Measurement and Statistics of Spectrum Occupancy

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1. Introduction

Based on the conception of spectrum sharing, Cognitive Radio as a promising technology for optimizing utilization of the radio spectrum has emerged to revolutionize the next generation wireless communications industry Staple & Werbach (2004) Ashley (2006). In order to facilitate this technology, the present spectrum allocation strategies have to be re-examined and the actual spectrum occupancy information has to be studied systemically. To assess the feasibility of Cognitive Radio technology, the statistical information of the current spectral occupancy needs to be investigated thoroughly.

While preliminary occupancy information can be retrieved from spectrum licences, essential details are often unknown generally, which include the location of transmitters,transmitter output power, and antenna type, etc. Additionally, licences do not specify how often the spectrum is being occupied. Furthermore, the local environment affects the propagation of radio waves a lot. While these affects can be simulated, the results are hardly precision. Hence, in order to categorize spectrum usage, practical spectrum monitoring are vastly preferable to theoretical analysis Carr (1999).

Two important characteristics of the spectrum are the propagation features and the amount of information which signals can carry. In general, signals sent using the higher frequencies have smaller propagation distances but a higher data carrying capacity. These propagation characteristics of the spectrum constrain the identified range of applications for which any particular band is suitable Saakian (2011). A portion of spectrum range from 30-3000 MHz is known to be suitable for a wide variety of services and is thus in great demand, which became the main investigation in our project.

We studied the 100-2500 MHz spectrum with the radio monitoring systems which technical details have been fully recorded in this article. In this chapter,we will present the detail statistics of spectrum occupancies with graphics and tables, which give the overall profile of current spectrum usage in this spectrum. The conclusion of the statistical information from the spectrum monitoring experiments shows that the spectrum occupancy range from 100-2500 MHz are low indeed in the measuring locations and period. The average occupancies for most bands are less than 20%. Especially, the average occupancies in the 100-2500 MHz spectrum are less than 5%. This suggests that Cognitive Radio technology can physically play an important role in future communications, if the current radio spectrum allocation strategies would be modified Wang & Salous (2009).

2. Radio spectrum occupancy monitoring

2.1 Considerations for spectrum monitoring

Cognitive radio technologies require reconsideration the current regulations and policies of spectrum management. Spectrum monitoring is a fundamental function to support spectrum management. Spectrum measurements are critical to policy regulators and researchers in the development of new spectrum access technologies. Specifically, spectrum occupancy studies inspect what spectrum bands have low or no active utilization and thus may be appropriate for spectrum sharing. They also provide information on the signal characteristics within these bands, which is needed to design spectrum sharing algorithms. Referred to ITU (n.d.) the considerations of spectrum monitoring activities in our project include the following:

- that licensed user information from the frequency management databases only indicates that the use of the frequency is authorized. The number of assignments on a frequency does not give any actual use information of that particular frequency.
- that efficient Spectrum Management can only satisfactorily proceed if the monitoring information provides the radio spectrum regulators with adequate reliable information about the actual usage of the spectrum.
- that results of spectrum occupancy measurements will give information about the current use of frequencies to establish that the spectrum is being used efficiently and to assess the feasibility of the new technologies.

The overall goal of spectrum monitoring activities of our project is to depict the current levels of spectrum usage in the range 100 to 2500 MHz and its implications for cognitive radio. Central objectives include the following:

- to provide information of spectrum efficiency for determining planned and actual frequency usage and occupancy, and for assessing the feasibility of spectrum sharing technique.
- to provide data for statistical modeling.

The measuring system should be chosen carefully to ensure capabilities exist with the spectrum management agency to effectively monitor and analyze the frequency bands.

2.2 Monitoring system and site

A successful spectrum survey requires careful selection of a measurement site. The location chosen for measuring will affect measured spectrum occupancy. For example, measurements made in Durham are probably representative of many towns that have similar scale and do not have heavy military activity or maritime radio navigation etc. Generally, a site for spectrum monitoring requires Sanders et al. (1996):

- "limited numbers of nearby transmitters to prevent intermodulation or saturation problems that can arise even though pre-selection and/or filtering is used for survey measurements
- limited man-made noise such as impulsive noise from automobile ignition systems and electrical machinery that can add to the received signals of interest."

Figure 1 shows that the measurement locations for the spectrum occupancy project was the roof and inside of Engineering Building, Durham University.

Fig. 1. Measurement location

Because of the complexity and sophistication of wireless communication technologies, it is an ever-increasing challenge to monitor the spectrum, particularly considering the rapid growth of wireless, satellite, and point-to-point communication devices. Key considerations in the design of spectrum monitoring systems include types of equipment, data rate and complexity of data capture and processing, degree of integration with software tools for analysis. While considered the limited project budget and the existing equipment, we integrated independently 3 different spectrum monitoring systems for different frequency bands to satisfy the technique requirements.

The monitoring system for 100-1500 MHz spectrum in this project was configured as Figure 2. The system consisted of an omnidirectional Dressler ARA-1500 active antenna range from 50 to 1500 MHz connected by a 6 m RF cable to a diplexer RSM-2000 which allows the DC current for the preamplifier to be applied to the centre conductor of the RF coax, eliminating the need for an additional DC power feed conductor. The RSM-2000 also contains a 20 dB RF adjustable attenuator allowing received signals to be attenuated over the entire frequency range. In order to increase the dynamic range of the system, a highpass filter Mini-Circuits SHP-100 was connected to the output of the RSM-2000. A Jim M-75 low noise amplifier was inserted in front of HP 8560A spectrum analyzer to decrease its noise figure. The GPIB bus was used for logging the trace data onto the hard disk of a PC and for transferring control command sequences to the spectrum analyzer. Table 1 lists the configuration parameters of spectrum analyzer for scanning 100-1500 MHz. Justifications will be given in the next section.

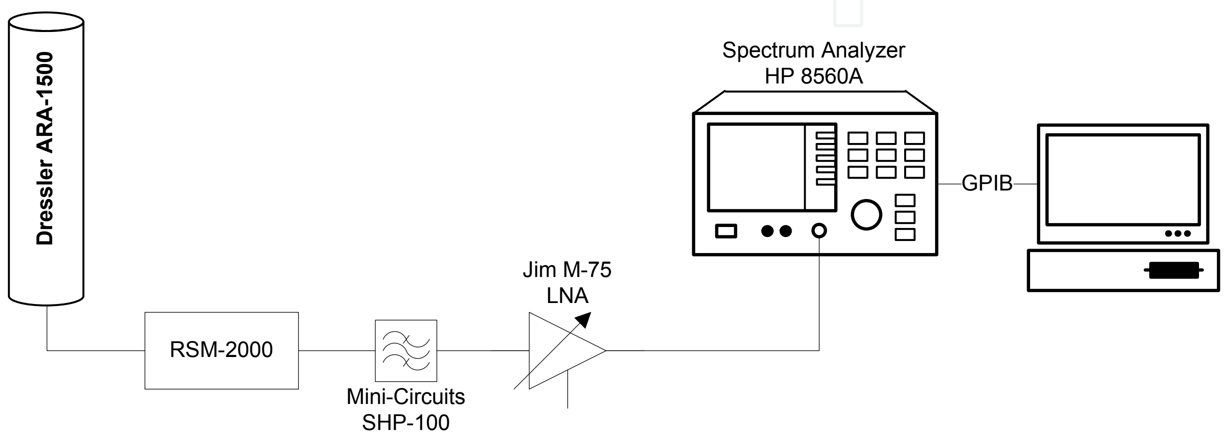


Fig. 2. Monitoring system for 100-1500 MHz spectrum

Model	HP 8560A
Frequency span (MHz)/ sweep	6
Resolution bandwidth (kHz)	10
Sweep time (s)	6
Detection mode	Sample
RF attenuator (dB)	10
Reference level (dBm)	-20

Table 1. Configuration parameters for scanning 100-1500 MHz

The monitoring system for 1500-2500 MHz spectrum was configured as in Figure 3. Instead of an omnidirectional antenna, an antenna array consisted of 4 directional Log-periodic antennas which enable the detection of signal incident directions. An RF switch controlled by the PC parallel port was used to choose a given antenna. Table 2 lists the configuration parameters of spectrum analyzer for scanning 1500-2500 MHz. Justifications will be given in the next section.

Model	HP 8560A
Frequency span (MHz)/ sweep	12
Resolution bandwidth (kHz)	10
Sweep time (s)	6
Detection mode	Sample
RF attenuator (dB)	10
Reference level (dBm)	-20

Table 2. Configuration parameters for scanning 1500-2500 MHz

3. Statistics of spectrum occupancy

It is often helpful to make some simple characterization of the data in terms of summary statistics and graphics. The spectrum measurements contained in this chapter can only be used to assess the feasibility of using alternate services or systems under restricted conditions. Extrapolation of data in this paper to general spectrum occupancy for spectrum sharing requires consideration of additional factors. These include spectrum management regulations, types of missions performed in the bands and new spectrum requirements in the development and procurement stages. Also, measurement area, measurement site, and measurement system parameters should be considered Freedman et al. (2007).

Highly dynamic bands where occupancy changes rapidly include those used by mobile radios (land, marine, and airborne) and airborne radars. These bands should be assigned a high priority and be measured often during a spectrum survey in order to maximize opportunities for signal detection. Bands that are not very dynamic in their occupancy such as those occupied by commercial radio and television signals or fixed emitters such as air traffic control radars need not be observed as often, because the same basic occupancy profile will be generated every time. Such bands should be given a low priority and less measurement time. An extreme case is that of the common carrier bands, which are essentially non-dynamic.

Boxplot in Figure 4 also known as a box-and-whisker diagram Freedman et al. (2007) is a convenient way of graphically depicting groups of numerical data. A boxplot shows a measure of central location (the median), two measures of dispersion (Q_1 and Q_3[1] and inter-quantile range IQR), the skewness (from the orientation of the median relative to the quartiles) and potential outliers (marked individually). Boxplots are especially useful when comparing two or more sets of data. Figure 5 shows overall occupancy statistics of each band in the frequency range 100 MHz to 2500 MHz, where the threshold was set to -100 dBm.
Figures 6 to 16 describe spectrum occupancy measurements and statistics of each band in the frequency range 100 MHz to 2500 MHz in Durham area during the period of 27/06/07 – 03/07/07. The spectrum occupancy in the *frequency domain* is shown in the top panel. This panel shows *Average* with time, in which the power values of each 10 kHz channel are linearly averaged during the measurement period, and *Maximum*, in which the result for any given

[1] The quantile function is the inverse of the cumulative distribution function. The p-quantile is the value with the property that there is probability p of getting a value less than or equal to it. Q_1 is 25-quantile, Q_3 is 75-quantile.

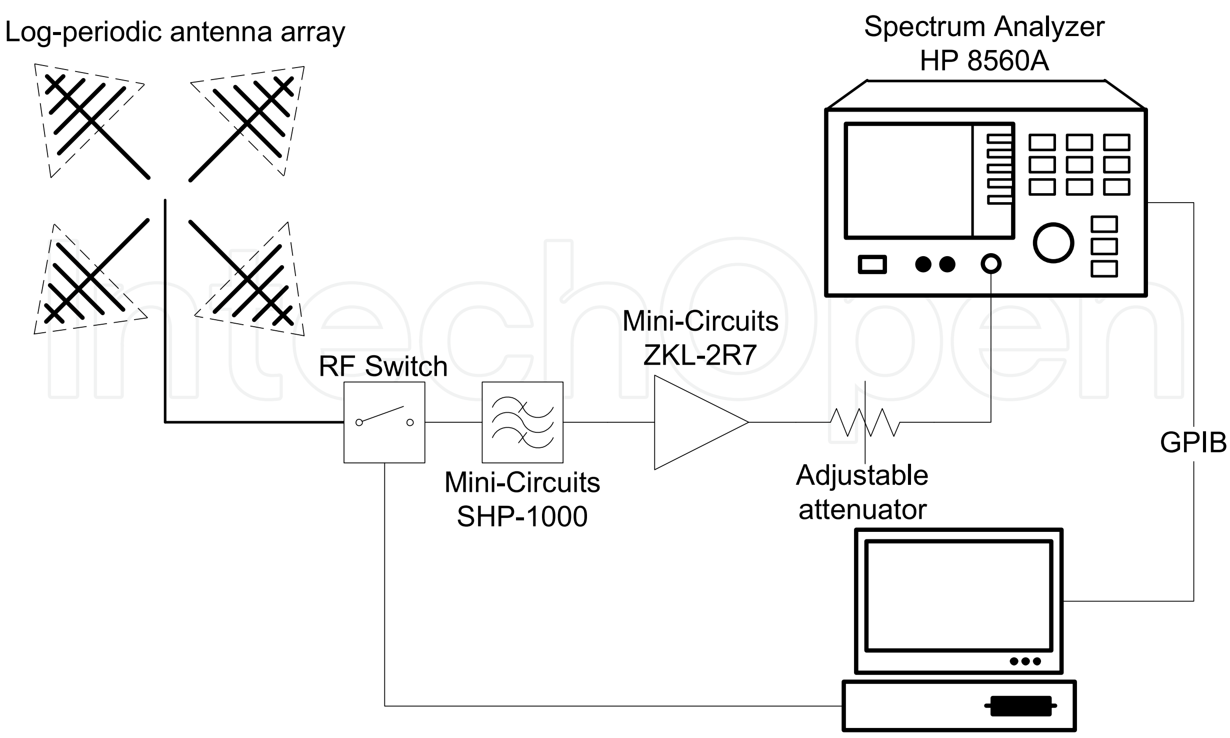


Fig. 3. Monitoring system for 1500-2500 MHz spectrum

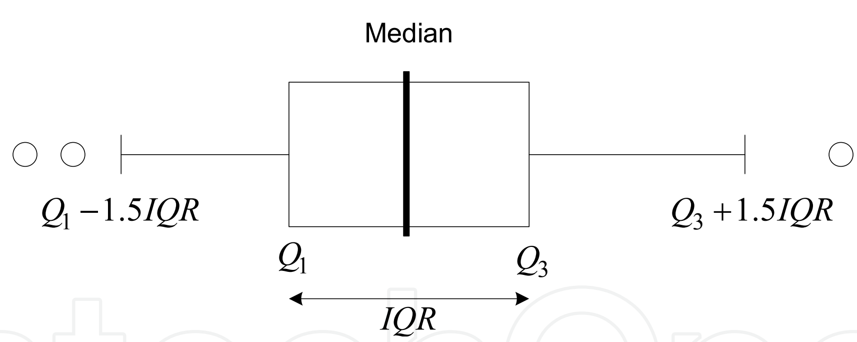


Fig. 4. Box-and-whisker diagram

channel is the maximum power ever observed in that channel in 7-day time. Together, the *Average* and *Maximum* results provide a simple characterization of the temporal behavior of a channel. For example, when the results are equal, it suggests a single transmitter which is always on and which experiences no fading. At the other extreme, a large difference between the mean and maximum measurements suggests intermittent use of the channel.

The middle panel shows the band occupancy in the *time domain* with thresholds -95 dBm and -100 dBm during the measurement period of 27/06/07 – 03/07/07. For example, the occupancy rate of the Air band shown in Figure 6 was calculated in each time point in a given threshold -95 dBm and -100 dBm respectively. Total 168 time points for each hour of 7-day were plotted in this panel.

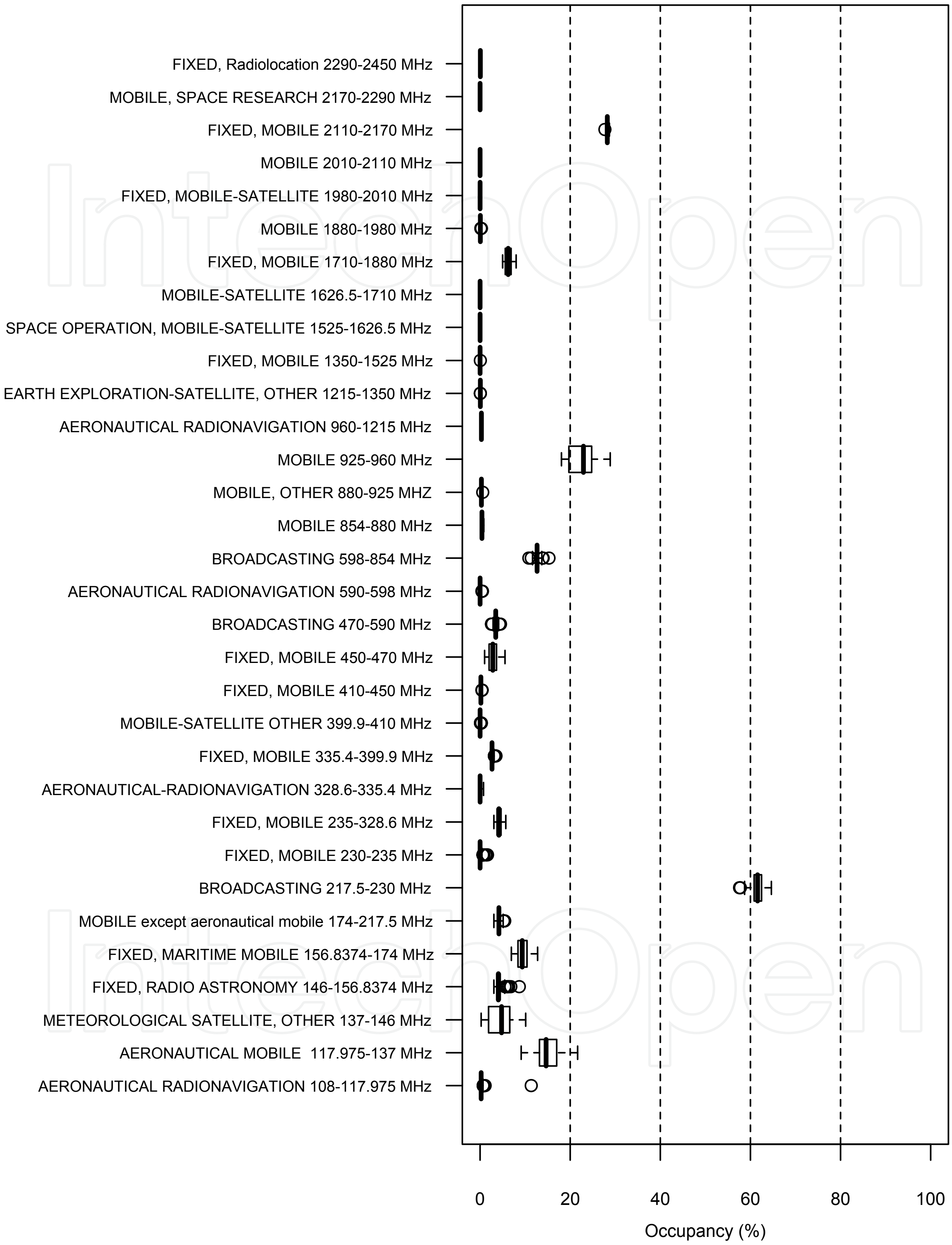
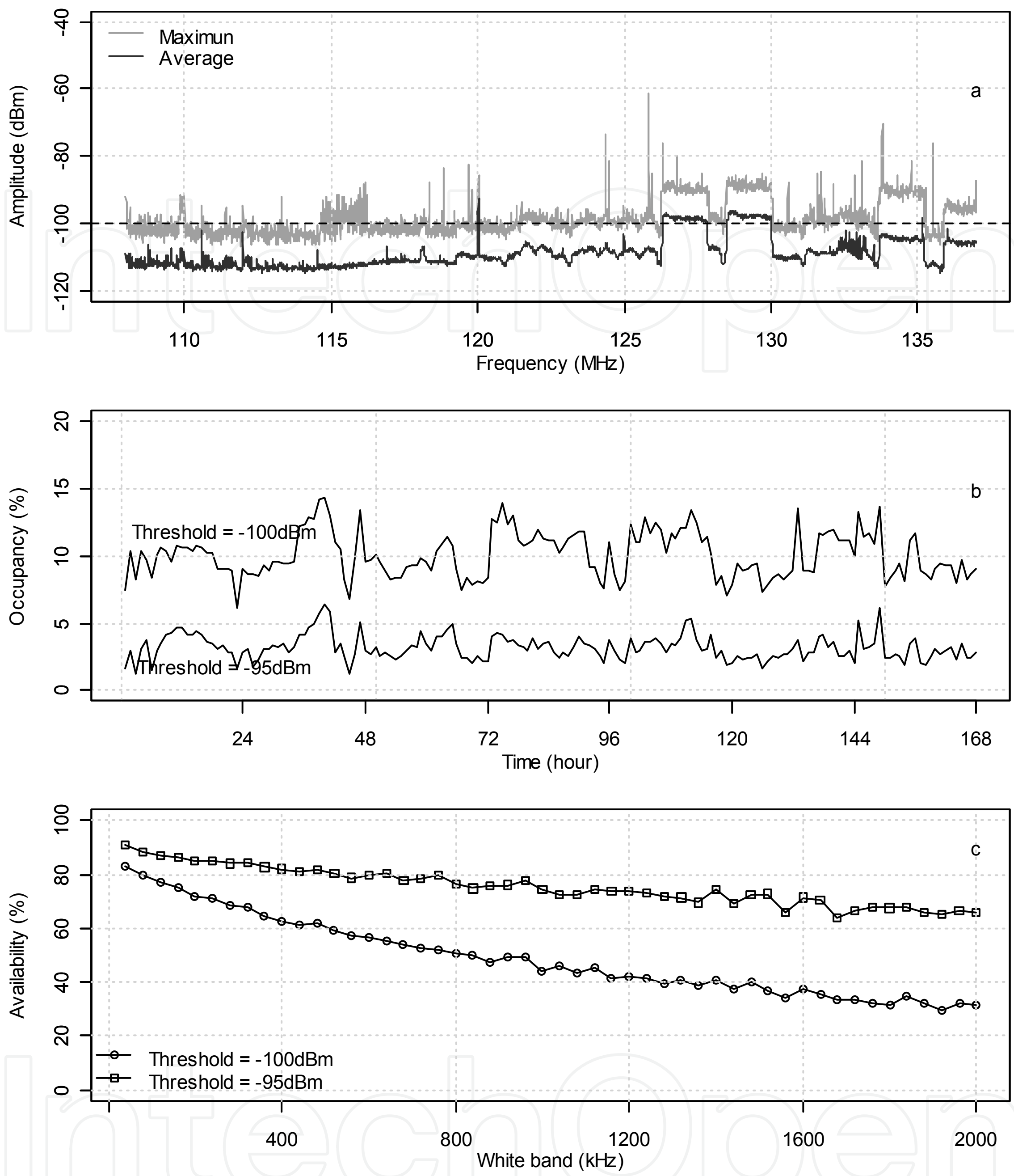


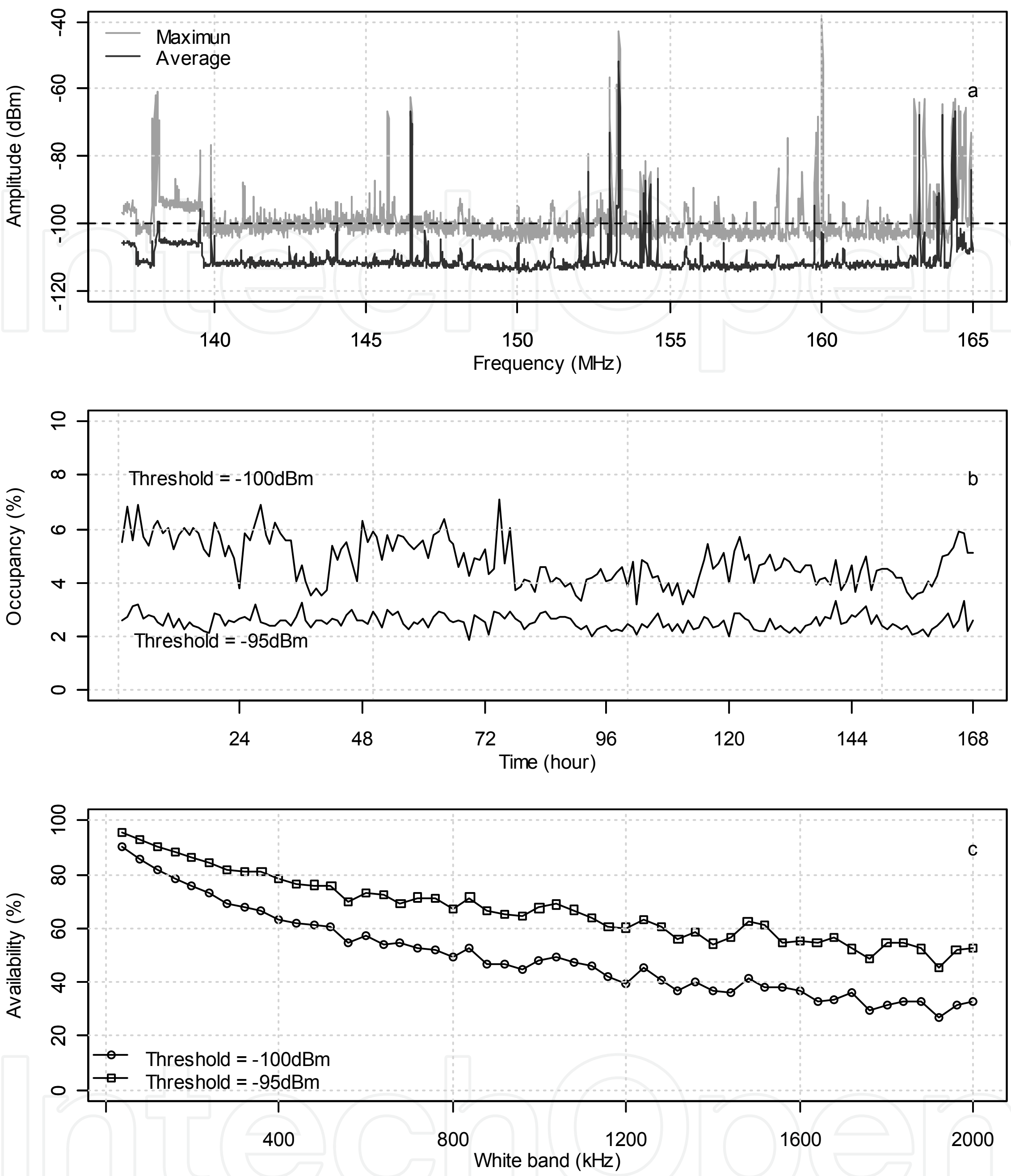
Fig. 5. Occupancy statistics of spectrum



Air Band 108-137 MHz

	-105 dBm	-95 dBm
Min	6.06	1.20
1st Quantile	8.81	2.58
Median	9.76	3.03
Mean	10.06	3.16
3rd Quantile	11.19	3.67
Max	14.28	6.33

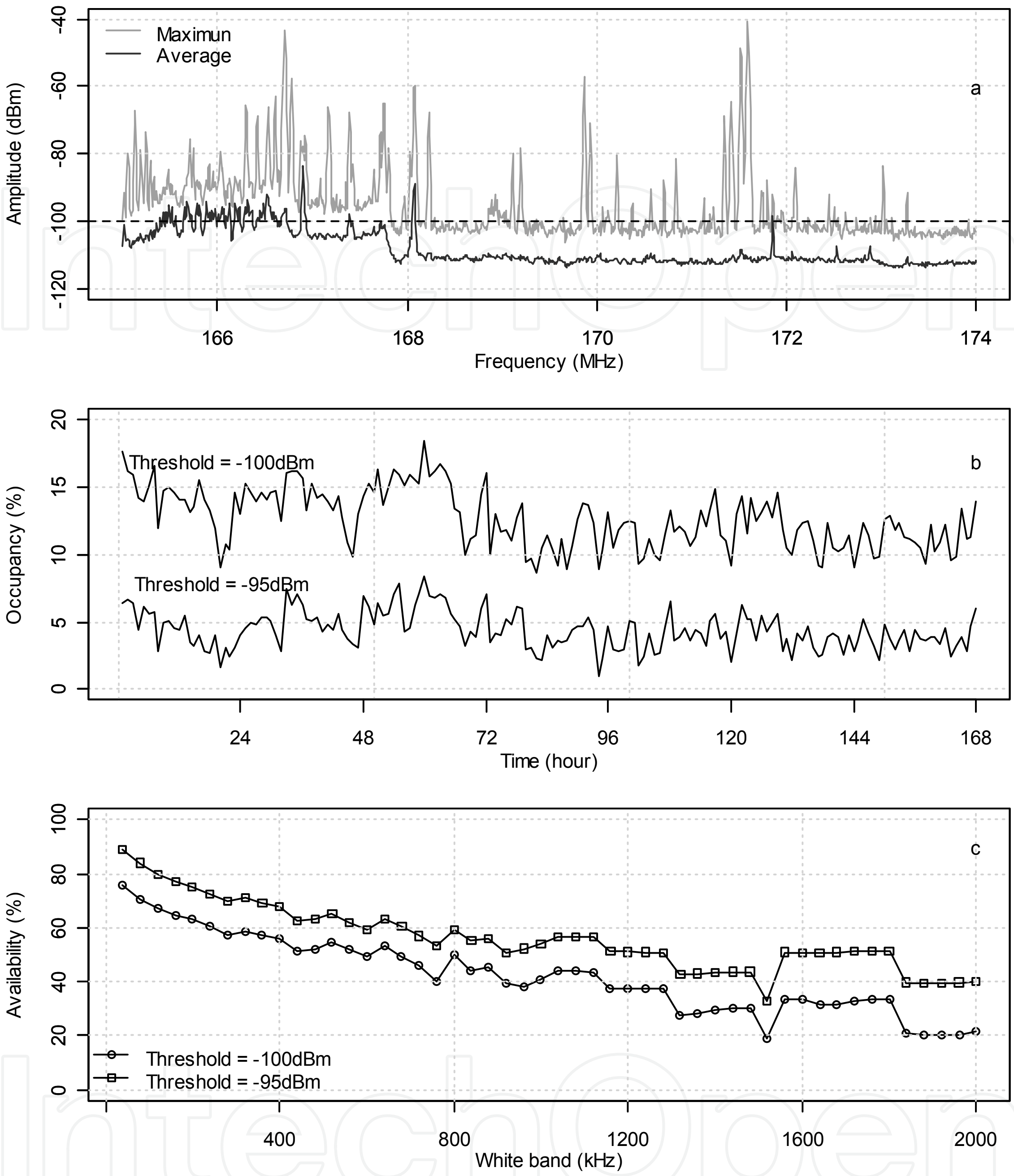
Fig. 6. Occupancy statistics of Air Band



Mid Band 137-165 MHz

	-105 dBm	-95 dBm
Min	3.24	1.93
1st Quantile	4.13	2.35
Median	4.81	2.53
Mean	4.84	2.52
3rd Quantile	5.54	2.71
Max	7.09	3.32

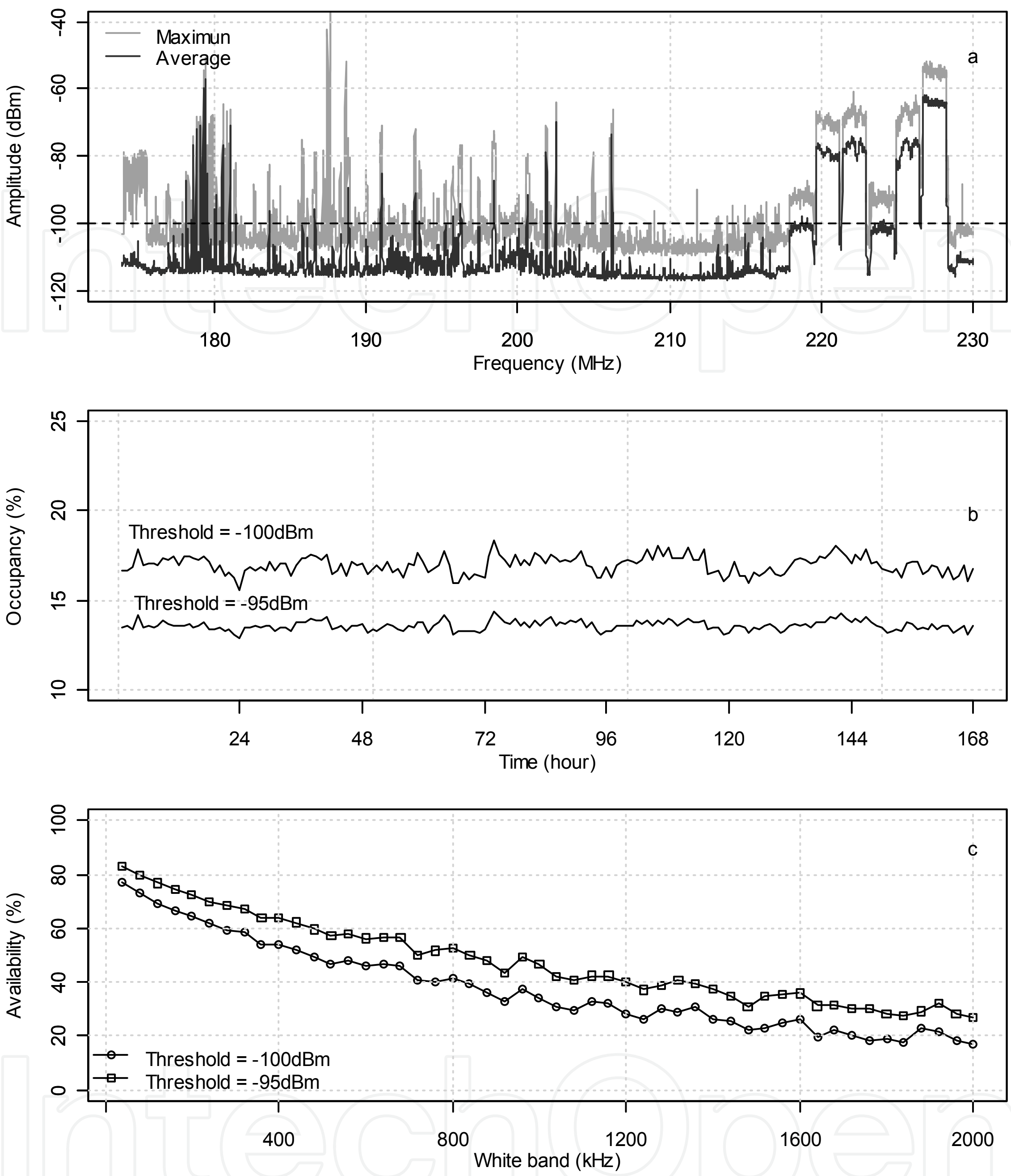
Fig. 7. Occupancy statistics of Mid Band



High Band 165-174 MHz

	-105 dBm	-95 dBm
Min	8.53	0.99
1st Quantile	10.74	3.30
Median	12.29	4.26
Mean	12.51	4.35
3rd Quantile	14.29	5.21
Max	17.94	8.31

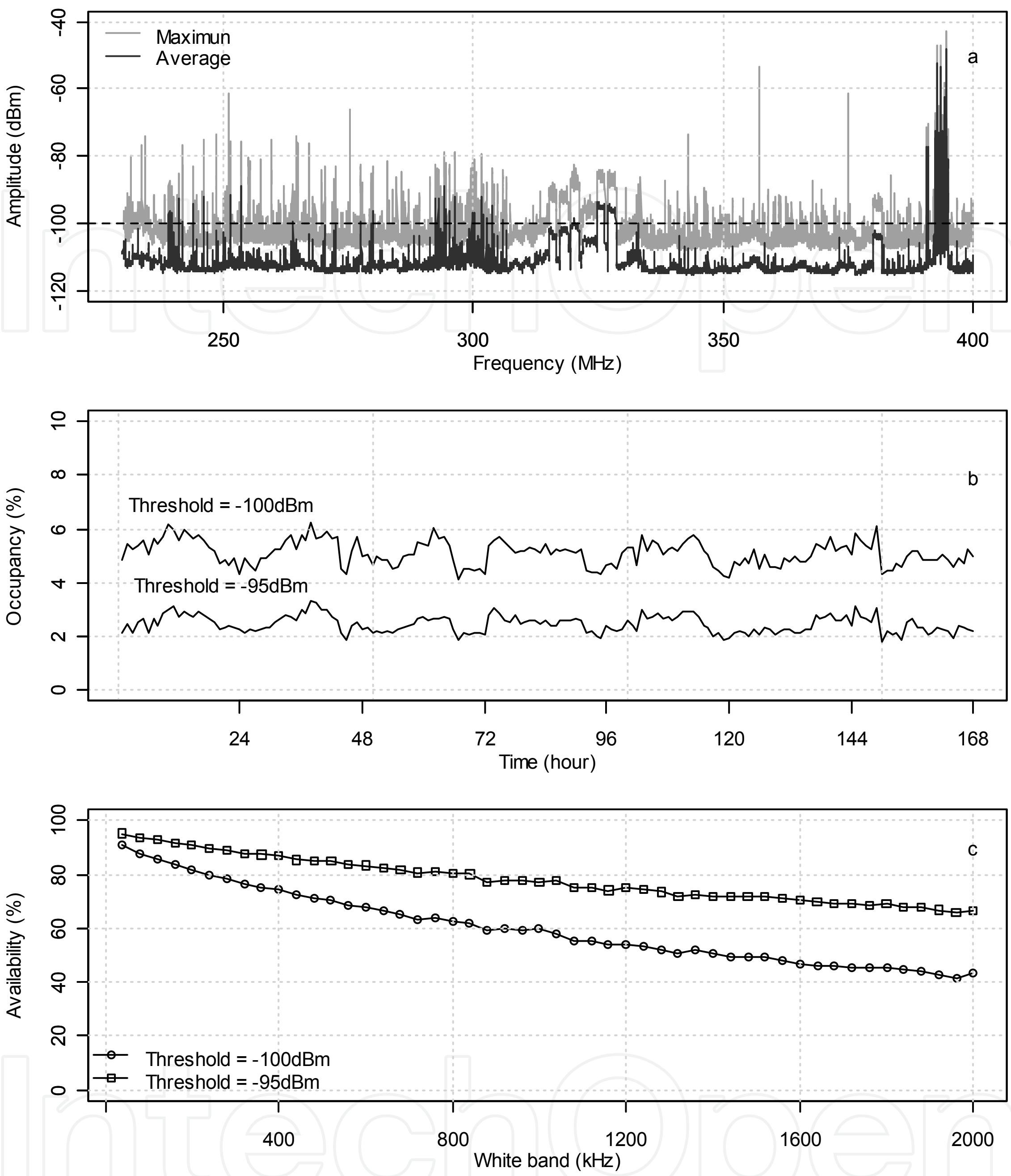
Fig. 8. Occupancy statistics of High Band



Band III 174-230 MHz

	-105 dBm	-95 dBm
Min	15.61	12.91
1st Quantile	16.61	13.42
Median	16.99	13.60
Mean	16.97	13.60
3rd Quantile	17.30	13.77
Max	18.36	14.37

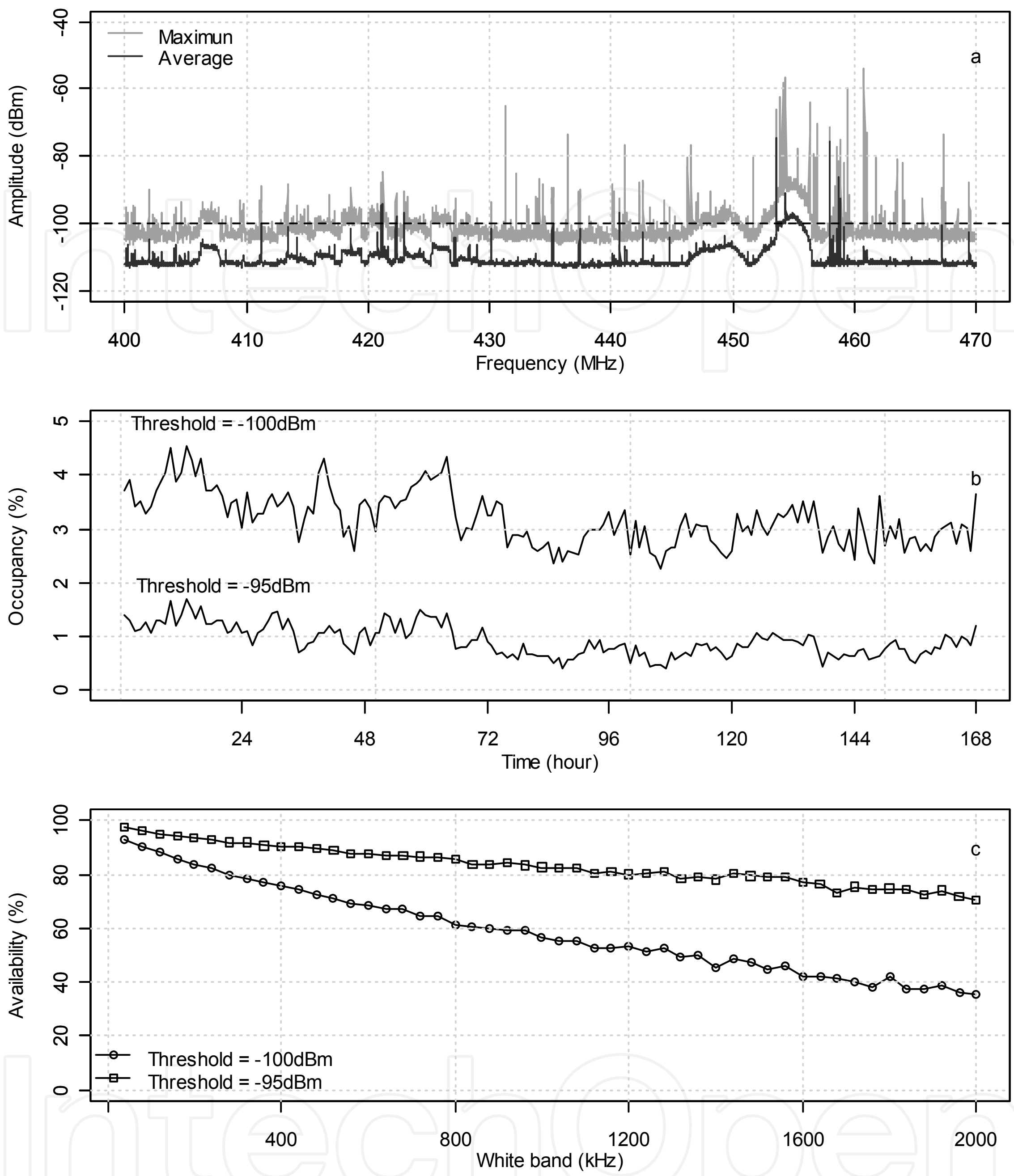
Fig. 9. Occupancy statistics of Band III



NATO Band 230-400 MHz

	-105 dBm	-95 dBm
Min	4.13	1.84
1st Quantile	4.77	2.20
Median	5.14	2.41
Mean	5.10	2.46
3rd Quantile	5.44	2.68
Max	6.19	3.29

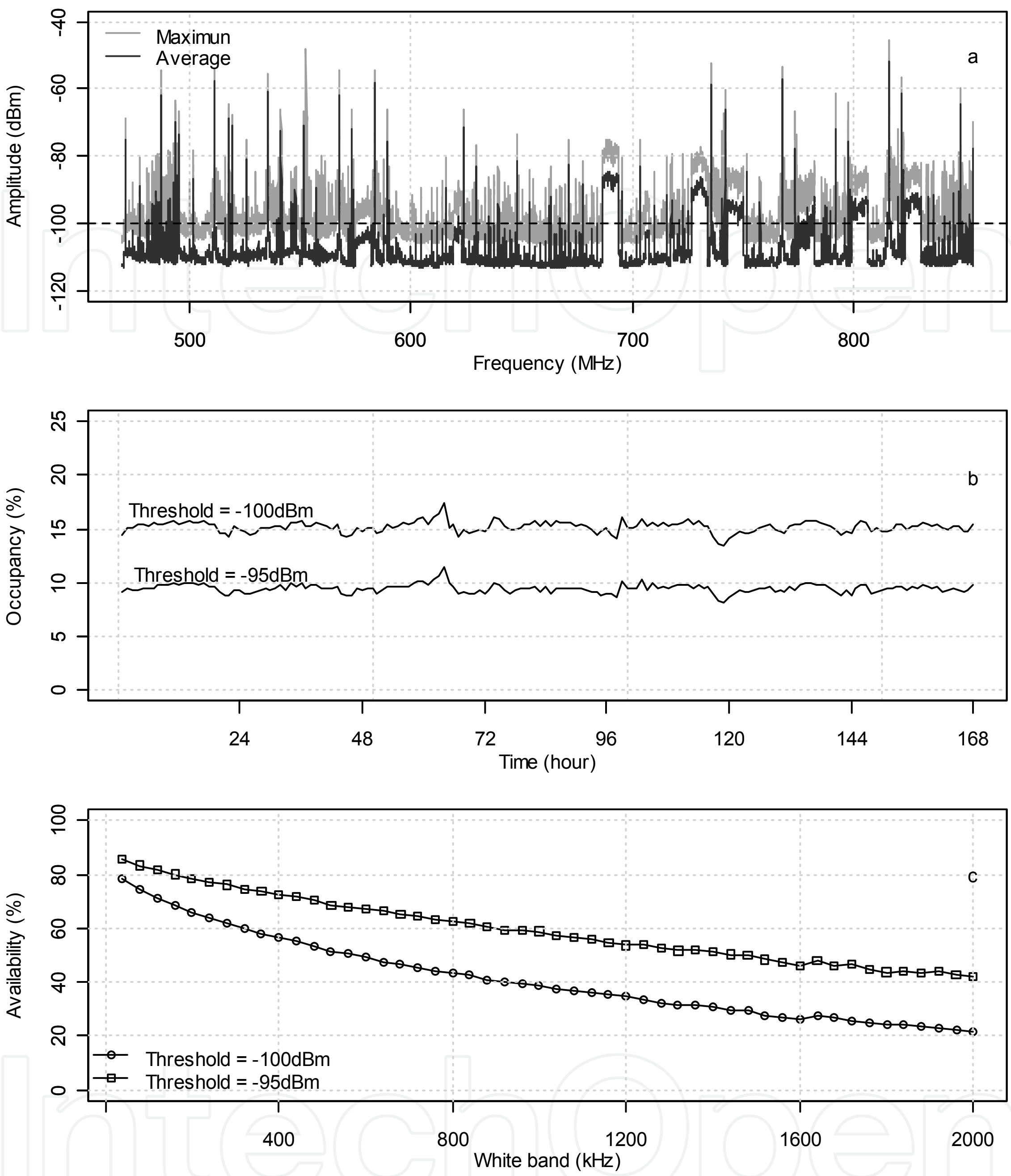
Fig. 10. Occupancy statistics of NATO Band



UHF 1 & 2 Band 400-470 MHz

	-105 dBm	-95 dBm
Min	2.25	0.40
1st Quantile	2.81	0.70
Median	3.12	0.90
Mean	3.18	0.93
3rd Quantile	3.51	1.11
Max	4.54	1.70

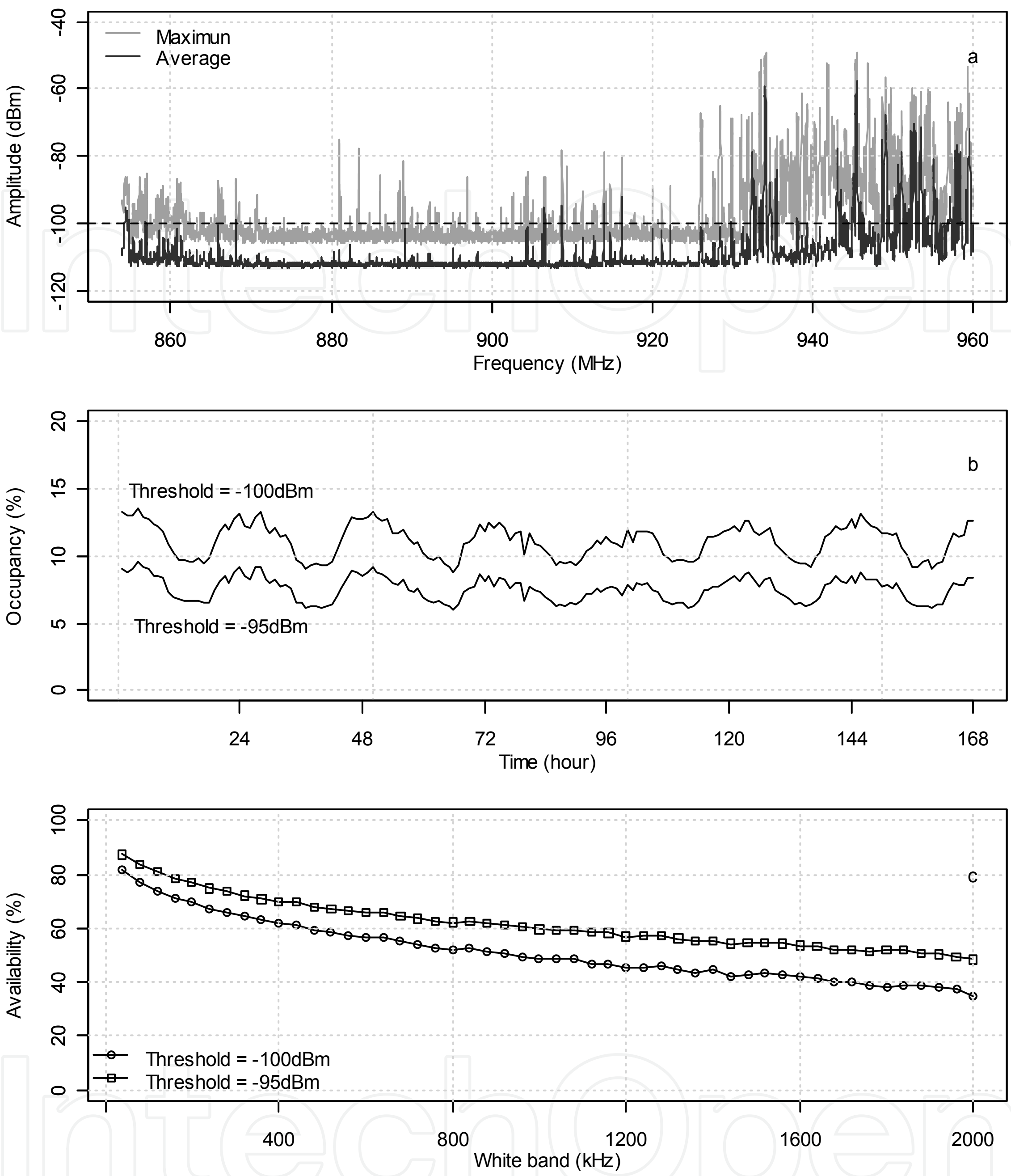
Fig. 11. Occupancy statistics of UHF 1 & 2 Band



TV, Band IV & V 470-854 MHz

	-105 dBm	-95 dBm
Min	13.56	8.19
1st Quantile	14.95	9.26
Median	15.34	9.48
Mean	15.26	9.49
3rd Quantile	15.57	9.74
Max	17.51	11.58

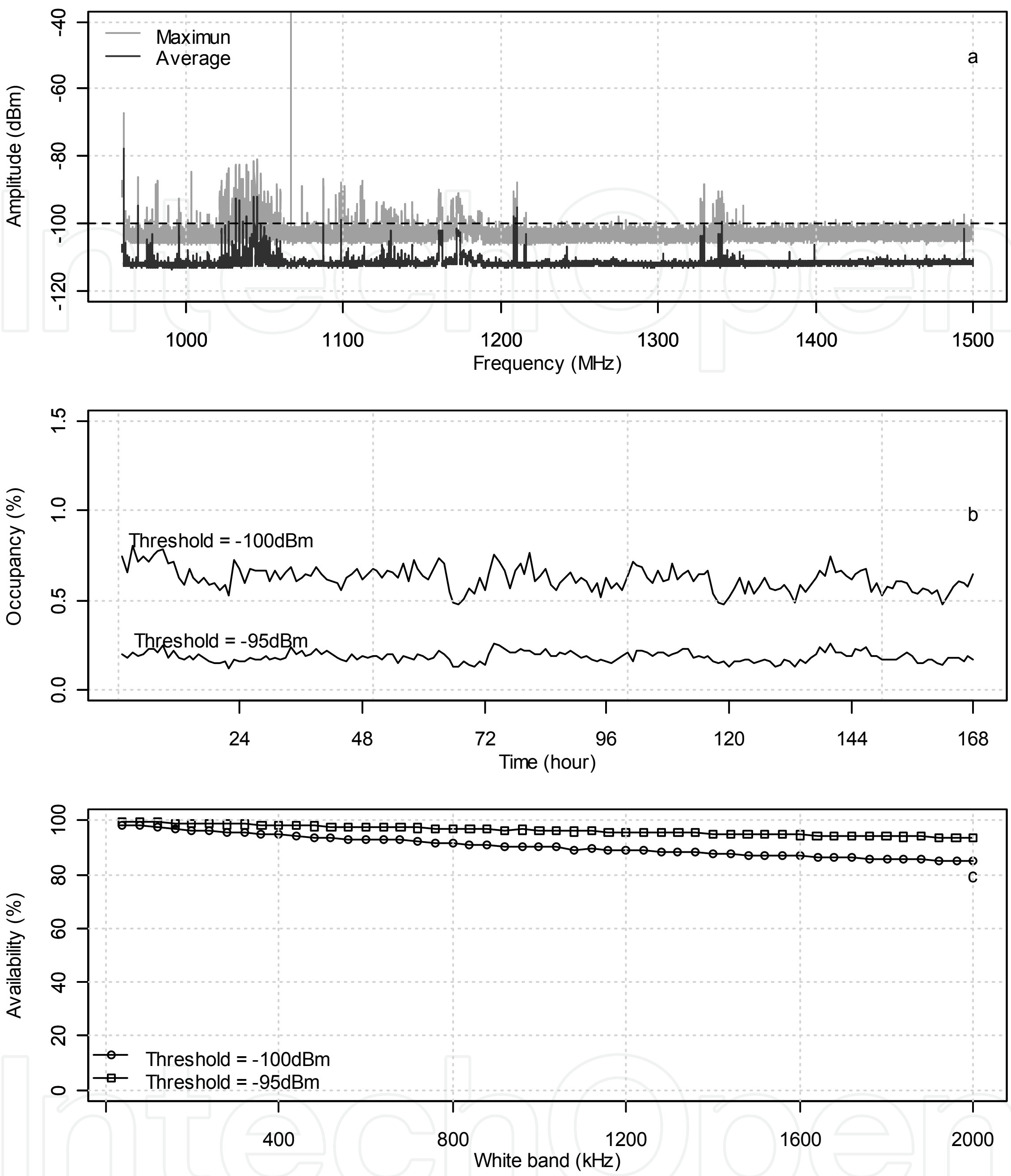
Fig. 12. Occupancy statistics of TV, Band IV & V



GSM & mobile 854-960 MHz

	-105 dBm	-95 dBm
Min	8.78	6.15
1st Quantile	9.74	6.72
Median	11.29	7.76
Mean	11.1	7.68
3rd Quantile	12.1	8.37
Max	13.65	9.80

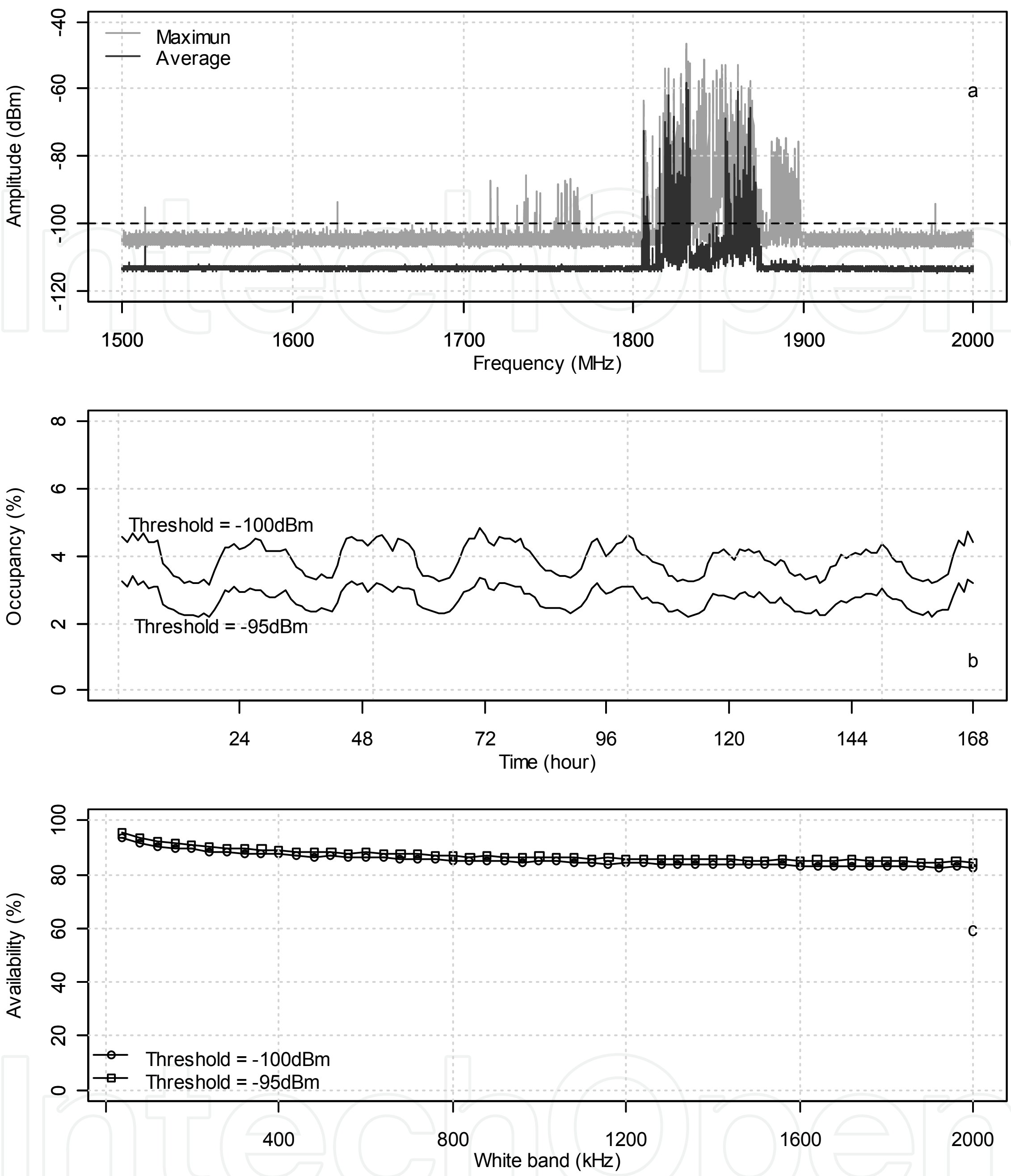
Fig. 13. Occupancy statistics of GSM & mobile Band



L Band (lower) 960-1500 MHz

	-105 dBm	-95 dBm
Min	0.40	0.06
1st Quantile	0.52	0.11
Median	0.56	0.13
Mean	0.56	0.14
3rd Quantile	0.59	0.16
Max	0.74	0.21

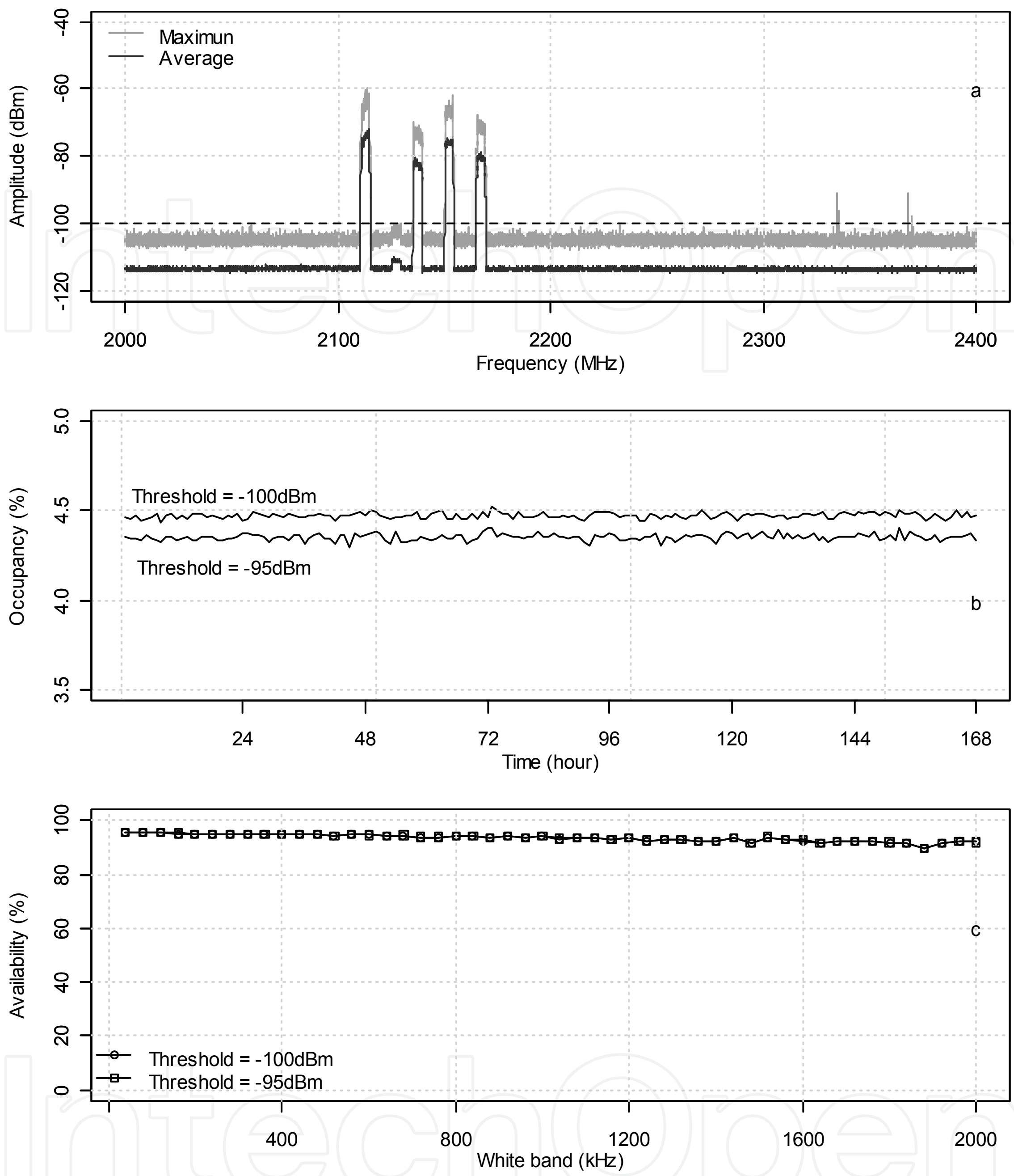
Fig. 14. Occupancy statistics of L (lower) Band



L Band (upper) 1500-2000 MHz

	-105 dBm	-95 dBm
Min	3.12	2.18
1st Quantile	3.43	2.40
Median	3.99	2.75
Mean	3.92	2.72
3rd Quantile	4.33	2.98
Max	4.82	3.34

Fig. 15. Occupancy statistics of L (upper) Band



S Band (lower) 2000-2400 MHz

	-105 dBm	-95 dBm
Min	4.43	4.30
1st Quantile	4.46	4.34
Median	4.48	4.35
Mean	4.47	4.35
3rd Quantile	4.49	4.36
Max	4.52	4.41

Fig. 16. Occupancy statistics of S (lower) Band

The bottom panel shows the statistical distributions of the *white spectrum*. *White spectrum* can be defined as the continuous idle spectrum in a given bandwidth and in a given threshold which can be used for communications. For example, in Figure 12, for -100 dBm threshold we can find about 60% white band with 1000 kHz bandwidth distributed in the total spectrum, if we divide the TV band (470 - 854 MHz) into 384 sub-bands with 1000 kHz bandwidth.

The statistics table of each figure shows the minimum and maximum occupancy rates, 1^{st}, 3^{rd} quartile values, and mean and median values. A median is described as the number separating the higher half of a sample, a population, or a probability distribution, from the lower half.

The statistics presented in these figures shows that the spectrum occupancies are really spares in the measuring locations and period. The average occupancies for most bands are less than 20%. Except the GSM and CDMA communication bands, the average occupancies in the 1 GHz to 2.5 GHz spectrum are less than 5%. The good propagation characteristics of this range of spectrum, in terms of propagating distance and data rates, make it an excellent candidate for cognitive radio technology. The data shows that, without additional spectrum, there are a great amount of spectrum resources for accommodating the cognitive radio systems if the current communication regulations could be changed.

4. Conclusion

There are generally positive findings in this project with respect to the prospects for cognitive radio. Statistics show that the spectral occupancies are spare indeed. Occupancy rates of most bands in VHF and UHF are less than 10% overall and the distribution of the white band indicates that the bands are capable of running wideband wireless communications. Of course, the current static spectrum allocation policies and spectrum management strategies have to be modified to motivate applications of the cognitive radio technology. While this study is to identify the low utilizations of bands, long term studies are crucial in developing spectrum sharing technologies and for spectrum management.

Above all, radio spectrum occupancies in time, frequency and space domains observed in this project are sparse indeed. This suggests that cognitive radio technologies have great prospects in the future wireless communication infrastructure, if current telecommunication policies and regulations are modified.

5. Acknowledgement

I am indebted to Durham University and British Telecom for their funding of my studies. I would like to record my gratitude to Sana Salous for giving valuable guidance and suggestions for improving the work, and Stuart Feeney for sharing his RF knowledge, Roger Lewenz and Peter Baxendale for their contributions in the development of the data acquisition software.

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Advances in Cognitive Radio Systems
Edited by Dr. Cheng-Xiang Wang

ISBN 978-953-51-0666-1
Hard cover, 150 pages
Publisher InTech
Published online 05, July, 2012
Published in print edition July, 2012

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Zhe Wang (2012). Measurement and Statistics of Spectrum Occupancy, Advances in Cognitive Radio Systems, Dr. Cheng-Xiang Wang (Ed.), ISBN: 978-953-51-0666-1, InTech, Available from: http://www.intechopen.com/books/advances-in-cognitive-radio-systems/measurement-and-statistics-of-spectrum-occupancy

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