Towards a more efficient spectrum usage: Spectrum Sensing and Cognitive Radio techniques

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Abstract

The traditional approach of dealing with spectrum management in wireless communications has been the definition of a licensed user granted with exclusive exploitation rights for a specific frequency. While interference is easily avoided, this approach is unlikely to achieve the objective to maximize the value of spectrum, and in fact spectrum measurements carried out worldwide have revealed significant spectrum underutilization. As a result, one of the current research trends in the wireless area are the so-called Dynamic Spectrum Access Networks (DSANs), in which unlicensed radios (secondary users) are allowed to operate in licensed bands provided that no harmful interference is caused to the licensees (primary users). One of the key enabling technologies for this paradigm is the Cognitive Radio (CR) that envisages a radio able to sense and be aware of its operational environment to dynamically and autonomously adjust its parameters accordingly to adapt to the different situations. Spectrum sensing, enabling the detection of unused spectrum bands becomes then one of the key elements of CR technologies. Under this framework, this paper provides on the one hand an insight to the different spectrum sensing techniques and associated standardisation activities. On the other hand, it presents also some spectrum occupation measurement activities, targeting the characterisation of how the spectrum is being used in the different bands in order to extract the relevant parameters for CR design. These are presented from a general methodological perspective as well as including the obtained results in a particular case study.

1 Introduction: Cognitive Radio techniques for Dynamic Spectrum Access

The current spectrum management situation is inherited from the early deployment of radio broadcasting channels in the early 1920's. At that time, no spectrum regulation management was in place and broadcasters competed by increasing their power levels to drown out their competitors. This situation led to high interference level and claimed for the creation of independent regulatory entities to ensure fairness amongst competitors and a better signal quality to end users. Then, frequencies were assigned, along with transmitted power bounds to broadcasters. On the other hand, licenses for exclusive rights guaranteed low interference level and good coexistence among incumbents. The deployment of wireless fixed or mobile communication systems followed the same philosophy of a low interference driven regulation strategy, ruled administratively by the regulators.

In spite of the better interference control, spectrum measurements carried out worldwide have revealed that the exclusive rights spectrum management approach exhibits significant spectrum underutilization in some bands, even if spectrum scarcity is claimed when trying to find bands to be allocated for new systems. This observation claims for a measurement driven flexible regulation strategy rather than a static administrative command and control scheme. As a result of this fact, one of the current trends in order to improve efficiency through a smarter spectrum management are the so-called Dynamic Spectrum Access Networks (DSAN), in which unlicensed radios, denoted in this context as Secondary Users (SU), are allowed to operate in licensed bands provided that no harmful interference is caused to the licensees, denoted in this context as Primary Users (PU). The proposition of the TV band Notice of Proposed Rule Making (NPRM) in the USA [1], allowing this secondary operation in the TV broadcast bands if no interference is caused to TV receivers, was a first milestone in this direction. In this approach, SUs will require to properly detecting the existence of PU transmissions and should be able to adapt to the varying spectrum conditions, ensuring that the primary rights are preserved. These events culminated in the creation of the IEEE 802.22 standard, developing a cognitive radio-based physical and medium access control layer for use by license-exempt devices on a non-interfering basis in spectrum portions allocated to the TV broadcast services.

The primary-secondary (P-S) spectrum sharing can take the form of cooperation or coexistence. Cooperation involves explicit communication and coordination between primary and secondary systems, and coexistence means that both systems are operated independently. When sharing is based on coexistence, secondary devices are essentially invisible to the primary. Thus, all the complexity of sharing is borne by the secondary and no changes to the primary system are needed. There can be different forms of coexistence, such as spectrum underlay (e.g. UWB) or spectrum overlay (e.g. opportunistic exploitation of white spaces in spatial-temporal domain sustained on spectrum sensing, coordination with peers and fast spectrum handover). As for cooperation, again different forms of P-S interactions are possible. For example, spatial-temporal white spaces that can be exploited by SUs can be signalled through appropriate channels or beacons. In addition, the interaction between PUs and SUs provides an opportunity for the license-holder to demand payment according to the different quality of service grades offered to SUs.

One of the key enabling technologies for DSAN development is Cognitive Radio (CR), which has been claimed to be an adequate solution to the existing conflicts between spectrum demand growth and spectrum underutilization. The term Cognitive Radio was originally coined by J. Mitola III in [2][3] and envisaged a radio able to sense and be aware of its operational environment so that it can dynamically and autonomously adjust its radio operating parameters accordingly to adapt to the different situations. CR concept was built in turn upon the Software Defined Radio (SDR) concept, which can be understood as a multiband radio supporting multiple air interfaces and protocols and being reconfigurable by software running on a Digital Signal Processor (DSP) or a general-purpose microprocessor. Consequently, SDR constituted the basis for the physical implementation of CR concepts.

Thanks to this capability of being aware of actual transmissions across a wide bandwidth and to adapt their own transmissions to the characteristics of the spectrum, CRs offer great potential for bringing DSANs to reality, and in fact DSANs are usually referred to as Cognitive Radio Networks (CRNs). The operating principle of a CR in the context of a DSAN is to identify spatial and temporal spectrum gaps not occupied by primary/licensed users, usually referred to as *spectrum holes* or *white spaces*, place secondary/unlicensed transmissions during such spaces and vacate the channel as soon as primary users return. The CR concept therefore implicitly relies on two basic premises: the existence of enough white spaces caused by primary spectrum underutilization and the ability of secondary users to effectively detect and identify the presence of licensed technologies in order not to cause harmful interference.

From a general operation perspective, a CR follows the so-called *cognition cycle* to enable the interaction with the environment and the corresponding adaptation. It consists in the *observation* of the environment, the *orientation* and *planning* that leads to making the appropriate *decisions* pursuing specific operation goals, and finally *acting* over the environment. Decisions on the other hand can be reinforced by *learning* procedures based on the analysis of prior observations and on the corresponding results of prior actuations. Then, when particularizing the cognition cycle to the dynamic spectrum access for a secondary user, the observation turns out to be the spectrum sensing in order to identify the potential white spaces, the orientation and planning steps would be associated with the analysis of the available white spaces, and finally the acting step would be in charge of selecting the adequate white space to make the secondary transmission, together with the setting of the appropriate radio parameters such as transmit power, modulation formats, etc.

There are a number of techniques to be developed for an implementation of efficient secondary spectrum usage through cognitive radio networks, and are classified in [4] as spectrum sensing, spectrum management, spectrum mobility and spectrum sharing mechanisms. These techniques are briefly discussed in the following:

- **Spectrum sensing:** It consists in detecting the unused spectrum bands that can be potentially exploited for secondary communications. A lot of different spectrum sensing techniques have been studied in the last years, such as the energy detector, which does not include any specific knowledge about the primary signal to be detected, the matched filter detection, which requires the knowledge of the specific primary signal formats, or the cyclostationarity feature detection. Also the possibility of combining sensing measurements from different sensors through appropriate fusion schemes has been considered in the so-called cooperative sensing. Even from a more general perspective, the possibility that the network provides knowledge about the current spectrum bands available through some control channel has also been considered. This is the case of e.g. the development of the so-called Cognitive Pilot Channel (CPC) in [5]. From this perspective, and having in mind the possibility of combining the knowledge provided by the network with the knowledge acquired by the sensing process, spectrum sensing concept can be generalised to the concept of spectrum awareness.
- **Spectrum management:** This refers to the selection of the most adequate spectrum band to carry out the transmission in accordance with the secondary user requirements. This selection should be made based on the characteristics of the channel in terms of e.g. the maximum capacity that can be obtained by the secondary users, and also taking into consideration the maximum interference that can be tolerated by primary receivers. The decision making process here can be benefited from the application of learning strategies that, based on experience acquired from prior decisions, can orient the decisions towards the selection of some channels in front of others. For example, when the primary user activity is high in some channels, it is more likely that primary users force the secondary transmitter to free the channel. Thus, if PU's activity characterisation was known by the SUs, it could prevent the secondary network from selecting these channels.
- **Spectrum mobility**: This functionality consists in establishing appropriate mechanisms to ensure that an on-going secondary communication can be continued whenever a primary user appears in the occupied bandwidth. This will thus involve the ability to detect the appearance of this primary user, which requires some continuous monitoring of the channel, e.g. through sensing mechanisms. Then, when the primary user appears, the occupied channel has to be freed, and an alternative channel has to be found where the communication can be continued, which is usually called *spectrum handover*. Handover has therefore a broaden meaning compared to the *horizontal handover* typically implemented in cellular systems to enable space mobility. In the case of the spectrum handover, the band and also the communication standard may change during the handover procedure, implying the so-called *vertical handover*. When both spatial and spectrum handover are considered in DSAN, the term of generalized handover is used [6].
- **Spectrum sharing**: This function targets the provision an efficient mechanism so that coexisting secondary users can share the available spectrum holes. Adequate Medium Access Control (MAC) protocols and scheduling mechanisms would be needed, and they would be very much dependant on how the secondary network is deployed, e.g. if it is infrastructure or infrastructure-less based, etc.

Although all the above functions have become a hot research topic during the last few years, there is still a lot of work to do before CRNs become a reality at the fullest extent. This will involve not only technical aspects, but also significant regulatory changes will be needed. In addition, this will also have implications from the techno-economic perspective, with the appearance of new business models to exploit the capabilities offered by CRNs, involving different possibilities ranging from secondary cellular operators that could offer services at cheaper prices at the expense of a somehow reduced quality, to the deployment infrastructure-less secondary networks that would enable the communication of short range devices.

Based on the above context, this paper focuses on the applicability of measurement techniques to the development of CRNs. In particular, Section 2 addresses the spectrum sensing techniques as one of the key procedures for the operation of CRNs. Then, Section 3 will focus on the different standardisation initiatives that have been carried out. Section 4 will then address particular aspects of spectrum measurement techniques and how the results from measurement campaigns can be used in CRN design. This will be followed by the results of a real case study of spectral measurements obtained in the area of Barcelona in Section 5. Finally, conclusions will be summarised in Section 6.

2 Spectrum Sensing Techniques

There has been a growing interest in signal detection in the context of Cognitive Radio [3], and more specifically in that of opportunistic radio (or overlay systems), where secondary CRNs can be operated over frequency bands allocated to some primary system in so far as this primary system is absent (free band detection) or, in a more general case, whenever harmful interference with primary systems can be avoided. In most cases, the presence of the primary system is assessed through direct detection of its communication signal, although beaconing is sometimes considered [7]. Thus, in many situations, the primary system detection problem is transposed onto the problem of detecting a communication signal in the presence of noise.

Signal detection is a very old and thought after signal processing issue. In the context of CRNs, the detection of PUs by the secondary system is critical in a cognitive radio environment. Indeed, misdetection would lead to harmful interference to the PU, while a high false alarm probability would make actual holes unavailable to secondary usage. However, PU detection is made difficult due to the challenges in accurate and reliable sensing of the wireless environment. Secondary users might experience losses due to multipath fading, shadowing, and building penetration which can result in an incorrect estimation of the wireless environment, which can in turn cause misdetection or false alarm at the SU. This brings the necessity for the cognitive radio to be highly robust to channel impairments and also to be able to detect extremely low power signals. These stringent requirements lead to important challenges for the deployment of CR networks. Surveys of these techniques in the context of spectrum sensing have been proposed for instance in [8][9].

Although some simple detectors can be achieved directly on the RF signal (e.g. energy detection), the detector is most of the time processed on the baseband digital signal to allow for more algorithmic options. In this case, the free band detector can be illustrated as in Figure 1.

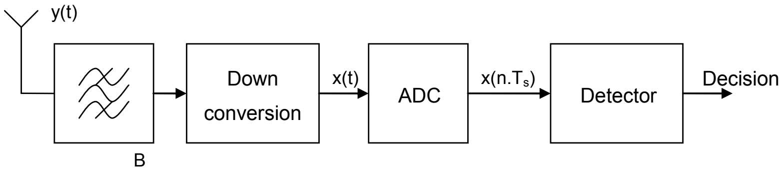

Figure 1 – Digital Free Band detector architecture.

Radio signal y(t) received at the antenna is first filtered on a bandwidth *B*, which is the band under consideration, then down converted to baseband, digitized (at a sampling frequency of $1/T_s$) before being sent to the detector. The function that the detector has to perform is the one of detecting signals in the presence of noise, which can be stated as the following hypothesis:

$$H_0 : r(t) = n(t) \qquad H_1 : r(t) = hs(t) + n(t) \tag{1}$$

where H_0 is verified when the band B is signal free and H_1 corresponds to B being occupied. $n(t)$ is noise and $s(t)$ is a telecommunication signal.

Many detection techniques may be considered depending on the detection performance and the implementation cost. Typically, detectors are categorized based on the required knowledge of the SU about the waveform of the PU. Among them we describe below the three most important options: the matched filter, the energy or power detection, and the feature detector which often exploits the cyclostationarity nature of the PU signal.

Using a matched filter is the optimal solution to signal detection in presence of noise as it maximizes the received signal to noise ratio (SNR) [10]. It is a coherent detection method, which necessitates the demodulation of the signal, which means that cognitive radio equipment has the *a priori* knowledge on the received signal(s), e.g. modulation type, pulse shaping filter, data packet format, etc. Most often, telecommunication signals have well-defined characteristics, e.g. presence of a pilot, preamble, synchronization words, etc., that permit the use of these detection techniques. Based on a coherent approach, matched filter has the advantage to only require a reduced set of samples, function of $O(1/SNR)$, in order to reach a convenient detection probability [11]. If X[n] is completely known to the receiver then the optimal detector for this case is:

$$T(Y)=\sum_{n=0}^{N-1}Y[n]X[n]\overset{<\ H1}{\underset{>\ H0}{}}\gamma \qquad (2)$$

The matched filter lacks genericity as it can be applied to only one specific waveform. One approach to make the detector independent to the waveform is to perform non-coherent detection through energy detection [12]. This sub-optimal technique has been extensively used in radiometry. Energy detection or radiometer method lies on a stationary and deterministic model of the signal mixed with a stationary white Gaussian noise. The basic functional method involves a squaring device, an integrator and comparator (Figure 2). The SNR can be calculated as in the figure so that the threshold K directly relates to some SNR value. If V is higher than the threshold K, then the presence hypothesis (H_1) is considered as fulfilled. Otherwise, the band is considered as signal free (H_0). In many practical implementations though, the signal energy is computed on one hand (integrator) and the threshold is computed after some calibration of the radiometer in absence of the signal. In this case, σ_0 is omitted in the calculation of V.

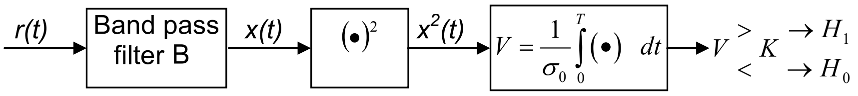

Figure 2 – Energy detector block diagram.

It can be implemented either in time domain or in frequency domain. Time domain implementation requires front-end filtering before the squaring operation. In frequency domain implementation, after front-end band-pass filtering, the received signal samples are converted to frequency domain samples using Fourier transform. Signal detection is then effected by comparing the energy of the signal samples falling within certain frequency band with that of a threshold value. The performance of the energy detector directly depends on the integration time, which is usually limited in telecommunication systems.

Then, an interesting alternative to energy detection consists in considering a cyclostationary model instead of a stationary model of the signal [13]. Indeed the telecommunication signals are modulated by sine wave carriers, pulse trains, repeated spreading, hopping sequences, or exhibit cyclic prefixes. This results in built-in periodicity which of course is not present in the noise. These modulated signals are characterized as cyclostationary because their momentum (mean, autocorrelation, etc) exhibits periodicity, thereby enabling to differentiate the modulated signal from noise. This is due to the fact that noise is a wide-sense stationary signal with null auto correlation (except at lag 0).

If *x(t)* is a random process of null mean, *x(t)* is cyclostationary at order *n* if and only if its statistic properties at order *n* are a periodic function of time. In particular, for *n*=2, process is cyclostationary in the large sense and respects:

$$c_{xx}\left(t,\tau\right)=E\left(x\left(t\right)x\left(t+\tau\right)\right)=c_{xx}\left(t+T,\tau\right) \tag{3}$$

where *T* represents a cyclic period.

When the PU signal is completely unknown it is theoretically possible to explore the presence of cyclic frequencies for any autocorrelation lag at any frequency. This approach is referred to as (also referred to as 2 dimension) Cyclostationary Spectrum Density (CSD) [14][15]. However, the comprehensive 2D CSD is never implemented in practice due to its huge implementation cost. To sort out this issue, 1D CSDs are preferred to limit implementation cost. The CSD can be performed on the time domain autocorrelation [16], or through the analysis of signal periodicity redundancy in the frequency domain [17]. In both cases however, a large FFT operator (512 to 2048) needs to be implemented, leading to significant hardware complexity. When additional knowledge of the PU signal is exploited by the SU, the FFT can be avoided and only specific known cyclic frequencies are explored, like in [18][19]. This can lead to significant complexity reduction as highlighted in the WIFI and DVB-T specific implementations presented in [20]. Besides, it was shown that restricting the modulation search space (i.e. shrinking the 2D CSD to a small subset of samples) also reduces the convergence of the algorithm, thereby enabling the exploitation of short duration opportunities [21].

3 Standardisation activities in the area of DSANs

The trend towards DSAN has urged standardization bodies to propose technologies to rationalize cognitive radio operation. These standards tackle cognitive radio from various angles. The first one relates to the amendment of existing standards to operate under certain regulatory conditions that require DSAN features. This is for instance the case in the TV White Space. The second one suggests analysing DSAN from a broader viewpoint in order to come up with a coherent and more general framework. In both cases, there is a need to guarantee interference free operation to prioritise systems (e.g. TV systems in the TV white space context) or coexistence among peers (e.g. with other unlicensed systems).

These non-interference or coexistence techniques can be divided into two categories: overlay and underlay. In the underlay case the secondary system operates with a very low power spectral density in order not to impact the primary (or other) users. Thereby, the underlay system is seen as low power additive noise by the primary systems. This is the case of ultra wide band (UWB) systems which operate over a wide bandwidth. Thus, the IEEE802.15.4a [22], within the IEEE802.15 group for Wireless Personal Area Networks, can be considered as a first attempt to enable spectrum sharing between an unlicensed secondary systems and primary (licensed) systems.

However, despite the strong restrictions on spectrum density for such systems (-41.3dBm/MHz), UWB systems operating in the low band (3-5GHz) have been forced to include detect and avoid (DA) features to ensure that they are switched off whenever a WIMAX system operates within the band (typically, at 3.5GHz). This turned the UWB system (at least in the low band) to operate in an overlay mode where the secondary system can operate only when the band is vacant of any primary spectrum usage. The overlay approach implies that sensing (in a broad sense) and cognitive techniques are used to detect the presence of incumbents, in order to decide whether communication can be initiated and to adapt the transceiver accordingly.

This overlay approach with a listen-before-talk strategy was at the heart of the IEEE 802.22 group on WRANs (Wireless Regional Area Networks), launched in 2005. This standard aims at exploiting the TV white space spectrum with a Cognitive Radio approach [23][24]. Physical and MAC layers of IEEE 802.22 are similar to IEEE 802.16 with some modifications related to the identification of the primary systems. This standard was given more prominence after the decision of the FCC to enable unlicensed access to CRNs in the TV bands [25].

Within the IEEE, the DSAN rationalization effort came in 2005 with the creation of a set of standardization projects related to CRN, and numbered IEEE 1900, which evolved in 2006 into IEEE Standards Coordinating Committee 41 (IEEE SCC41) on "Dynamic Spectrum Access Networks" [26]. The scope of IEEE SCC41 is to facilitate the development of research ideas into standards as to transfer the use of research results for public use. Very recently, the committee was transferred to the IEEE Communication Society (ComSoc) standards and was renamed the IEEE ComSoc DYnamic SPectrum Access Networks (DYSPAN) committee. Because, DSAN was a new area in wireless communication, it was found useful to precisely define the terminology to enable a common understanding. This was the scope of the 1900.1-2008 standard [27]. As mentioned above, coexistence among systems is of paramount importance for CRN. This was the scope of 1900.2-2008 that was issued the same year [28]. Similarly, the IEEE 802.19 standard defined general coexistence metrics for all IEEE 802 networks but with a focus on operation in the unlicensed bands. Although focusing on IEEE 802 networks, the guidelines of the standard can be applicable to other unlicensed wireless systems.

In the 1900 series, the 1900.4 group is the one developing a complete framework for CRNs. The 1900-2009 standard considers the architectural building blocks enabling network-device distributed decision making for optimized radio resource usage in heterogeneous wireless access networks [29]. The standard includes entities comprising network and device resource managers as well as the information to be exchanged between these entities. The aim of this framework is to optimize radio resource usage in a cognitive driven environment. Currently two projects are active within this group: P1900.4.1 which addresses "Interfaces and Protocols Enabling Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Networks" and P1900.4a on "Architecture and Interfaces for Dynamic Spectrum Access Networks in White Space Frequency Bands". The first one focuses on the interfaces between the architectural entities defined in [29]. The latter is an amendment of [29] to enable mobile wireless access for any radio technology. Finally, P1900.5 is developing a standard on Policy Language and Policy Architectures for Managing Cognitive Radio for DSAN.

Compared to classical wireless networks, determining the presence of other systems is a key feature. This can be done through spectrum sensing or by querying a data archive. How these entities are interfaced to the communication systems is being analysed by the P1900.6 Working Group. The standard project specifies a functional interface comprising a number of logical entities (service access points) attached to sensing, communication and application.

Outside the IEEE Standard Association and ComSoc standards, other standardization organizations have put significant interest in CRNs. This is the case of ECMA with standard 392 [30]. This standard defines a MAC and PHY for cognitive use of TVWS in WLAN-like scenarios. It was released by ECMA international at the end of 2009. In addition to MAC and PHY, ECMA-392 also includes specifications for MUX sub layer for higher layer protocols. ECMA-392 was developed by technical committee TC48, task group TG1, and therefore it is also known as ECMA TC48-TG1 standard. The standard is based on the contribution of the Cognitive Networking Alliance (CogNeA) [31] formed at the end of 2008 and composed by ETRI, Hewlett-Packard, Philips, Samsung, (board), and Georgia Institute of Technology and Motorola (contributors). Texas Instruments was previously indicated as a member.

With similar scenarios and applications to ECMA, the project IEEE P802.11.af was launched more recently in December 2009 [32]. It aims at creating an amendment to the IEEE 802.11 by modifying both PHY and MAC to meet the regulatory requirements for channel access and coexistence in the TV white space (TVWS). The group suggests the use of OFDM PHYs focused on 5 MHz channel width to comply with the 6, 7 or 8MHz TV channels depending on countries. Because this standard aims at operating outside the ISM band, no backward compatibility is required with former versions of

IEEE802.11, but it is not intended to go beyond 802.11a/g capacity in terms of achievable data rate. The main benefit of 802.11 WLANs in the TVWS is seen in the wider applicability of 802.11 to newly available spectrum portions and the resulting increased commercial relevance. This project considers geo-location based systems without sensing capabilities. This shall be a significant difference from other TVWS oriented standards (e.g. IEEE802.22 or ECMA392). This geo-location- based operation was made possible in the US by the 2nd memorandum on TVWS "Super WiFi" operation [33].

With a wider application in mind, DYSPAN has suggested a new project to define PHY and MAC for white spaces, which would be defined for white space DSAN, but which does not build upon an existing standard. This project was submitted to NesCom as P1900.7. Approval is expected in early 2011.

In Europe, the ETSI Technical Committee on Reconfigurable Radio Systems (RRS) has defined a "Functional Architecture for the Management and Control of Reconfigurable Radio Systems" [34][35] in order to improve the utilization of spectrum and radio resource usage. Different functional entities have been identified in the Functional Architecture (FA), including the Dynamic Spectrum Management entity, the Dynamic, Self-Organising Network Planning and Management block, the Joint Radio Resource Management entity, and finally, the Configuration Control Module (CCM). This effort relates to the same objective as the one of IEEE1900.4 to define a global framework for CRNs.

It can be analyzed from this list that standardization activity related to DSAN is rather recent and evolves along with the decisions or trends at the regulation level, which is at the moment focused on TV white space operation [35][36]. New groups are being created at a sustained pace showing a very strong interest of stakeholders in this topic. Another interesting point that can be noticed is the organizations who express interest in DSANs. Whereas classical telecommunication standardisation bodies mainly gather telecom operators and vendors, DSANs open the door to organisations that see DSANs as a means to grant spectrum access with a non traditional telco business model. The members of the TV white space coalition give a clear snapshot of this trend, with members like Microsoft, Google, Dell, HP, Intel, Philips, Earthlink, and Samsung [37].

4 Measurements for the Identification of Spectrum Availability

Measurements of the radio environment can provide valuable insights into current spectrum usage and a proper understanding of spectrum usage patterns can be very useful to define adequate dynamic spectrum policies and to identify appropriate frequency bands for the deployment of future CR networks. Similarly, the identification of usage patterns can be exploited in the development of useful spectrum usage models and more efficient CR techniques. Several measurement campaigns covering both wide frequency ranges [38]-[43] as well as some specific licensed bands [44]–[48] have been performed in diverse locations and scenarios in order to determine the degree to which allocated spectrum bands are occupied in real wireless communication systems. This section provides a summary of the different spectrum measurement methodologies, equipments and metrics that are typically considered in such campaigns. Finally, it provides some hints on the applicability of measurement-based methodologies to the design of CR networks.

4.1 Spectrum Measurement Methodologies and Equipments

There are many factors that need to be considered when defining a strategy to meet a particular radio spectrum occupancy measurement need. Some basic dimensions to specify are [49]: frequency (frequency span and frequency points to be measured), location (measurement site selection), direction (antenna pointing angle), polarization (receiving antenna polarization) and time (sampling rate and measurement period). The measurement setup employed in the evaluation of spectrum occupancy should be designed taking into account the previous factors since they play a key role in the accuracy of the obtained results. The measurement setup should be able to detect, over a wide range of frequencies, a large number of transmitters of the most diverse nature, from narrow band to wide band systems and from weak signals received near the noise floor to strong signals that may overload the receiving system.

Depending on the purposes of each specific study (e.g. broadband measurement campaigns, measurements over specific bands, temporal resolution targeted by the measurements, etc.), different configurations have been used in previous spectrum measurements ranging from simple setups with a single antenna directly connected to a spectrum analyzer [47] to more sophisticated designs [38][40]. Different configurations between both extreme points may determine various tradeoffs between complexity and measurement capabilities.

Spectrum analyzers are one of the most commonly used equipments in the different measurement campaigns, since they usually allow measuring large bandwidths although at the expense of limited time resolutions, typically in the order of seconds that could not be appropriate for certain levels of modelling. When higher time resolutions are required, other measurement platforms can be used such as vector signal analysers or more specific platforms such as Universal Software Radio Peripheral (USRP) and GNU Radio architecture. This measurement platform is able to perform spectrum measurements over narrower bandwidths than a spectrum analyser, but with much higher time resolutions, in the order of micro- and nano-seconds. This provides not only power spectrum measurements, as it is the case of a spectrum analyser, but true signal samples, from which the signal phase information can be extracted. If only power measurements of the spectrum utilisation are available, as it is the case of spectrum analyser based measurements, the energy detection method, as described in Section 2 is the only possibility left.

With respect to the antenna equipment, when covering small frequency ranges or specific licensed bands a single antenna may suffice. However, in broadband spectrum measurements from a few MHz up to several GHz two or more broadband antennas are required in order to cover the whole frequency range. Most of spectrum measurement campaigns are based on omni-directional measurements in order to detect primary signals coming for any directions. To this end, omni-directional vertically polarized antennas are the most common choice.

4.2 Spectrum Occupancy Metrics

Another important methodological aspect in a measurement campaign is the specification of adequate metrics to evaluate and quantify the level of spectral occupancy. While some of them are directly provided by the measurement equipment and some others are obtained by post-processing the measured data. Some examples of metrics that have been typically used are:

a) Power spectral Density
It is well known from Fourier theory that any time-domain electrical phenomenon can be expressed as the sum of one or more sine waves of appropriate frequency, amplitude, and phase. The Power Spectral Density (PSD) of a signal is the graphical representation of its frequency content, with the abscissa being the frequency and the ordinate being the amplitude (the phase information is not captured by a spectrum analyser). PSD can be measured in different ways in order to obtain different PSD graphs, mainly the average PSD, maximum PSD and minimum PSD. When considered together, average, maximum and minimum PSD provide a simple characterisation of the temporal behaviour of a channel. For example, if the results are quite similar, it suggests a single transmitter that is always on, experiences a low level of fading and so is probably not moving either. At the other extreme, a large difference among average, maximum and minimum PSD suggests more intermittent use of the spectrum and therefore indicates a potential opportunity for CRNs.

b) Spectral occupancy percentage or duty cycle
The relevant metric to determine the degree to which spectrum is used in the temporal dimension is the spectral occupancy percentage, or simply the spectral occupancy, also referred to as duty cycle. It is defined as the fraction of time that a given channel or frequency band is determined to be occupied by a licensed signal. CRNs may take advantage of idle time periods to opportunistically access the available spectrum. Therefore, frequency bands with low duty cycles offer an interesting opportunity

for the deployment of CRNs. When computing the duty cycle, an overall value for a given frequency band can be determined in order to quantify the degree to which spectrum is used by a certain licensed system and hence identify the most interesting bands for the deployment of CRNs. Nevertheless, the temporal evolution of this metric (e.g., averaged of 1-hour periods or days) can also provide interesting information about the temporal utilisation of the spectrum. Note that the detection of whether a frequency band is being used by a licensed user can be carried out by different sensing methods providing different trade-off between required sensing time, complexity and detection capabilities, as explained in section 2.

c) Amplitude Probability Distribution (APD)
Key characteristics of the licensed system such as signal bandwidth, transmitter mobility and number of transmitters can be easily estimated by evaluating the histogram of the received amplitude samples. This is known as the Amplitude Probability Distribution (APD) analysis method [42]. APD is a three-dimensional histogram with one axis being amplitude, one being frequency span, and another being the probability of each amplitude value throughout the whole measurement period. The underlying principle of APD analysis is that different equipments and devices show distinct behaviour in terms of PSD and signal characteristics and therefore these transmitter characteristics can be inferred from the statistical distribution of the amplitude probability. As an example, a single peak with narrow and sharp shape and large amplitude is associated to a fixed transmitter with rather constant power. The height and the width of the peak jointly describe the stability of the transmission power. The higher and the narrower the peak the more constant the transmission power is. On the other hand, a single wide peak with large amplitude could represent a transmitter applying amplitude modulation techniques or having mobility. A wider distribution with many peaks but small maximum amplitudes is associated to many devices received from different distances, or congregation of various services with distinct power regulations. Finally, the received power allows in some cases to infer the rough operating power of the transmitter directly from the APD histogram.

4.3 Applicability to the design of CR systems

Empirical data derived from spectrum occupancy measurement campaigns exhibit a wide set of useful applications for the design of CR systems, ranging from the simplification of analytical studies up to the development of new techniques and algorithms for dynamic spectrum access or simulation tools based on these models. Then, real field measurement data could be used as the support for the evaluation of different CR mechanisms proposed in the literature, in most of the cases addressing only a system level approach.

CR network operation can be optimised by making use of databases capturing the knowledge about the radio environment of a given geographical area, including elements such as geographical aspects, available services, spectral regulations, positioning of transmitters, transmitter profiles, primary user activity patterns, etc. The term Radio Environment Map (REM) has been used in [50] to refer to such a database used as the support to a CR network. It can be clearly envisaged that, through the adequate feeding of the REM through results coming out from measurements it can be possible to improve the accuracy in its information, and with the corresponding dissemination procedures to make this information available to CR nodes, which can eventually combine it with their own spectrum sensing results, it is possible to improve the performance of the decision making procedures in a CR network.

Similarly, measurements can be used for the characterisation of the level of spectral occupation in the frequency, time and space dimensions enabling the formulation of models to describe with a high level of accuracy the utilisation and activity patterns of the different frequency bands. When addressing the definition of spectrum occupation models there are three main elements to define. The first one is the set of parameters, characteristics or properties of the spectrum occupation to be represented and reproduced through the model. They can be the duration of the activity/inactivity periods of the different channels as well as their corresponding probability distributions, the fraction of time that the channels remain occupied, the distribution of occupation among channels of the same band, the distribution of the occupation in a given geographical area and the corresponding spatial correlations, the evolution of the power level present in the different channels of a given band, etc. The formulation of a new spectrum occupation model should also identify the set of tools used to carry out the modelling. Then, it is possible to distinguish between models based on Markov chains, or on fitting curves to specific parameterized analytical expressions, or on probability density functions, stochastic processes, random fields, time series, etc. Finally, another important aspect to take into account is the information provided by this model, which refers either to the behaviour of the abovementioned parameters or to other system level aspects, such as the time evolution of the instantaneous spectrum occupation for different frequency channels or geographical areas.

One of the simplest and most widely used temporal spectrum occupation models is the first order Markov model with idle and busy states [51]–[53]. It can be easily parameterized by means of empirical measurements as done in [52] for the ISM band of 2.4 GHz using a vector signal analyser over specific types of traffic or in [53] using a spectrum analyser. In the latter, the target was to find out the statistical distributions that best fit the idle and busy periods for different technologies, and obtaining that a geometrical distribution can fit in a quite acceptable way the actual measurements for many of the considered technologies. It was also obtained that in some cases there exists a correlation between the durations of the idle and busy periods, which was tried to be qualitatively reproduced in works such as [54][55]. One of the aspects identified in current empirical models is that distributions usually depend strongly on the time resolution of the measurements. In that sense, it can be envisaged the extension of existing models to reproduce at least two different levels of time resolution, one for an instantaneous channel occupation using high time resolution models (e.g. using vector analysers) and a second one able to reproduce the load variations in a longer term time scale (e.g. using spectrum analysers). The modelling in this case could be based on Markov models but also on other techniques such as random walks [56] or time series [57]. Similarly, in [58] Fourier analysis is used to identify periodicities in the spectral occupation patterns that could be used to decide the appropriate sensing instants.

As for the modelling of spectral occupation in the frequency dimension, one of the first models was the Laycock-Gött model [59], which tried to capture the duty cycle of different channels in the HF band. While this model was acceptable for the large coverage areas existing in the HF band and thus the observed pattern could fit in large geographical areas, the generalisation to other bands with smaller coverage areas and more variability in the occupation depending on the position is hardly feasible. In that sense, another model in the context of CR was developed in [60] and further extended in [53], analysing the statistical distribution of the duty cycle among channels belonging to the same band and proposing to model it through a modified beta function which also showed a good fitting when applied to bands assigned to different technologies.

Finally in the area spatial dimension modelling in [56] the spatial distribution of the spectral occupation in a real cellular system is analysed based on monitoring the call arrival rates and making use of variograms to obtain the variability of the spectrum spatial occupation among sectors of a given cell. In [61] the spatial characterisation of the spectrum occupancy through PSD measurements was carried out making use of the random field theory. The procedure makes use of empirical PSD measurements in different points to adjust a semivariogram model that reproduces the statistical properties of the average PSD values observed in a certain geographical area.

5 Measurement Case Study in the Urban Area of Barcelona

This section presents a case study of spectral occupation measurements in the urban area of Barcelona, with the objective to illustrate with real measurements the methodologies described in the previous section.

5.1 Measurement setup and configuration

The employed measurement configuration relies on a spectrum analyser to which various external devices have been attached in order to improve the detection capabilities of the system and hence obtain more accurate and reliable results. The design is composed of two broadband antennas that cover the frequency range from 75 to 7075 MHz, a switch to select the desired antenna, several filters to remove undesired signals, a low-noise pre-amplifier to enhance the overall sensitivity and thus the ability to detect weak signals, and a high performance spectrum analyser to record the spectral activity. A simplified scheme with all the devices and their main technical features is shown in Figure 3.

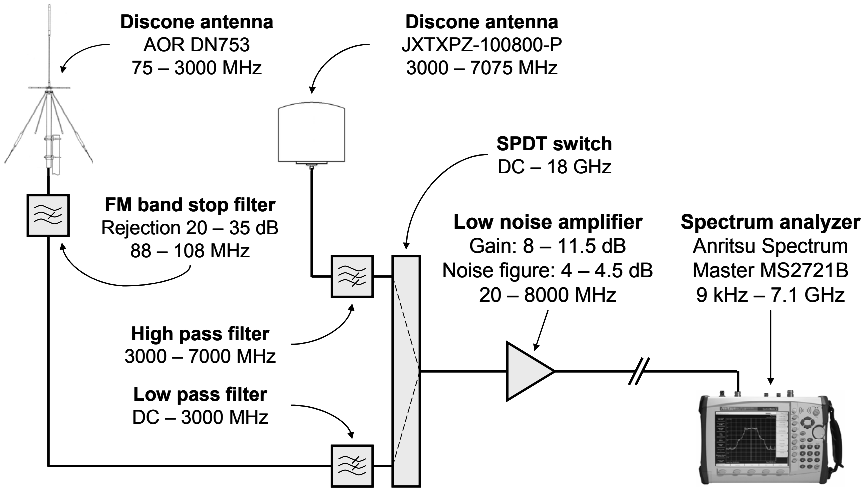

Figure 3 – Measurement setup employed in this study (complete scheme).

The antenna subsystem is shown in Figure 4. Two wideband discone-type antennas are used to cover the frequency range from 75 to 3000 MHz (AOR DN753) and 3000 to 7075 MHz (A-INFO JXTXPZ-100800/P). Discone antennas are wideband antennas with vertical polarisation and omni-directional receiving pattern in the horizontal plane. Even though some transmitters are horizontally polarized, they usually are high-power stations (e.g., TV stations) that can be detected even with vertically polarized antennas. The exceptionally wideband coverage (allowing a reduced number of antennas in broadband spectrum studies) and the omni-directional feature (allowing the detection of primary signals coming for any directions) make discone antennas attractive in radio scanning and monitoring applications, and have been a preferred option for many spectrum studies.

The Radio Frequency (RF) subsystem performs antenna selection, filtering and amplification. The desired antenna is selected by means of a Single Pole Double Throw (SPDT) switch that enables a high isolation (90-100 dB) and low insertion loss (0.1-0.2 dB). In order to remove undesired signals, three filters are included. A band stop filter blocks signals in the frequency range of Frequency Modulation (FM) broadcast stations (87.5-108 MHz). Usually, such stations are high power transmitters that may induce overload in the receiver thus degrading the receiver performance by an increased noise floor or by the presence of spurious signals, which inhibits the receiver's ability to detect the presence of weak signals. Since the FM band is of presumably low interest for secondary use due to its usually high transmission power and expected high occupancy rate, a FM band stop filter has been employed in order to remove FM signals and avoid overload problems, improving the detection of weak signals at other frequencies. Low pass and high pass filters have been used to remove out-of-band signals and reduce the potential creation of inter-modulation products. To compensate for device and cable losses and increase the system sensitivity, a low noise pre-amplifier has been included. The selected mid-gain amplifier provides significant sensitivity improvements while guaranteeing the Spurious-Free Dynamic Range (SFDR) required by the measured signals.

The Anritsu Spectrum Master MS2721B high performance handheld spectrum analyser has been used to provide power spectrum measurements and record the spectral activity over the complete frequency range. It provides a measurement range from 9 kHz to 7.1 GHz, low noise level and a built-in pre-amplifier that facilitates the detection of weak signals, fast sweep speed automatically adjusted, and the possibility to connect an external USB storage device to save measurements for later data post-processing.

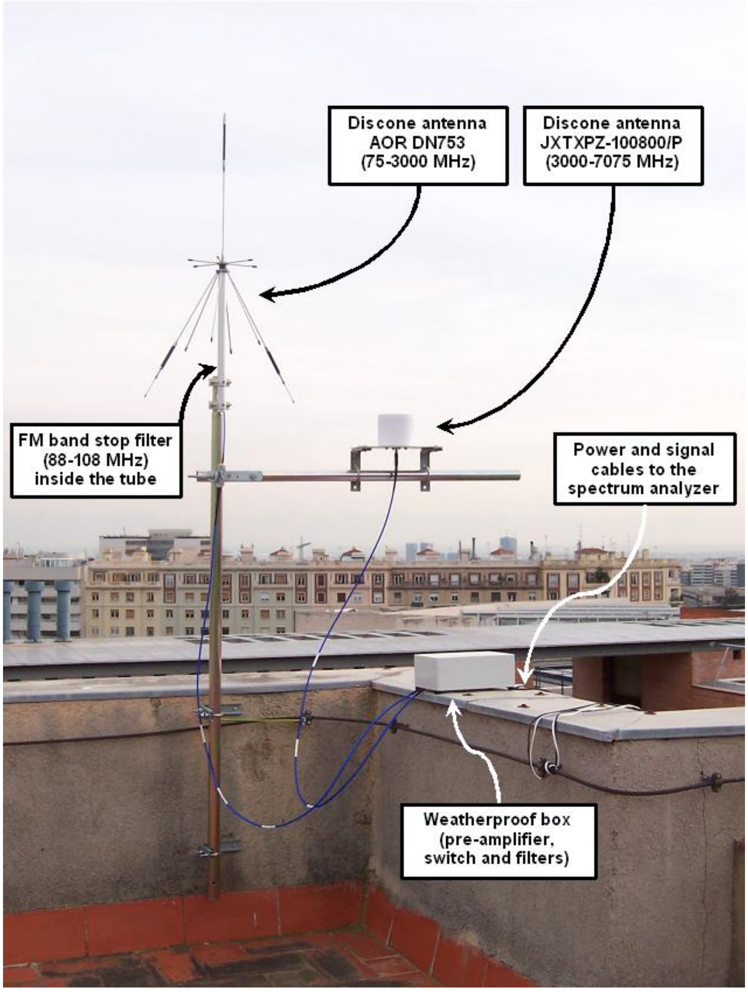

Figure 4 – Measurement setup employed in this study (antenna subsystem).

Since the different operating modes of spectrum analysers can significantly alter the results of the measurement, proper parameter selection is crucial to produce valid and meaningful results. The different parameters of the spectrum analyser have been set according to the basic principles of spectrum analysis as well as some particular considerations specific to CR. Table 1 shows the main spectrum analyser configuration parameters.

The measured frequency range (75-7075 MHz) has been divided into 25 blocks with variable sizes ranging from 45 MHz up to 600 MHz. The division has been performed following the local Spanish governmental spectrum allocations [63] and taking into account the transmitted signal bandwidth for each band (for example, frequency bins of 81.8 kHz were used to measure 200-kHz GSM channels while 745.5 kHz and 727.3 kHz bins were employed for 8-MHz TV and 5-MHz UMTS channels respectively).

The Resolution BandWidth (RBW) plays an important role in the obtained measurements. Narrowing the RBW increases the ability to resolve signals in frequency and reduces the noise floor (increasing the sensitivity) at the cost of an increased sweep time and hence a longer measurement period. Based on the results presented in [62], a 10-kHz RBW has been selected as an adequate trade-off between detection capabilities and required measurement time. The Video BandWidth (VBW) is a smoothing function that dates to analogical spectrum analysers, but is now nearly obsolete. To eliminate this analogical form of averaging, the VBW has been set equal to the RBW.

Each one of the 25 sub-bands considered in this work has been measured during 24 hours. The number of recorded traces/sweeps during such measurement period is a function of the sampling rate (i.e., the sweep time), which is automatically adjusted by the spectrum analyser according to various configuration parameters, including the frequency span. For example, for the configuration parameters shown in Table 1, the employed spectrum analyser sweeps at an approximate average speed of 25 ms/MHz, thus leading to average sweep times ranging from around 1 second for a 45 MHz span to around 15 seconds for a 600 MHz span.

Table 1 – Spectrum analyser configuration.

	Parameter	**Value**	
Frequency	Frequency range	75-3000 MHz	3000-7075 MHz
	Frequency span	45-600 MHz	
	Frequency bin	81.8-1090.9 kHz	
	Resolution BW	10 kHz	
	Video BW	10 kHz	
Time	Measurement period	24 hours	
	Sweep time	Auto	
Amplitude	Built-in pre-amp	Deactivated	Activated
	Reference level	– 20 dBm	– 50 dBm
	Reference level offset	0 dB	– 20 dB
	Scale	10 dB/division	
	Input attenuation	0 dB	
	Detection type	Average (RMS) detector	

For measurements below 3 GHz, where some overloading signals may be present, only the external amplifier has been used. For measurements above 3 GHz, where the received powers are lower, both the external and the spectrum analyser's internal amplifier have been employed resulting in a noise floor reduction of 20 dB. To simplify the data post-processing, the noise floor values in the 75-3000 MHz and 3000-7075 MHz bands have been equalized by adding a 20dB offset to the power levels measured between 3000-7075 MHz (reference level offset). The reference level (the maximum power of a signal that enters the spectrum analyser and can be measured accurately) has then been adjusted according to the maximum power observed in each region, while the scale is adjusted according to the minimum signal level. No input attenuation has been employed. An average type detector has been used. This detector averages all the power levels sensed in one frequency bin in order to provide a representative power level for each measured frequency bin.

5.2 Measurement scenario

Most of the existing spectrum occupancy studies are based on measurements performed in outdoor environments and more particularly in outdoor high points such as building roofs, balconies and towers. The main advantage of high points is that they provide direct line-of-sight to many kinds of primary transmitters and therefore enable a more accurate measurement of their actual spectral activity. Nevertheless, this scenario may not be representative of the spectrum occupancy that would be perceived by a CR terminal in many other interesting practical situations where the secondary user is not placed in a static high point (e.g., a mobile CR user communicating inside a building or while walking in the street between buildings). The measurement of real network activities in additional scenarios of practical significance is therefore necessary for an adequate and full understanding of the dynamic use of spectrum.

The different geographical locations considered in this case study are illustrated in Figure 5. For outdoor high point measurements (location 1), the equipment was placed in the roof of a three-floor urban building belonging to the Department of Signal Theory and Communications of the Universitat Politècnica de Catalunya (UPC), Barcelona, Spain (latitude: 41º 23' 20" north; longitude: 2º 6' 43" east; altitude: 175 meters). The selected place is a strategic location with direct line-of-sight to several transmitting stations located a few tens or hundreds of meters away from the antenna and without buildings blocking the radio propagation. This strategic location enabled us to accurately measure the spectral activity of, among others, TV broadcast stations, several nearby base stations for cellular mobile communications and a military head quarter as well as some maritime and aeronautical transmitters due to the relative proximity to the harbour and the airport. For indoor experiments, the measurement equipment was placed inside the same building (location 2), in the middle floor. For measurements in narrow streets (locations 3–7), between buildings (locations 8–10) and open areas (locations 11–12), the measurement equipment was moved within the UPC's campus.

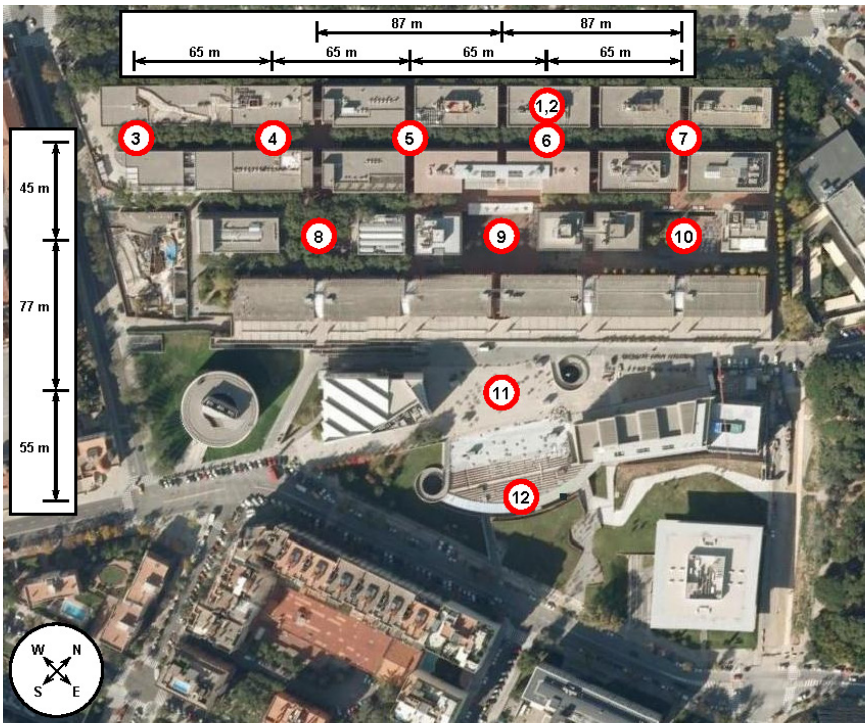

Figure 5 – Measurement locations and scenarios in urban environment.

5.3 Spectrum occupancy results

The obtained measurement results are summarized in Table 2. As it can be appreciated for the results of location 1, spectrum experiences a relatively moderate use below 1 GHz and a low usage between 1 and 2 GHz, while remains mostly underutilized between 2 and 7 GHz. In fact, while the average duty cycle between 75 and 2000 MHz is 31.02%, the value for this parameter between 2000 and 7075 MHz is only 2.75%. The overall average duty cycle over the whole frequency range considered in this study is only 17.78% for location 1, which reveals the existence of significant amounts of unused spectrum that could potentially be exploited by future CRNs. When considering other deployment scenarios, the results are even more promising. The comparison of the results obtained for locations 1 (outdoor) and 2 (indoor) constitutes an illustrative example (see Table 2). From a qualitative point of view, the results obtained in location 2 follow the same trend as in location 1, with higher duty cycles at lower frequencies. As a matter of fact, the average spectrum occupancy is moderate below 1 GHz and very low above 1 GHz for location 2. However, significantly lower average occupancy rates are observed for the indoor location, which can be explained by the fact that most of wireless transmitters are located outdoor and the propagation loss due to outdoor-to-indoor signal penetration leads to lower signal strengths in the indoor scenario, thus resulting in lower occupancy rates. The lower average duty cycles obtained for the indoor case suggest the existence of an even higher amount of free spectrum for CR in such environments.

Table 2 – Average duty cycle statistics in locations 1 and 2.

Frequency range (MHz)	Average duty cycle (%)					
	Loc. 1	Loc. 2	Loc. 1	Loc. 2	Loc. 1	Loc. 2
75 – 1000	42.00	33.70	31.02	21.54	17.78	12.10
1000 – 2000	13.30	1.94				
2000 – 3000	3.73	1.63	2.75	1.39		
3000 – 4000	4.01	1.44				
4000 – 5000	1.63	1.09				
5000 – 6000	1.98	1.34				
6000 – 7075	1.78	1.38				

The previous results indicate that the amount of spectrum opportunities can be related to the radio propagation conditions, which can be corroborated by analyzing the spectrum occupancy level perceived at various locations. In that respect, Figure 6 plots the duty cycle in different locations for the case of TV bands. Duty cycle values are normalized with respect to the value in location 1. It can be appreciated that this normalized average duty cycle observed at each location is lower than one, meaning that the perceived spectrum occupancy is lower in closed regions. For example, in locations 4 and 6, where radio propagation blocking caused by buildings is more intense, the normalized duty cycle is lower than in other more open areas such as locations 3, 5 and 7. Comparing locations 8, 9 and 10, the deepest and most faded region (location 9) exhibits the lowest normalized average duty cycle. Regarding the open areas (locations 11 and 12), the normalized duty cycle is in general higher than in the rest of outdoor locations at the ground level. In this case, it is interesting to note that a higher spectral activity level was recorded in location 11 despite the presence of some surrounding buildings with respect to the open region in location 12. The detection by the measurement equipment of some additional signal components reflected in such buildings could explain the recording of higher activity levels in a less open region. In any case, it is interesting to observe that the amount of spectrum opportunities can be directly related to the radio propagation conditions of the considered scenario, with lower occupancy rates observed in more closed regions and vice versa.

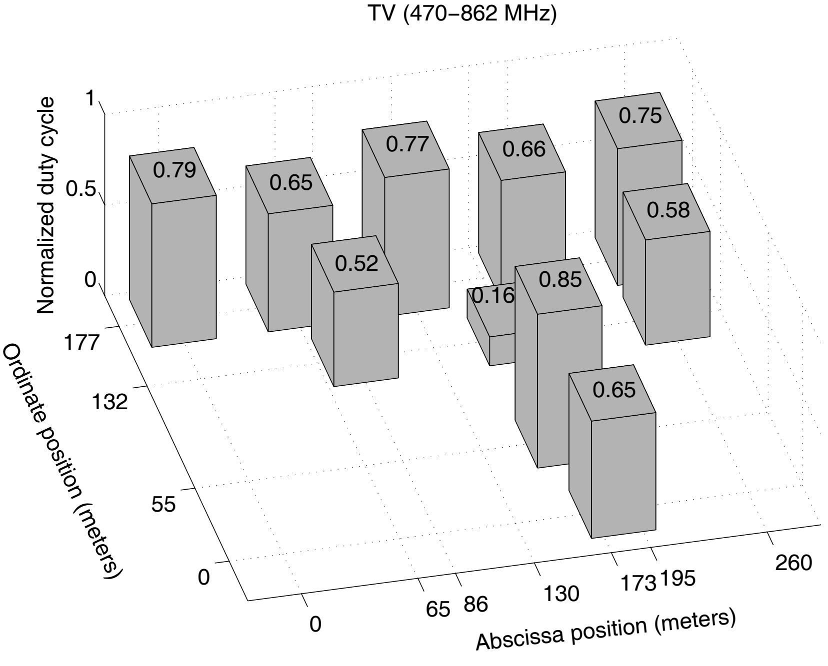

Figure 6 – Normalized average duty cycle statistics in locations 3 to 12 for TV band (470-862 MHz). From left-to-right and up-to-down, the positions of the bars in each graph correspond to the physical locations of points 3–12. The duty cycle at each location has been normalized with that of location 1.

Although the previous results clearly indicate low spectrum utilization levels, they do not provide a clear picture of how spectrum is used in different frequency bands allocated to different specific services. Figure 7 summarizes the band-by-band average spectrum occupancy statistics observed at location 1. The obtained results demonstrate that some spectrum bands are subject to intensive usage while some others show moderate utilization levels, are sparsely used and, in some cases, are not used at all. The highest occupancy rates were observed for bands allocated to broadcast services (TV as well as analogical and digital audio), followed by digital cellular services as PMR/PAMR, paging, and mobile cellular communications (E-GSM 900, DCS 1800 and UMTS) among others. Other services and applications, e.g. aeronautical radio navigation and location or defense systems, show different occupancy rates depending on the considered allocated band. In general, the average spectrum occupancy observed in frequency and time in this study was found to be significantly low, thus indicating that most of the spectrum offers possibilities for secondary CR usage, even those bands with the highest observed activity levels in terms of average duty cycle.

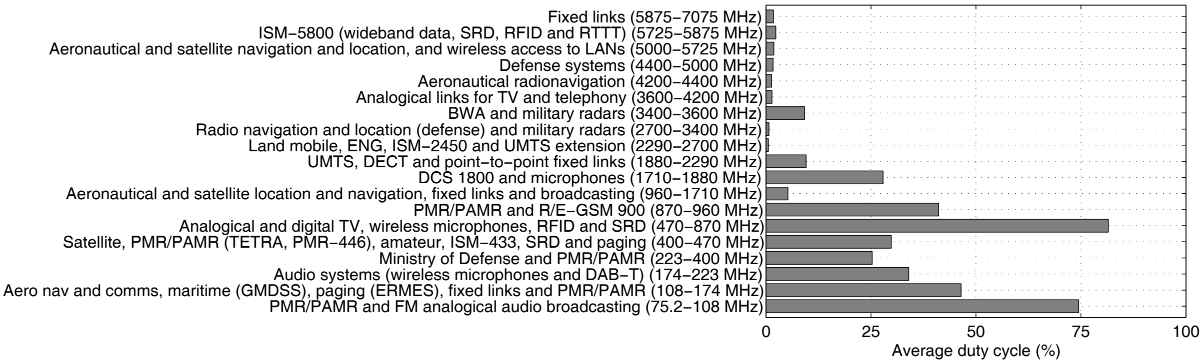

Figure 7 – Band-by-band average duty cycle statistics.

6 Conclusions

Dynamic Spectrum Access Networks are one of the current active research areas in the wireless community. They aim at enhancing spectrum efficiency by allocating underutilized spectrum dynamically. Regulation and etiquette implies that DSANs can only operate provided that no harmful interference is caused to the other incumbents. One of the key enabling technologies for this paradigm is the Cognitive Radio envisaging a radio able to sense and be aware of its operational environment to dynamically and autonomously adjust its parameters accordingly. Under this framework, this paper focused on the applicability of measurement-based techniques in the design of Cognitive Radio Networks. In particular, it has first focused on the spectrum sensing through which secondary users can detect the presence or absence of a primary system in a given band. An overview of the most usual spectrum sensing techniques, namely matched filter, energy or power detection and cyclostationarities properties detection has been given. Then, the paper has presented a summary of the main standardisation activities that have addressed the CRN concept worldwide.

Measurements of the radio environment can provide valuable insights on how the spectrum is used in the different bands and locations and, by a proper understanding of the primary user behaviour it is possible to devise efficient mechanisms for CRN operation, for example by building databases in which different primary user characteristics are stored and made available to the CR users. This information can be combined with the results of real time spectrum sensing to improve the performance of the different decision making mechanisms. This paper presented some of the methodological factors to define a spectrum occupancy measurement campaign, including the possible equipments as well as some significant metrics. This has been illustrated with a case study corresponding to an urban area, analysing the primary user occupation in different bands from 75MHz to 7GHz. Measurements have revealed that the amount of spectrum opportunities can be directly related to the radio propagation conditions of the considered scenario, with lower occupancy rates observed in more closed regions and vice versa.

Acknowledgements

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