized. The campaign parameters that we used are listed in Table 1.

Table 1: Parameter Settings

Parameter Name	Value
Bandwidth	150 MHz
Frequency Bins	1601
Resolution Bandwidth	300 kHz
Bin-width	93.7 kHz
No. of sweeps	10000
Sweep Time	2 ms approx.
Processing Time	22 ms
Integration Time	4 minutes
Measurement Duration	1 day (24hrs)

3.2 Contribution, Methodology & Analytics

3.2.1 Research Contribution

The main contribution of this research work includes:

a) CO, FBO and SRO calculation for the above said band in a hospital environment to characterize existing interferers.

b) A novel center frequency and bandwidth estimation algorithm named as Spatial Sample Clustering (SSC).

c) An overhauled, robust, and much more objective mechanism for spectrum occupancy evaluations with a sufficiently low desired probability of false alarm, $PFA_{DES} = 0.05$.

SSC enables us to calculate occupancies for different radio technologies simultaneously by identifying and classifying signals belonging to those technologies. To test the proposed approach and SSC prior to original campaign in hospital, a 5 minutes long experiment was performed at the CWC premises, University of Oulu. The measurement equipment was set to monitor 2.4 GHz ISM band and in the near proximity, 2 smart phones plus a TelosB ZigBee device [23] were operating. The premises come in the coverage of an open, citywide WLAN named as panOulu. Smart phones were made to send a song library over Bluetooth, and ZigBee device was transmitting every two seconds. SSC was found to be able to distinguish between IEEE 802.11b/g (20 MHz system), IEEE 802.11n (40 MHz system), Bluetooth Smart (2 MHz system) and ZigBee (1 MHz system) with correct center frequency estimates. The desired probability of false alarm is a metric that is set while establishing dynamic noise thresholds. It is a quantitative metric that establishes a limit to misclassification of noise samples into legitimate signal sample space.

3.2.2 Research Methodology for Hospital Campaign

The methodology adopted for this research work was passive, i.e., at first the measurements were recorded continuously over 24 hours and then post processing and analysis were undertaken offline. A script running over control PC was responsible for collecting and saving measurements from spectrum analyzer. This control script had been using virtual instrument software architecture (VISA) libraries [21]. Transmission control protocol/internet protocol (TCP/IP) transactions between the script and spectrum analyzer were taking place over Ethernet. This particular script was developed in-house. The frequency band chosen for observation spanned 150 MHz from 2.35 GHz to 2.50 GHz. The reason to start from 2.35 GHz was the fact that recently a quite band is allocated to provide 40 MHz of interference-free resources for medical devices, spanning from 2.36 to 2.40 GHz. Statistical integration time was chosen to be 4 minutes, in which 10000 sweeps over the band under observation were performed. Each sweep lasted for approximately 2 ms and 1601 samples per sweep were collected. It took 22 ms for saving a single sweep in an external hard drive. Resolution bandwidth was chosen to be 300 kHz which is roughly $^1/_4$ of the channel bandwidth, concerning the smallest narrowband system in terms of channel bandwidths, existing in the band, e.g., 1 MHz ZigBee channel or 1 MHz Bluetooth channel.

3.2.3 Dynamic Noise Threshold

In order to dig legitimate signals very close to noise levels especially in case of low SNR or spread spectrum scenarios, one cannot rely upon static noise thresholds. From previous research works, we adopted a dynamic noise threshold algorithm known as median forward consecutive mean excision (Med-FCME) [14]. Contrary to previous implementations, we applied it per sweep. The idea was to establish a noise threshold for every sweep because after a single sweep we encountered a 22 ms long blind period, when measurement equipment was saving the sweep data, and supposedly the noise floor fluctuated. Clean sample rejection rate (CSRR) is a measure to quantify the number of noise-only samples wrongly classified as outliers having signal components by FCME. The concept of CSRR is presented in [24]. CSRR can be preset as a probabilistic limit so that we tolerate only a given amount of misclassification, i.e., a false alarm. This metric is termed as desired probability of false alarm, PFA_{DES} . This desired probability of false alarm value is given as a parameter to the FCME algorithm which calculates a threshold for consecutive mean excision T_{CME} as

$$T_{CME} = -\ln(PFA_{DES}) \tag{1}$$

and then performs the iterative algorithm to find out the noise thresholds. We set a target CSRR for our measurements to be 5%, i.e., $PFA_{DES} = 0.05$. Hence, $T_{CME} = 2.99$. After establishing a noise threshold, the sample matrix was modified. Only those samples were retained in the sample matrix, which were found above the noise threshold, i.e., potential signal samples were retained. Suppose $\boldsymbol{\alpha}$ is the original sample matrix and $\boldsymbol{\beta}$ is the modified sample matrix, then mathematically,

$$\beta_{i,j} = \alpha_{i,j} \;\; if \;\; \alpha_{i,j} > Threshold(i) \tag{2}$$

where i =1,2,3,. . .,10000 and j =1,2,3,. . .,1601.

3.2.4 Spatial Sample Clustering (SSC)

The modified sample matrix is then sent to SSC block for identification and classification based upon center frequency alignment and bandwidth occupied. SSC takes in samples, sweep by sweep and borrows a few of the concepts from binary search algorithms for clustering the samples [25]. The key point here is the choice of pivots and the maximum allowed gap between two samples to mark signal boundaries. The idea is that most probably we would find the sample with highest power in near proximity of the main lobe of the signal that would be chosen as a pivot sample. And then the nearby samples are clustered around the pivot. If two samples on any side of the pivot are apart from each other more than a maximum allowed gap, then the sample nearest to the pivot is assumed to be the signal boundary. For identifying multiple signals in a single sweep, clusters and gaps are found sequentially. Figure 2 depicts the idea of pivot selection and marking the signal boundaries. In order to infer the center frequency of the signal, SSC first calculates the bandwidth occupied by the signal as

$$BW_{Measured} = N \triangle f \tag{3}$$

where N is the number of samples inside the signal boundaries marked, and $\triangle f$ is the bin-width, i.e., sample bandwidth. In order to compensate for channel nulls and under sampling of the signal, SSC uses the concept of relative bandwidths. Actually, ITU-R is essentially recommending relative bandwidth concept when it states the premise of 50% bandwidth. In this research work we established relative bandwidth measures heuristically based on actual data. The idea of relative bandwidths is that one may expect a percentage of a channel with a bandwidth $\boldsymbol{B}$, above noise threshold at a given time. For example, in a 40 MHz IEEE 802.11n channel, 33.75 MHz is used by subcarriers and a 50% relative bandwidth means that we expect at least 16.86 MHz of the channel above noise threshold to mark it occupied with confidence.

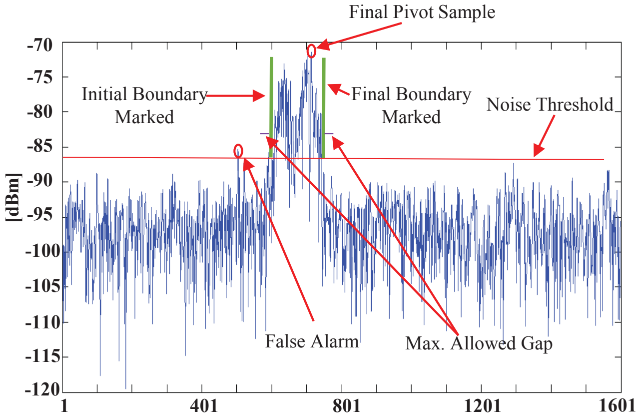

Figure 2: Pivot & Signal boundaries in SSC

Based on preliminary analysis 50%, 20% and 40% relative bandwidths for IEEE 802.11n, IEEE 802.11b/g, and narrowband systems respectively, were selected. SSC compares the measured bandwidth with the relative bandwidths and determines the channel bandwidth and hence the system pertaining to that particular channel bandwidth. For example if

$$BW_{Measured} \geq Rel_{BW40} \tag{4}$$

where $BW_{measured}$ is the actual measured bandwidth by the measurement equipment and Rel_{BW40} denotes the relative bandwidth, then the channel is marked as a 40 MHz wide channel. The center frequency is found by calculating Minkowski distances [26] among a set of the known center frequencies of the IEEE 802.11n in 2.4 GHz band and the frequency sample with highest received power i.e., pivot. Center frequency is selected by evaluating minimum Minkowski distance.

SSC performs its operations around pivots, and when it finds a sample above noise threshold, it marks it as a temporary initial boundary. Then it essentially looks for the continuation of the potential signal. To overcome channel nulls, SSC tolerates a defined bandwidth null portion, i.e., a gap between two samples which are above noise level. This gap is determined heuristically by considering the known channel separations of the systems. For example, maximum gap allowed for wideband signals, had been 1.87 MHz, i.e., 20 samples. So if the encountered gap exceeds

$$GAP_{MAX} = 20 \times 93.7 \text{ kHz} = 1.87 \text{ MHz} \tag{5}$$

and the potential signal bandwidth falls in a category defined by relative bandwidth of a system, initial and final boundaries are confirmed. Initial boundary is marked by the first sample which was previously marked as a temporary initial boundary and the final boundary is marked by that sample after which the gap started. If the gap is found but the potential signal does not fall into any category, it is considered as a false alarm. The bandwidth of the signal is the bandwidth enclosed by the initial and final boundary. As mentioned earlier, pivot selection is very important here. A pivot is just a sample with higher power than others. If another sample in close proximity is found at power higher than the prior one, before finding a legitimate gap, it is replaced by the new one as pivot of the potential signal. The bandwidth of the signal in relation to the relative bandwidths characterizes the system and then SSC calculates Minkowski distance between the selected pivot sample and the set of legitimate center frequencies of the system. The one with the minimum distance is selected as the center frequency of the signal.

SSC can estimate bandwidths and center frequencies, but it cannot distinguish between certain parameters of different systems in some cases. For example, in case of 20 MHz WLAN systems, it cannot distinguish between an orthogonal frequency division multiplexing (OFDM) and a direct sequence spread spectrum (DSSS) system. Same is the case with 2 MHz Bluetooth Smart and wireless mouse or keyboard. SSC is also responsible for making structures of signals identified with their timing information and categorizes them into their respective systems, so that occupancy evaluations could be performed.

3.2.5 Occupancy Evaluations

Occupancies are evaluated by statistically integrating over 4 minutes of time even though ITU-R suggests 5 minutes, 15 minutes, etc. We selected 4 minutes for ease of operation because our 10000 sweeps were being completed in 4 minutes. Three types of occupancy metrics were calculated; CO, FBO and SRO. Suppose N is the number of signal occurrences in a given channel k belonging to a certain system m in integration time τ then the probability that the kth channel is occupied is given as

$$p_m^k = \frac{\sum_{i=1}^{N} O(f_k, \tau_i)}{N} \tag{6}$$

where f_k is the frequency span of the channel belonging to a system m and τ_i is the slice of time τ at the ith occurrence, i.e., ith sweep and $O(f_k, \tau_i)$ represents occupancy. Multiplying p_m^k with 100, the channel occupancy (%) is found as

$$CO(m, k, \tau) = p_m^k \times 100. \tag{7}$$

For FBO calculation, assume there are L samples spanning in the whole band under observation, N sweeps, and ψ is the noise threshold. A binary sample matrix B_{SM} is produced from the original sample space S as,

$$B_{SM} = \begin{cases} 1 & \text{if } S(N, L) \geq \psi \\ 0 & \text{if } S(N, L) < \psi \end{cases} \tag{8}$$

then FBO after a single sweep i is given by,

$$FBO(i) = \frac{\sum_{j=1}^{L} B_{SM}(i, j)}{L} \tag{9}$$

and hence FBO_τ at integration time τ is given by,

$$FBO_\tau = \frac{\sum_{i=1}^{N} FBO(i)}{N}. \tag{10}$$

Multiplying FBO_τ with 100 we get FBO (%). In order to calculate SRO, we need priory information about maximum resources that particular system can allocate without causing interference, e.g., IEEE 802.11b/g usually allocates 3 non-overlapping channels out of 14 overlapping channels. For a specific system m with maximum allowed number of resources R_{MAX} and the number of resources actually occupied r, we can calculate SRO as,

$$SRO(m) = \frac{\sum_{i=1}^{R_{MAX}} CO(m,r,i)}{R_{MAX}}. \tag{11}$$

3.3 Data Analysis

Twenty four hours long data divided into 4 minutes long blocks was collected. The emphasis of this paper is upon analyzing a single day. In order to be processed, data was passed through dynamic noise threshold, SSC and occupancy evaluation blocks.

3.3.1 Occupancy Analysis

Occupancy analysis was undertaken for the data collected on Friday 13 th of December, 2013. Figure 3 shows a plot regarding one 4 minutes long block of data.

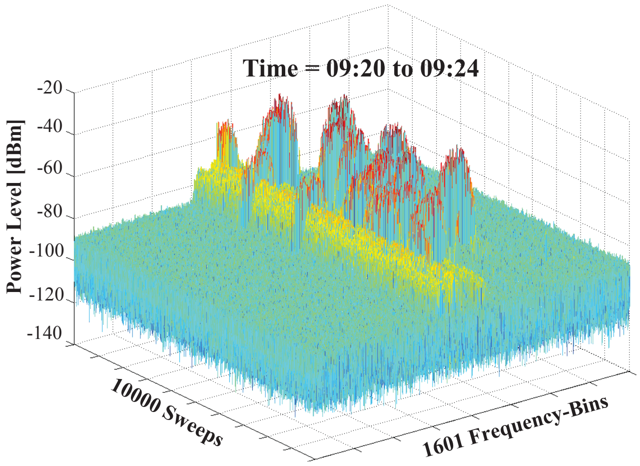

Figure 3: Raw, unprocessed interference plot

This is unprocessed, raw interference plot displaying all the traffic in the band as well as the noise floor. The processed data plots reveal the systems working in our band of interest. Figure 4 displays the channel occupancy (CO) analysis of IEEE 802.11b/g system in the whole day. Channel 1 of the system is occupied the most, maximum occupancy level recorded was 11%. Channel no. 6 was found to be moderately occupied with maximum occupancy level 7%. Channel no. 11 was least occupied with maximum level of 3%. Figure 5 depicts the channel occupancy analysis of IEEE 802.11n system. Channel 3 and Channel 9 seemed to have been occupied with pretty low occupancies. Maximum occupancy level recorded was 0.7% in channel 3. Figure 6 shows the channel occupancy analysis of narrowband systems. It should be noted that the color schemes used in temperature plots, i.e., Figures 4-6 are locally significant. For example the red color in Figure 4 marks near about 10% occupancy whereas in Figure 5, it marks near about 0.6% occupancy. The band from 2.35-2.40 GHz is found completely empty, which means the newly allocated quite band 2360 to 2400 MHz for medical purposes is open for exploitation. SSC was unable to distinguish among different narrowband systems. There had been 2 MHz wide signals as well as 1 MHz wide signals. Bluetooth Smart or Bluetooth low energy (LE) use 2 MHz wide signals with frequency hopping and Some proprietary protocols like the one used in Logitech Mice/Keyboards utilize 2 MHz bandwidth with time division multiplexing. SSC cannot infer a hopping pattern so it was not possible to discriminate with confidence among 2 MHz wide signals. Enough doubt is left to distinguish a ZigBee system from a 1 MHz wide Bluetooth system, as both use the same channel scheme. That is why all narrowband systems are shown in one single plot without any further processing. It also means SRO for narrowband systems cannot be calculated as we are unable to distinguish among systems.

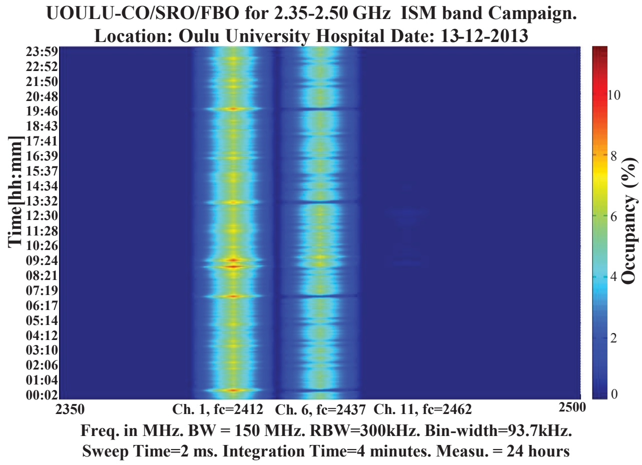

Figure 4: CO, IEEE 802.11b/g

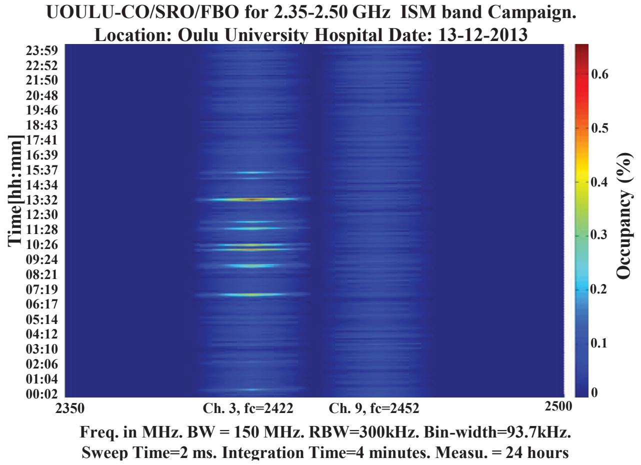

Figure 5: CO, IEEE 802.11n

Figure 7 shows the FBO and SROs for the whole day. Interesting finding is that the system independent metric FBO seems almost to follow the pattern of a system dependent metric, which is the highest, i.e., the most significant SRO of a system. In our case, IEEE 802.11b/g had been the most impactful system with highest SRO among all, and FBO nearly follows its distribution. Of course it is quite legit and logical as occupancies for IEEE 802.11n are very close to zero.

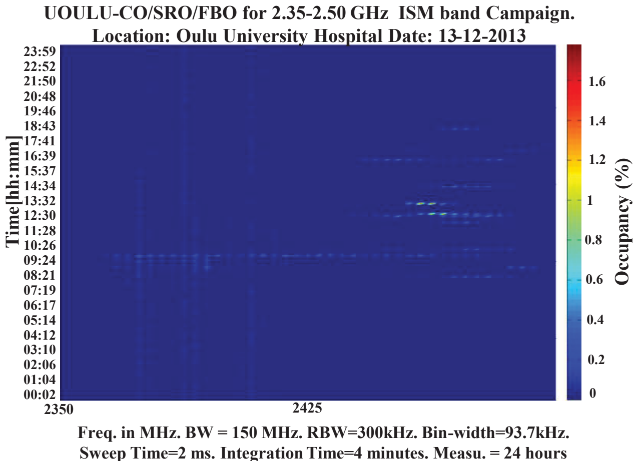

Figure 6: Occupancy, Narrowband Systems

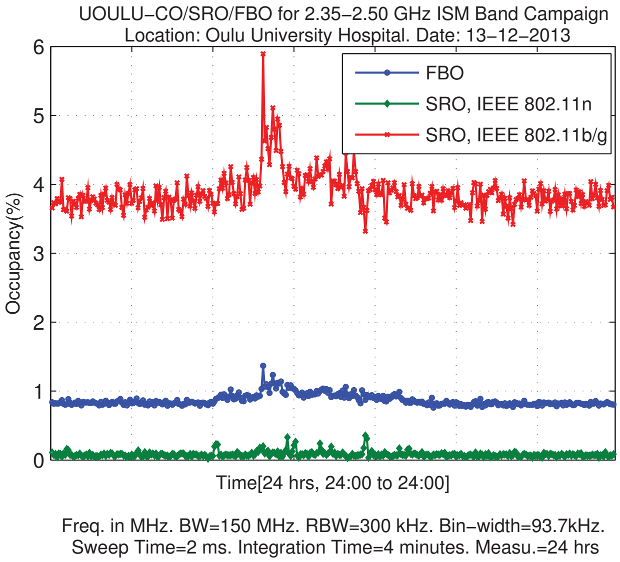

Figure 7: FBO, SRO for the identified systems

Figure 8 and 9 describe channel occupancy comparisons within systems. Out of 14 legitimate channels of IEEE 802.11b/g system, three channels (1, 6 and 11) were found to be occupied, which is the so called safest configuration, i.e., three non- overlapping channels. One strange observation was that whenever the Channel 1 was highly occupied, occupancy level of Channel 6 fell down.

However, there exists an explanation for such a behavior. IEEE 802.11b/g only specifies center frequencies and a spectral mask. IEEE 802.11b spectral mask requires that the signal power should be at least 30 dB less than its peak power at ±11 MHz and at least 50 dB less at ±22 MHz from the center frequency. If there is a very powerful transmitter, signal can be quite strong even beyond ±22 MHz point which means all channels will actually overlap, even the non-overlapping ones. This phenomenon gives rise to a problem known as near-far problem where two communication systems encounter interference when a foreign station that transmits on an adjacent channel is in much closer proximity than the intended one. What we are witnessing in Figure 8 is actually near-far problem, where the access point which is assigned Channel 1 is much closer to our measurement equipment as compared to the access point which is assigned Channel 6.

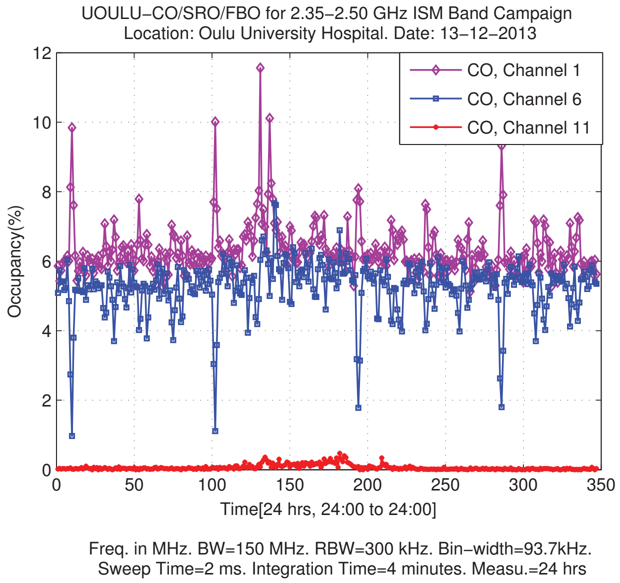

Figure 8: CO comparison, IEEE 802.11b/g system

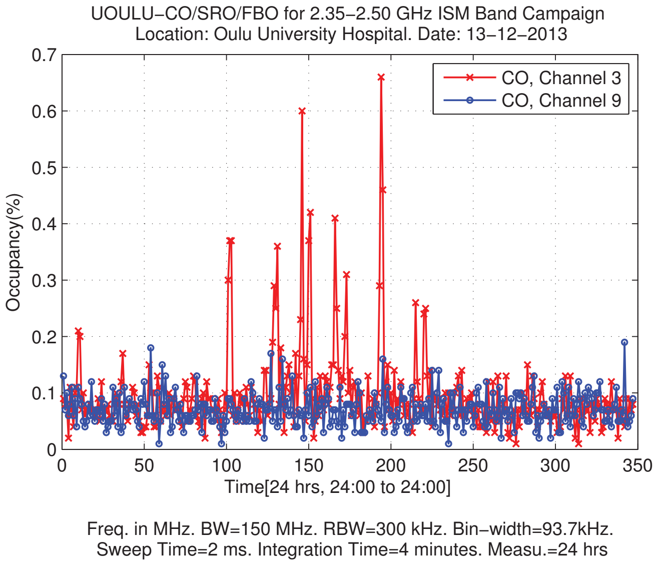

Figure 9: CO comparison, IEEE 802.11n system

In case of IEEE 802.11n system, adjacent channel interference is not seen. However the occupancies are very low as compared to IEEE 802.11b/g system. Another interesting inference from the analysis is the comparison of peak channel occupancy of the most dominant system, the SRO of that particular system and the overall FBO. When the channel occupancy of IEEE 802.11b/g Channel 1 (most dominant system) was 11% at almost 10 O'clock, SRO for the system was 6% and the FBO was less than 2%. It means 98% of the band resources were still available during the integration time of 4 minutes when the traffic was at its peak.

4. SUMMARY

The need was felt for a robust, overhauled spectrum occupancy evaluation for ISM band, including the new quite band for interference free communication. Medical devices working under the umbrella of wireless body area networks will be affected quite relentlessly by the interference caused by the devices working already in the ISM band. An SOE campaign was undertaked and certain stochastic parameters including CO, FBO and SRO were evaluated as well as a novel bandwidth estimation algorithm was proposed. The most dominant system found was IEEE 802.11b/g based WLAN system which reached maximum occupancy level of 11% at Channel 1. At peak time, SRO for IEEE 802.11b/g system reached 6%, whereas at the same time FBO was still under 2%. It implies that over the integration time of 4 minutes, 98% of the spectrum resources were free. The mandatory PHY for WBANs is IR-UWB (impulse radio ultra-wide band), so a study of 3 to 10 GHz spectrum would be worthwhile in the future. Longer campaigns and Stochastic mathematical modelling for SOE will open new gateways to predict the behaviour and mechanics of spectrum occupancy in hospital environment.

5. ACKNOWLEDGMENTS

The research work carried out for this paper has been partly funded by the Finnish Funding Agency for Innovation (Tekes) through EWiHS project and Academy of Finland through DWHN project.

6. REFERENCES

[1] V. Valenta, et al., Survey on spectrum utilization in Europe: Measurements, analyses and observations. In *"Proceedings of the 5th International Conference on Cognitive Radio Oriented Wireless Networks Communications", 2010*

[2] IEEE standard for local and metropolitan area networks - part 15.6: Wireless body area networks. *IEEE Std 802.15.6-2012*

[3] M. Islam, et al., Spectrum survey in Singapore: Occupancy measurements and analyses. In *"Proceedings of the 3rd International Conference on Cognitive Radio Oriented Wireless Networks and Communications", 2008*

[4] D. Datla, et al., A spectrum surveying framework for dynamic spectrum access networks. *"IEEE Transactions on Vehicular Technology", 2009*

[5] M. Hoyhtya, et al., Measurements and analysis of spectrum occupancy with several bandwidths. In *"IEEE International Conference on Communications", 2013*

[6] ITU-R handbook for spectrum monitoring. *ITU-R Handbook*, 2011.

[7] ITU-R SM.2256. 2012. spectrum occupancy measurements and evaluation. *ITU-R Report*, 2012.

[8] ITU-R SM.2180. 2010. impact of ISM equipment on radio communication services. *ITU-R Report*, 2010.

[9] M. López-Benítez et al., An overview of spectrum occupancy models for cognitive radio networks. In *"6th International Conference on Networking", 2011*

[10] M. López-Benítez et al., On the spectrum occupancy perception of cognitive radio terminals in realistic scenarios. In *"2nd International Workshop on Cognitive Information Processing", 2010*

[11] M. Biggs, et al., Occupancy analysis of the 2.4 GHz ISM band. *"IEEE Proceedings on Communications", 2004*

[12] D. Denkovski, et al., Parameter settings for 2.4GHz ISM spectrum measurements. In *"3rd International Symposium on Applied Sciences in Biomedical and Communication Technologies", 2010*

[13] J. Kokkoniemi and J. Lehtomaki. Spectrum occupancy measurements and analysis methods on the 2.45 GHz ISM band. In *"7th International Conference on Cognitive Radio Oriented Wireless Networks and Communications", 2012*

[14] J. J. Lehtomaki, et al., Energy detection based estimation of channel occupancy rate with adaptive noise estimation. *"IEICE Transactions on Communications", 2012*

[15] C. Ghosh, et al., A framework for statistical wireless spectrum occupancy modeling. *"IEEE Transactions on Wireless Communications", 2010*

[16] A. J. Gibson and L. Arnett. Measurements and statistical modelling of spectrum occupancy. In *"6th International Conference on HF Radio Systems and Techniques", 1994*

[17] Z. Wang and S. Salous. Spectrum occupancy statistics and time series models for cognitive radio. *"Journal of signal processing systems". 2011*

[18] M. Wellens, A. de Baynast, and P. Mahonen. Performance of dynamic spectrum access based on spectrum occupancy statistics. *"IET Communications",2008*

[19] L. Stabellini. Quantifying and modeling spectrum opportunities in a real wireless environment. In *"IEEE Wireless Communications and Networking Conference", 2010*

[20] T. Yucek and H. Arslan. Spectrum characterization for opportunistic cognitive radio systems. In *"IEEE Military Communications Conference", 2006.*

[21] Agilent Tech. Specification Guide. *http://www.cp.literature.agilent.com*

[22] ARA. Data Sheet for CMA-118/A Antenna. *http://www.datasheetlib.com/datasheet/814410/*

[23] Crossbow. Data Sheet for TelosB Mote. *http://www.willow.co.uk/TelosB*

[24] J. Lehtomaki, et al., Spectrum sensingwith forward methods. In *IEEE Military Communications Conference, 2006*

[25] H. Lim and N. Lee. Survey and proposal on binary search algorithms for longest prefix match. In *"IEEE Communications Surveys Tutorials", 2012*

[26] J. Merigo et al., A new minkowski distance based on induced aggregation operators. In *"International Journal of Computational Intelligence Systems"*