LOW COST SPECTRUM MEASUREMENTS

14

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Recently a lot of attention has been given to the use of TV White Spaces for rural communications. Several monitoring campaigns have been carried out to measure spectrum occupancy worldwide, concluding that most of the spectrum is underutilized. In this chapter we present the design and implementation of two low cost systems to measure spectrum occupancy and to geo-tag the measurements to allow mobile measurement campaigns. The first system is based on the Raspberry Pi system on chip and on an affordable spectrum analyser. After calibrating the system against a professional spectrum analyser, we used it to measure the spectrum occupancy in urban and rural Venezuela, showing that there is plenty of vacant UHF TV spectrum. The second system is based on the popular Arduino board and has been used to measure spectrum occupancy in Malawi and Zambia. Then, we present a couple of representative results obtained from both devices during measurement campaigns. Finally, we conclude the chapter with some remarks about our experience on mobile spectrum measurements.

14.1 THE NEED FOR SPECTRUM MEASUREMENTS

Spectrum occupancy has become topical as the quest for efficient access to the spectrum continues. This is evidenced by empirical measurements of the radio environment in a bid to ascertain the spectrum usage by different wireless services.

Occupancy measurement campaigns efforts where initially carried out in USA using discone antennas, spectrum analyzers and a laptop[1].

1. D. Juyong, D.M. Akos and P.K. Enge, L and S bands spectrum survey in the San Francisco bay area, Position Location and Navigation Symposium, 2004, Pages 566-572

These occupancy measurements (as many others) showed information only about American spectrum regulation and utilization.

In Europe, a spectrum occupancy measurement was conducted in the frequency range from 75 MHz to 3 GHz in an outdoor environment in urban Barcelona, Spain [2]. Furthermore [3] takes a survey of Spectrum utilization in Europe and reports three major campaigns namely in the suburb of the city of Brno in the Czech Republic and in the suburb and the city of Paris in France during years 2008 and 2009 respectively. More recently, a Spectrum Occupancy measurement was carried out in Romania both in urban as in rural areas[4].

In Asia, researchers in Singapore[5] measured a 24 hour spectrum usage in 12 weekdays in the band 80 MHz-5850 MHz. The authors conclude from their measurements that their work is preliminary in its nature and, future long term studies need to be performed to determine any potential secondary usage on those channels that have low or no active utilization.

In Africa, measurements have been carried out in South Africa[6] by means of the Meraka Cognitive Radio Platform developed using the Universal Software Radio Peripheral hardware and the GNU Radio software. The authors present early results in rural and urban Southern Africa indicating that there are substantial white spaces available in both areas derived from digital dividend.

A measurement campaign carried out in Bogota is described in [7], using a high cost spectrum analyzer with a steep learning curve and sophisticated signal processing equipment.

The majority of researches reach a common conclusion on the necessity for further occupancy measurements at different locations over longer times. This thus motivates the need for more occupancy measurement. On concluding their investigations, some authors affirm that, to obtain local spectral pattern usage in multiple locations, the challenges for measurement-campaigns are not only cost (in equipment) but also the long time required to perform the measurements [8].

14.1.1 *On Low cost Spectrum Monitoring*

This chapter describes the design of a low-cost system to measure spectrum occupancy and geo-tag spectrum measurements. To make a monitoring system usable in Developing Countries (where TVWS have the highest potential) some design requirements have to be met. These design challenges include cost, power consumption, usability, data logging capabilities and availability of source code. Consequently, we propose a system considering the following design premises:

- **Low cost.** Commercial high-end spectrum analyzers are expensive (in the order of many thousand dollars), bulky, and are not typically available in University labs in Developing Countries. With a total cost of few hundred dollars, our system can be easily

2. M. Lopez-Benitez et al., Evaluation of Spectrum Occupancy in Spain for Cognitive Radio Applications, in IEEE 69th Vehicular Technology Conference, 2009, Pages 1-5

3. V. Vaclav et al., Survey on Spectrum Utilization in Europe: Measurements, Analyses and Observations, in 5th International ICST Conference on Cognitive Radio Oriented Wireless Networks and Communications, 2010

4. A.Martian et al., "Perspectives on dynamic spectrum access procedures in TV White Spaces," Wireless Personal Multimedia Communications (WPMC) 2013, June 2013

5. M. H. Islam et al., Spectrum Survey in Singapore: Occupancy Measurements and Analyses, in Proc. 3rd International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CrownCom 2008), 2008, Pages 1-7

6. M.T. Masonta, D. Johnson and M. Mzyece, "The White Space Opportunity in Southern Africa: Measurements with Meraka Cognitive Radio Platform," Springer Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, Vol. 92, Part 1,pp. 64-73, 2012

7. L.Pedraza et al;, "Spectrum Occupancy Statistics in Bogota-Colombia", Proceedings of the IEEE Colombian Conference on Communications and Computing (COLCOM), 22-24 May 2013

8. Vo Nguyen Quoc Bao, Le Quoc Cuong, Le Quang Phu, Tran Dinh Thuan, Nguyen Thien Quy and Lam Minh Trung, Vietnam spectrum occupancy measurements and analysis for cognitive radio applications, in International Conference on Advanced Technologies for Communications (ATC), 2011, Pages 135-143

acquired by Universities and civil society organizations worldwide. Similar systems cost one or two orders of magnitude more. We used the following low-cost parts to build up our systems:

- A Raspberry Pi[9] single-board computer. This credit-card-sized device was developed in the UK to promote the teaching of basic computer science in schools. It has a Broadcom BCM2835 system on a chip (SoC), which includes an ARM1176JZF-S 700 MHz processor, VideoCore IV GPU and 512 megabytes of RAM. It does not include a built-in hard disk or solid-state drive, using instead an SD card for booting and long-term storage. The B model with two USB sockets and an Ethernet connection sells for $35. The A model, with only one USB socket, sells for $25. The Raspberry Pi runs a Debian ARM distribution so it can use any Linux based software.
- A hand-held spectrum analyzer. Recently an affordable and easy to use device to make spectrum measurements has become available, the RF Explorer[10]. There are five RF Explorer models, covering the most-used bands below 2.5 GHz. In our system we use the Sub 1 GHz model, employing the Silicon Labs Si4431 receiver chip (covering 240 MHz to 960 MHz). The price of this model is 120 $ (as of November 2013).
- An embeddable computer. The Arduino[11] board is a low-cost micro controller platform, also considered as a small computer, capable of coordinating different sensors and actuators. The capabilities of this small computers are intended to solve lightweight problems while reducing the operational costs and space. The price of the model used is about 60 $.

9. http://www.raspberrypi.org/

10. http://www.rfexplorer.com/

11. http://arduino.cc

- **Low power consumption.** Based on low power devices, the system must run for an entire working day with a small battery. In our case, both the Raspberry Pi and the Arduino board, power is provided via a micro USB connector, compatible with mobile phone chargers or any other 5 V supply (such as batteries, solar panels, etc). The Raspberry Pi B model requires about 5 W of power, while the A model requires 2 W[12]. For typical Arduino board, the energy requirements goes around the hundreds of milliwatts.

12. Richard Heeks and Andrew Robinson. 2013. Ultra-low-cost computing and developing countries. Commun. ACM 56, 8 (August 2013), 22-24

- **Ease of use.** Once switched on, the system has to run automatically without any human intervention. Non technical personnel can carry the system around and collect measurements. On the other hand, technical personnel can easily select the frequencies of interest with only a basic knowledge.
- **Data logging.** Weeks of measurements can be stored in the device's SD card with no need to download them on a PC. Collected

measurements are stored in comma separated values (CSV) files for later processing.

- **Calibration.**

  To assess our set of measurements, we compared both systems against a professional Agilent N9344C recently calibrated spectrum analyser. A calibrated Agilent 8648C signal generator provided signals at 10 different power levels, i.e., from -95 dBm to -50 dBm, for the set of measured frequencies. From the calibration processes we can say that there are many characteristics to comply with a low-cost solution and it is quite challenging to balance the trade-offs. The calibration measurement show a systematic error lower than 4.5 dB over the range of interest. The measurements underestimate the true value of the signal, and the error is greater at higher frequencies, which in this case correspond to the cellular service.

- **Open Source.** The components of the system should be based on the open source concept. The system should be easily modified thanks to the availability of the source code.

Furthermore, the proposed systems, WhispPi and ASCII-32, are particularly suited to perform measurements while moving, either on foot or in a vehicle, thus facilitating the gathering of spectrum occupancy in relation with geographical position.

14.2 THE WHISPPI DEVICE

WhispPi [13] was designed on the principle that data from the spectrum analyzer have to be stored in a device with a battery backup for mobile measurements. In addition to spectrum, the position and the time of measurements are saved on the same device. Moreover, the Raspberry Pi allows fine tuning of the different components of the system through regular UNIX scripting.

The system is made out of four components:

1. A Raspberry Pi, used to control the data acquisition and geotagging of the data.

2. An RF Explorer, that has already proved its usefulness for spectrum efficiency advocacy in a previous measurement campaign[14].

3. A USB GPS, to collect the exact position and time of the measurement.

4. A small battery with micro USB output to power the Raspberry Pi which then powers the spectrum analyzer.

13. Arcia-Moret, A., Pietrosemoli, E., and Zennaro, M. Whisppi: White space monitoring with raspberry pi. In IEEE Global Information Infrastructure and Networking Symposium (GIIS 2013) (October 28-31. Trento, Italy 2013).

14. M.Zennaro et al, "On the Relevance of Using Affordable Tools for White Spaces Identification", Proceedings of the IEEE CNBuB2012, Barcelona-Spain, 8-12 October 2012

Figure 14.1: The WhispPi device

The spectrum analyzer, the GPS and the battery are connected to the Raspberry Pi via USB cables. To make the system easier to carry, an enclosure has been designed and printed with a 3D printer. The overall system is shown in Figure 14.1.

With the presented configuration, we were able to obtain 1 full measurement every 6 secs. A single measurement, essentially comprises a span of a 600 MHz geo-localized sample. Note that the full processing of the spectrum sample was completely delegated to the RF Explorer, which in our experience consumed most of the time per sample. Moreover, we sampled in the fastest possible configuration, i.e., with the widest span (of 600 MHz) for a reasonable bin (of 5.6 MHz) to detect a TV channel.

14.2.1 Specifics of Spectrum Monitoring for WhispPi

Mobile monitoring the RF spectrum requires a portable spectrum analyzer. High-end spectrum analyzers are traditionally expensive and bulky, so they are not suited for nomadic use. Some portable Spectrum Analyzers have a GPS on board, but are out of reach for most Universities. New affordable devices such as the ones listed below enabled us to develop a low cost solution for spectrum monitoring.

The main features of the RF Explorer are:

- Spectrum Analyzer measurements with Peak Max and Hold, Normal, Overwrite and Averaging modes

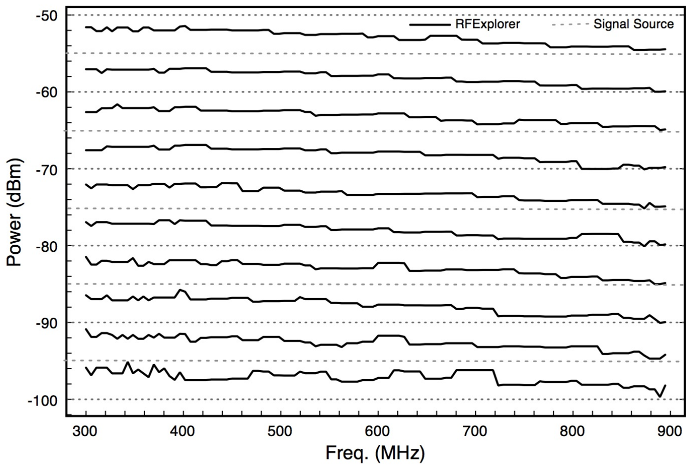

Figure 14.2: Calibration of the RF Explorer.

- High capacity Lipo battery for 16 hours of continuous run, rechargeable through USB port
- SMA antenna connector (50 ohms)
- Dynamic range: -115 dBm to 0 dBm
- Absolute Max input power: +5 dBm
- Can be fitted with internal Expansion Modules for additional band and functionality (signal generator)

It has an LCD display (128x64 pixels) that offers great visibility outdoors. While it is fully functional as an independent unit, optionally can be connected to a PC via USB for additional features.

14.2.2 Calibration of WhispPi

A calibrated signal generator provided signals at 10 different power levels, i.e., from -95 dBm to -50 dBm in 5 dB steps, for each of the 113 measured frequencies. From the results displayed in Fig. 14.2, we can infer that in the frequency range from 300 MHz to 900 MHz, the RF Explorer displayed value is consistently slightly less than the power applied to its input, with a maximum discrepancy of 4.5 dB. In the UHF TV spectrum range that extends up to 806 MHz the under estimation is bounded to 2.8 dB.

14.3 THE ASCII-32 DEVICE

ASCII-32, shown in Figure 14.3, is a low-cost device to identify and geotag RF spectrum in the sub 1-GHz band. The name ASCII-32 is derived

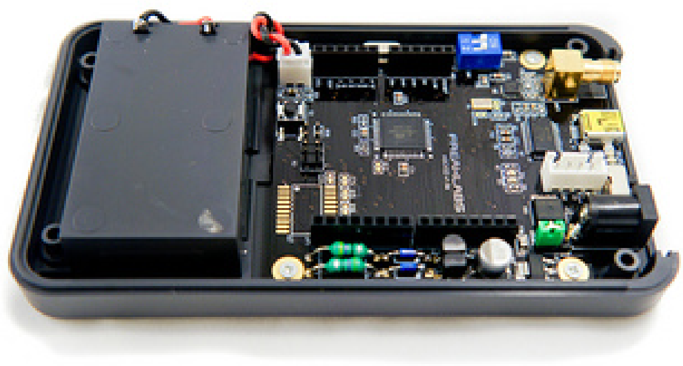

Figure 14.3: Low-cost ASCII-32 device

from the ASCII character set, where the number 32 corresponds to a white space. Selling for $ 110, ASCII-32 is affordable for universities and civil society organizations in Developing Countries.

The main component of the design is the SI4313 low cost wideband receiver IC. It covers a frequency range from 240 to 960 MHz which adequately spans the spectrum of TVWS. Although this IC has the circuitry to decode multiple wireless signalling protocols, in this application the main function used is the energy detection. After tuning to a certain frequency, one function of the IC is to sense the amount of energy, recording the value in dBm on the RSSI (Received Signal Strength Indicator) register. This is the same function as a standard spectrum analyzer, however at a vastly different cost scale.

The essential part of the design is to use a micro-controller to tune the IC to each frequency in pre-determined bandwidth intervals and measure the amount of energy at each frequency. By doing this quickly enough, it's possible to build up a plot of the occupied spectrum within the 240 to 960 MHz frequency range. This implements the spectrum analyzer functionality of the device.

Besides the spectrum analyzer functions, there are other requirements specific to white space identification. Two of those are GPS location and local storage. By adding a GPS to the device, it is possible to tag the occupied spectrum for a specific location. Bulk local storage, in the form of inexpensive micro SD cards, allows vast amounts of data to be stored for later processing and visualization. This combination allows the geographic variance of spectrum occupation to be measured, recorded, and visualized and automates the task of doing wide area site surveys for white space identification.

Finally, the manufacturer[15] added small details on to the design in the form of battery and power management and a ruggedized enclosure. This improves the portability of the device and allows it to be taken around

15. http://www.freaklabs.org

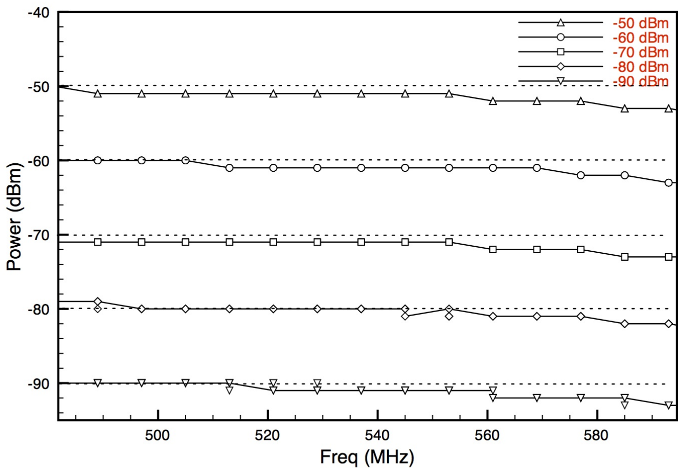

Figure 14.4: Measured power by ASCII-32 when input with pre-calibrated values

Table 14.1: Comparison of ASCII-32 and WhispPi

	Cost	Observable Bandwidth	Sampling Frequency	Processing Flexibility
ASCII-32	110$	100 MHz	High	Low
WhispPi	180$	600 MHz	Low	High

easily and unintrusively. Conventional spectrum analyzers are often subject to import duties (even for temporary usage) in many countries significantly encumbering the logistic of measurement campaigns.

14.3.1 *Calibration of ASCII-32*

Figure 14.4 shows the calibration results, the Y axis shows power in dBm. The reference calibrated power from the signal generator is represented as dotted horizontal lines, while the corresponding readings from the ASCII-32 device are represented by different symbols (upward triangle for -50 dBm, circle for -60 dBm, and so on). From the figure, we can infer that in the frequency range of interest, from 482 MHz to 554 MHz, the device is providing accurate results with a maximum difference of ±2 dB from the calibrated value.

Discussion

Table 14.1 shows the comparison of the two designed systems. Here we point out the salient characteristics that defined their usability. Remark that, although ASCII-32 is more portable and provides a better sampling frequency, WhispPi is capable of observing a broader portion of the spectrum for a single sample. The data processing becomes easier since Raspberry Pi board provides provides higher computing capabilities.

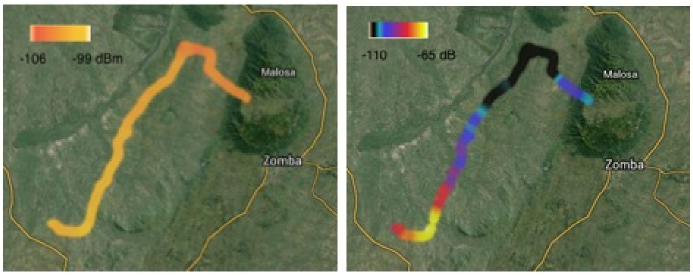

Figure 14.5: Heatmaps of Frequencies 498 MHz (on the left) and 546 MHz (on the right) in Malawi's Measurement Campaign.

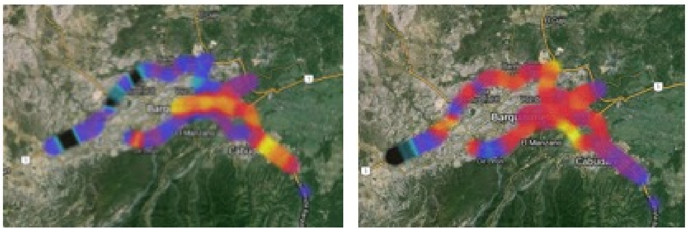

Figure 14.6: Heatmaps of UHF Channel 62 (on the left) and Channel 24 (on the right) in Venezuela's Measurement Campaign.

Moreover, it provides a network interface that allows adding automatic uploading of collected data. On the other hand, ASCII-32 provides higher sampling frequency suitable for higher heat-mapping resolution during vehicular measurement campaigns.

14.4 UHF BAND ACTIVITY AND WHITE SPACES

In this section we provide some examples of the possible graphical displays obtained from the collected data. The rendering stage is mainly independent from the device, however, the resolution of a heatmap depends on the sampling frequency.

Fig. 14.5 shows a heatmap of two representative channels during a journey in Malawi in June 2013. During this measurement campaign we travelled 130 km observing the spectrum with ASCII-32. The figure shows the contrast of a busy channel versus a free channel along the trajectory. The figure on the left shows that there is a free TV channel at the central frequency of 498 MHz. Observe that power levels during the whole path range from -106 dBm to -99 dBm. This contrast with the figure on the right that shows a busy channel on 546 MHz. During this journey we could collect more than 25000 samples for the 130 km route, i.e., one sample every 5 meters in a high speed highway.

Site	Leg Length (km)	White Spaces (%)
Mérida city	20	75
Ejido	10	86
Lagunillas	85	92
El Vigia	20	92
Santa Cruz de Mora	9	87
Mucuchies	10	96
Barinitas	20	90
Barinas	23	84
Guanare	41	86
Acarigua	50	87
Barquisimeto	20	66

Table 14.2: Summary of White Spaces in Venezuela Western Region as of June 2013.

Fig. 14.6 shows part of the result of a measurement campaign carried out in Venezuela in June 2013 recorded with WhispPi. This figure shows a heatmap for two types of busy channels. The figure on the left shows spectrum activity corresponding to channel 24 (530 MHz to 536 MHz), on one of the biggest cities of Venezuela, Barquisimeto, of about 1.600.000 inhabitants. The figure on the right shows the activity in Channel 24 in urban and suburban areas of Barquisimeto.

In Table 14.2 we summarize the white spaces findings during the measurement campaign carried out in western Venezuela. We observed that in urban and suburban areas the amount of white spaces (expressed as number of available channels) goes from 66% to 75% and in suburban and rural areas the amount of white spaces goes from 86% to 96%. It is worth noting that this quantity of White Spaces corresponds to a region in which the TV service is still analogue, and so we can expect an increase of spectrum availability after the transition to digital TV broadcasting.

14.5 LESSONS LEARNED

In this chapter we have presented the construction and use of affordable tools and techniques to assess the amount of white spaces in developing regions. The designed systems are easy to set up and well suited to long term mobile spectrum measurements. With these tools we were able to account for white spaces on the UHF TV band.

There is a trade off to consider when performing measurements with low cost equipments, namely the sampling frequency versus the observable bandwidth. So far, we have noticed that higher sampling frequency implies less observable bandwidth. Moreover, by exploring different trade-offs of these parameters, one can obtain valuable information about not only current activity in the channel but also what-if scenarios for future deployments.