Towards 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 through the definition of a licensed user granted exclusive exploitation rights for a specific frequency. While interference is easily avoided, this approach is unlikely to achieve the objective of maximizing the value of the spectrum. In fact, spectrum measurements carried out worldwide have revealed significant spectrum underutilization. As a result, the so-called dynamic-spectrum-access networks (DSANs) are one of the current research trends in the wireless area. In such networks, 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 cognitive radio (CR). This envisages a radio able to sense and be aware of its operational environment so as to dynamically and autonomously adjust its parameters to adapt to different situations. Spectrum sensing, enabling the detection of unused spectrum bands, then becomes one of the key elements of cognitive-radio technologies. Within this framework, on the one hand this paper provides insight into the different spectrum-sensing techniques and associated standardization activities. On the other hand, the paper also presents some spectrum-occupation measurement activities, targeting the characterization of how the spectrum is being used in the different bands, in order to extract the relevant parameters for cognitive-radio design. These are presented from a general methodological perspective, and also include the results obtained in a particular case study.

1. Introduction: Cognitive-Radio Techniques for Dynamic Spectrum Access

The current spectrum-management situation was inherited from the early deployment of radio broadcasting channels, in the early 1920s. 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 levels, and led to the creation of independent regulatory entities to ensure fairness amongst competitors, and better signal quality to end users. Frequencies were then assigned to broadcasters, along with transmitted-power bounds. On the other hand, licenses for exclusive rights guaranteed low interference levels 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, administratively ruled by the regulators.

In spite of 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 supports a measurement-driven flexible regulation strategy, rather than a static administrative command and control scheme. As a result of this fact, in order to improve efficiency through smarter spectrum management, one of the current trends is the development of so-called dynamic-spectrum-access networks (DSANs). In these networks, unlicensed radios – denoted secondary users (SU) in this context – are allowed to operate in licensed bands provided that no harmful interference is caused to the licensees, denoted primary users (PU) in this context. 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, secondary users will be required to properly detect the existence of the transmissions of primary user, 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. This developed a cognitive-

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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.

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. Coexistence means that both systems are operated independently. When sharing is based on coexistence, secondary devices are essentially invisible to the primary. All the complexity of sharing is thus 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 the spatial-temporal domain sustained by spectrum sensing, coordination with peers, and fast spectrum handover). As for cooperation, different forms of primary-secondary interactions are again possible. For example, spatial-temporal white spaces that can be exploited by secondary users can be signaled through appropriate channels or beacons. In addition, the interaction between primary users and secondary users provides an opportunity for the license-holder to demand payment according to the different quality-of-service grades offered to secondary users.

One of the key enabling technologies for dynamic-spectrum-access network development is cognitive radio (CR). This 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]. It 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. The cognitive-radio concept was in turn built upon the software-defined radio (SDR) concept. This can be understood as a multi-band 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, the software-defined radio constituted the basis for the physical implementation of cognitive-radio concepts.

Thanks to this capability of being aware of actual transmissions across a wide bandwidth, and of adapting their own transmissions to the characteristics of the spectrum, cognitive radios offer great potential for bringing dynamic-spectrum-access networks to reality. In fact, dynamic-spectrum-access networks are usually referred to as cognitive-radio networks (CRNs). The operating principle of a cognitive radio in the context of a dynamic-spectrum-access network is to identify spatial and temporal spectrum gaps not occupied by primary/licensed users. These are usually referred to as *spectrum holes* or *white spaces*. The cognitive radio must place secondary/unlicensed transmissions in such spaces, and vacate the channel as soon as the primary users return. The cognitive-radio 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 operational perspective, a cognitive radio follows the so-called *cognition cycle* to enable 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 operational goals, and finally *acting* over the environment. On the other hand, decisions can be reinforced by *learning* procedures, based on the analysis of prior observations and on the corresponding results of prior actuations. When particularizing the cognition cycle to the dynamic spectrum access for a secondary user, the observation then turns out to be the spectrum sensing in order to identify the potential white spaces. The orientation and planning steps are associated with the analysis of the available white spaces. Finally, the acting step is in charge of selecting adequate white space to make the secondary transmission, together with the setting of the appropriate radio parameters such as transmitted power, modulation formats, etc.

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

1.1 Spectrum Sensing

This consists of detecting the unused spectrum bands that can be potentially exploited for secondary communications. A lot of different spectrum-sensing techniques have been studied in recent years. These include the energy detector, which does not include any specific knowledge about the primary signal to be detected; matched-filter detection, which requires knowledge of the specific primary signal formats; and cyclostationarity feature detection. The possibility of combining sensing measurements from different sensors through appropriate fusion schemes has also been considered in 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 was the case for the development of the so-called cognitive pilot channel (CPC) in [5], for example. 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, the spectrum-sensing concept can be generalized to the concept of spectrum awareness.

1.2 Spectrum Management

This refers to the selection of the most adequate spectrum band to carry out the transmission in accordance with the secondary user's requirements. This selection should be made based on the characteristics of the channel in terms of the maximum capacity that can be obtained by the secondary users, for example, and also taking into consideration the maximum interference that can be tolerated by primary receivers. The decision-making process here can benefit from the application of learning strategies, which, 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 will force the secondary transmitter to free the channel. Thus, if a primary user's activity characterization was known by the secondary users, it could prevent the secondary network from selecting these channels.

1.3 Spectrum Mobility

This functionality consists of establishing appropriate mechanisms to insure that ongoing 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. When the primary user then appears, the occupied channel has to be freed. An alternative channel has to be found where the communication can be continued, which is usually called *spectrum handover*. Handover has therefore a broadened meaning, compared to the *horizontal handover* typically implemented in cellular systems to enable space mobility. In the case of spectrum handover, the band and also the communication standard may change during the handover procedure, implying a so-called *vertical handover*. When both spatial and spectrum handover are considered in a dynamic-spectrum-access network, the term generalized handover is used [6].

1.4 Spectrum Sharing

This function targets the provision of an efficient mechanism so that coexisting secondary users can share the available spectrum holes. Adequate medium access control (MAC) protocols and scheduling mechanisms are needed, and they are 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 hot research topics during the last few years, there is still a lot of work to do before cognitive-radio networks become a reality in the fullest extent. This will involve not only technical aspects, but significant regulatory changes will also be needed. In addition, this will also have implications from the technological and economical perspectives, with the appearance of new business models to exploit the capabilities offered by cognitive-radio networks. This involves different possibilities, ranging from secondary cellular operators that could offer services at cheaper prices at the expense of somehow reduced quality, to the deployment of infrastructure-less secondary networks that would enable communication of short range devices.

Based on the above context, this paper focuses on the applicability of measurement techniques to the development of cognitive-radio networks. In particular, Section 0 addresses the spectrum sensing techniques as one of the key procedures for the operation of cognitive-radio networks. Section 3 then focuses on the different standardization initiatives that have been carried out. Section 4 addresses particular aspects of spectrum-measurement techniques, and how the results from measurement campaigns can be used in cognitive-radio-network design. This is followed by the results of a real case study of spectral measurements, obtained in the area of Barcelona, in Section 5. Finally, conclusions are summarized in Section 6.

2. Spectrum-Sensing Techniques

There has been a growing interest in signal detection in the context of cognitive radio [3]. More specifically, there is interest in opportunistic radio (or overlay systems), where secondary cognitive-radio networks 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]. In many situations, the primary system-detection problem is thus transposed into 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 cognitive-radio networks, the detection of primary users by the secondary system is critical in a cognitive-radio environment. Indeed, misdetection would lead to harmful interference to the primary users, while a high false-alarm probability would make actual holes unavailable to secondary usage. However, detection of primary users is made difficult due to the challenges of accurate and reliable sensing of the wireless environment. Secondary users might experience losses due to multipath fading, shadowing, and building penetration. These can result in an incorrect estimation of the wireless environment, which can in turn cause misdetection or false alarm at the secondary users. This brings the necessity for the cognitive radio to be highly robust to channel impairments, and to also be able to detect extremely low power signals.

These stringent requirements lead to important challenges for the deployment of cognitive-radio 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 based on the RF signal (e.g., energy detection), most of the time, the detection is processed based 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. The radio signal, $y(t)$, received at the antenna is first filtered with a bandwidth, *B*, which is the band under consideration. The signal is then down-converted to baseband, and digitized (at a sampling frequency of $1/T_s$) before being sent to the detector. The function that the detector has to perform is that of detecting signals in the presence of noise, which can be stated as the following hypothesis:

$$H_0 : r(t) = n(t) , \qquad (1)$$

$$H_1 : r(t) = hs(t) + n(t) ,$$

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 knowledge required of the secondary users about the waveform of the primary users. Among these, we describe below the three most important options: the matched filter, energy or power detection, and the feature detector, which often exploits the cyclostationarity nature of the primary user's signal.

Using a matched filter is the optimal solution to signal detection in the 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. This means that cognitive-radio equipment has *a priori* knowledge of the received signal(s), e.g., the modulation type, the pulse shaping filter, the data-packet format, etc. Most often, telecommunication signals have well-defined characteristics, e.g., the presence of a pilot, preamble, synchronization words, etc., which permit the use of these detection techniques. Based on a coherent approach, a matched filter has the advantage of only requiring a reduced set of samples, a function of the $O(1/\mathrm{SNR})$, 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

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

The matched filter lacks generality, as it can be applied to only one specific waveform. One approach to make the detector independent of the waveform is to perform non-coherent detection through energy detection [12]. This suboptimal technique has been extensively used in radiometry. Energy detection or the radiometer method relies on a stationary and deterministic model of the signal, mixed with stationary white Gaussian noise. The basic functional method involves a squaring device, an integrator, and a 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 fulfilled. Otherwise, the band is considered to be signal free (H_0). However, in many practical implementations, the signal energy is computed on the one hand (integrator), and the threshold is computed after some calibration of the radiometer in the absence of the signal. In this case, σ_0 is omitted in the calculation of *V* (Figure 2).

This can be implemented in either the time domain or in the frequency domain. Time-domain implementation requires front-end filtering before the squaring operation. In the frequency-domain implementation, after front-end bandpass filtering, the received signal samples are converted to frequency-domain samples using the Fourier transform. Signal detection is then effected by comparing the energy of the signal samples falling within a 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.

An interesting alternative to energy detection consists of considering a cyclostationary model of the signal, instead of a stationary model [13]. Indeed, 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 differentiation of the modulated signal from the noise. This is due to the fact that the 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 of order *n* if and only if its statistic properties at order *n* are a periodic function of time. In particular, for $n = 2$, a process is cyclostationary in the large sense and respects

$$c_{xx}(t, \tau) = E\left[\left(\ \right)\right] = c_{xx}(t + T, \tau) , \qquad (3)$$

where *T* represents a cyclic period.

When the primary user's signal is completely unknown, it is theoretically possible to explore the

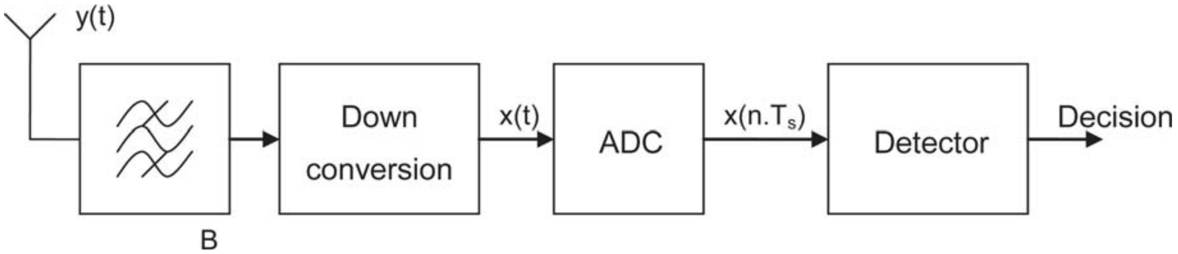

Figure 1. The architecture of the digital free-band detector.

presence of cyclic frequencies for any autocorrelation lag at any frequency. This approach is referred to as the cyclostationary spectrum density (CSD) (this is also referred to as the two-dimensional cyclostationary spectrum density) [14, 15]. However, the comprehensive two-dimensional cyclostationary spectrum density is never implemented in practice, due to its huge implementation cost. To sort out this issue, one-dimensional cyclostationary spectrum densities are preferred to limit implementation cost. The cyclostationary spectrum density can be performed using the time-domain autocorrelation [16], or through the analysis of signal periodicity redundancy in the frequency domain [17]. However, in both cases a large FFT operation (512 to 2048) needs to be implemented, leading to significant hardware complexity. When additional knowledge of the primary user's signal is exploited by the secondary users, the FFT can be avoided, and only specific known cyclic frequencies are explored, as in [18, 19]. This can lead to significant complexity reduction, as highlighted in the Wi-Fi- and DVB-T-specific implementations presented in [20]. Besides, it was shown that restricting the modulation search space (i.e., shrinking the two-dimensional cyclostationary spectrum density to a small subset of samples) also reduces the convergence of the algorithm, thereby enabling the exploitation of short-duration opportunities [21].

3. Standardization Activities in the Area of Dynamic-Spectrum-Access Networks

The trend towards dynamic-spectrum-access networks has motivated standardization bodies to propose technologies to rationalize cognitive-radio operation. These standards tackle cognitive radio from various angles. The first angle relates to the amendment of existing standards to operate under certain regulatory conditions that require dynamic-spectrum-access network features. For instance, this is the case in the TV white space. The second angle suggests analyzing dynamic-spectrum-access networks 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 prioritize systems (e.g., TV systems in the TV white space context), or for 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. The underlay system is thereby seen as low-power additive noise by the primary systems. This is the case of ultra-wideband (UWB) systems, which operate over a wide bandwidth. The IEEE 802.15.4a standard [22], within the IEEE 802.15 group for wireless personal area networks, can thus be considered a first attempt to enable spectrum sharing between unlicensed secondary systems and primary (licensed) systems.

However, despite the strong restrictions on spectrum density for such systems (–41.3 dBm/MHz), UWB systems operating in the low band (3-5 GHz) have been forced to include detect-and-avoid (DA) features, to insure that they are switched off whenever a WIMAX system operates within the band (typically, at 3.5 GHz). This causes 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 accordingly adapt the transceiver.

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]. The 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 cognitive-radio networks in the TV bands [25].

Within the IEEE, the dynamic-spectrum-access network rationalization effort came in 2005, with the creation of a set of standardization projects related to cognitive-radio networks. It was 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 for transferring

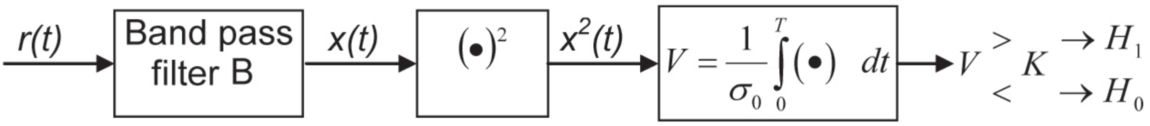

Figure 2. A block diagram of the energy detector.

the use of research results for public use. Very recently, the committee was transferred to the IEEE Communication Society (ComSoc) standards effort, and was renamed the IEEE ComSoc DYnamic SPectrum Access Networks (DYSPAN) committee. Because the dynamic-spectrum-access network 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 a cognitive-radio network. This was the scope of 1900.2-2008, which 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 cognitive-radio networks. 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. Two projects are currently active within this group. The first is P1900.4.1, which addresses "Interfaces and Protocols Enabling Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Networks." The second is P1900.4a, on "Architecture and Interfaces for Dynamic Spectrum Access Networks in White Space Frequency Bands." The first project focuses on the interfaces between the architectural entities defined in [29]. The latter project 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 analyzed 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 Standards Association and ComSoc standards, other standardization organizations have shown significant interest in cognitive-radio networks. This is the case of ECMA, with standard 392 [30]. This standard defines a MAC and physical layer for cognitive use of TVWS (TV white space) in WLAN-like scenarios. It was released by ECMA international at the end of 2009. In addition to MAC and physical layer, ECMA-392 also includes specifications for the MUX sub-layer for higher-layer protocols. ECMA-392 was developed by technical committee TC48, task group TG1, and it is therefore also known as the 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 of ETRI, Hewlett-Packard, Philips, and Samsung, the board; and Georgia Institute of Technology and Motorola, contributors. Texas Instruments was previously indicated as a member.

With similar scenarios and applications to ECMA, project IEEE P802.11.af was launched more recently, in December 2009 [32]. It is aimed at creating an amendment to IEEE 802.11 by modifying both the physical layer and MAC to meet the regulatory requirements for channel access and coexistence in the TV white space (TVWS). The group suggested the use of OFDM physical layers focused on 5 MHz channel width to comply with the 6, 7, or 8 MHz TV channels, depending on countries. Because this standard aims at operating outside the ISM band, no backward compatibility is required with former versions of IEEE 802.11, 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 TV white space 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 will be a significant difference from other TV-white-space-oriented standards (e.g., IEEE 802.22 or ECMA 392). This geo-location-based operation was made possible in the US by the second memorandum on TV white space "Super WiFi" operation [33].

With a wider application in mind, DYSPAN has suggested a new project to define physical layer and MAC for white spaces. These would be defined for a white-space dynamic-spectrum-access network, but do 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-organizing 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 objective of IEEE 1900.4, to define a global framework for cognitive-radio networks.

It can be understood from this list that standardization activity related to dynamic-spectrum-access networks is rather recent. It has evolved 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 concerns the organizations that express interest in dynamic-spectrum-access networks. Whereas classical telecommunication standardization bodies mainly gather telecom operators and vendors, dynamic-spectrum-access networks open the door to organizations that see dynamic-spectrum-access networks as a means to grant spectrum access with a non-traditional telecommunications business model. The members of the TV white-space coalition give a clear snapshot of this trend, with members such as 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. A proper understanding of spectrum-usage patterns can be very useful for defining adequate dynamic spectrum policies, and to identify appropriate frequency bands for the deployment of future cognitive-radio networks. Similarly, the identification of usage patterns can be exploited in the development of useful spectrum-usage models and more-efficient cognitive-radio 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, equipment, 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 cognitive-radio networks.

4.1 Spectrum-Measurement Methodologies and Equipment

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 by taking into account the previous factors, since they play a key role in the accuracy of the results obtained. The measurement setup should be able to detect a large number of transmitters of the most diverse nature over a wide range of frequencies, from narrowband to wideband 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. These have ranged 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 pieces of equipment in the different measurement campaigns. This is because they usually allow measuring large bandwidths, although at the expense of limited time resolution, typically of the order of seconds, which might not be appropriate for certain levels of modeling. When higher time resolutions are required, other measurement platforms can be used. Examples include vector signal analyzers, or more-specific platforms, such as the universal software radio peripheral (USRP) and the GNU radio architecture. This measurement platform is able to perform spectrum measurements over bandwidths narrower than a spectrum analyzer, but with much higher time resolution, of the order of microseconds or nanoseconds. This provides not only power spectrum measurements, as it is the case with a spectrum analyzer, but true signal samples, from which the signal's phase information can be extracted. If only power measurements of the spectrum utilization are available – as in the case of spectrum-analyzer-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 spectrum-measurement campaigns are based on omnidirectional measurements, in order to detect primary signals coming from any direction. To this end, omnidirectional 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 for evaluating and quantifying the level of spectral occupancy. While some of these metrics are directly provided by the measurement equipment, some others are obtained by post-processing the measured data. Some examples of metrics that have been typically used are the following.

4.2.1 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 analyzer). Power spectral density can be measured in different ways in order to obtain different power-spectral-density graphs; the main values used are the average power spectral density, the maximum power spectral density, and the minimum power spectral density. When considered together, the average, maximum and minimum power spectral densities provide a simple characterization of the temporal behavior of a channel. For example, if the results are quite similar, this would suggest a single transmitter that is always on and is experiencing a low level of fading, and so is also probably not moving. At the other extreme, a large difference among average, maximum, and minimum power spectral densities suggests more intermittent use of the spectrum, and therefore indicates a potential opportunity for cognitive-radio networks.

4.2.2 Spectral-Occupancy Percentage or Duty Cycle

The relevant metric for determining 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 the 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. Cognitive-radio networks may take advantage of idle-time periods to opportunistically access the available spectrum. Frequency bands with low duty cycles therefore offer an interesting opportunity for the deployment of cognitive-radio networks. 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 cognitive-radio networks. Nevertheless, the temporal evolution of this metric (e.g., averaged over one-hour periods or days) can also provide interesting information about the temporal utilization 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 tradeoffs among required sensing time, complexity, and detection capabilities, as explained in Section 2.

4.2.3 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]. The amplitude probability distribution is a three-dimensional histogram, with one axis being the amplitude, one axis being the frequency span, and the third axis being the probability of each amplitude value throughout the whole measurement period. The underlying principle of amplitude-probability-distribution analysis is that different equipment and devices show distinct behaviors in terms of power spectral density and signal characteristics. These transmitter characteristics can therefore 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 with a fixed transmitter with rather constant power. The height and the width of the peak jointly describe the stability of the transmitted power. The higher and the narrower the peak, the more constant is the transmitted power. 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 with many devices received from different distances, or with a congregation of various services with distinct power regulations. Finally, in some cases the received power allows inferring the rough operating power of the transmitter directly from the amplitude-probability-distribution histogram.

4.3 Applicability to the Design of Cognitive Radio Systems

Empirical data derived from spectrum-occupancy measurement campaigns exhibit a wide set of useful applications for the design of cognitive-radio systems. These range 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. Real field-measurement data could then be used as the support for the evaluation of different cognitive-radio mechanisms proposed in the literature, which in most cases have addressed only a system-level approach.

Cognitive-radio network operation can be optimized by making use of databases capturing the knowledge about the radio environment of a given geographical area, including elements such as geographical aspects, available

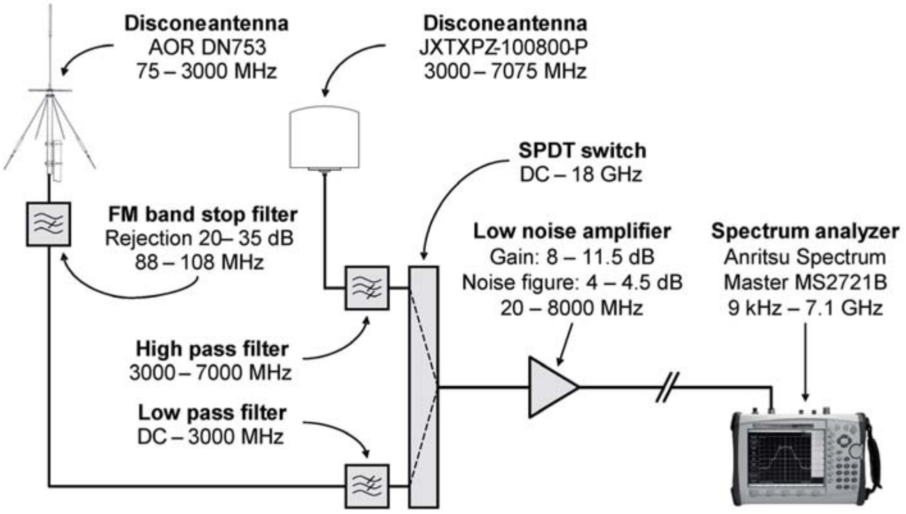

Figure 3. The measurement setup employed in this study (complete schematic).

services, spectral regulations, positioning of transmitters, transmitter profiles, primary user activity patterns, etc. The term radio-environment map (REM) was used in [50] to refer to such a database, used as the support of a cognitive-radio network. It can be clearly envisaged that through adequate feeding of the radio-environment map through results coming from measurements, it could be possible to improve the accuracy of its information. With the corresponding dissemination procedures to make this information available to cognitive-radio nodes (which could eventually combine the information with their own spectrum-sensing results), it would be possible to improve the performance of the decision-making procedures in a cognitive-radio network.

Similarly, measurements can be used for the characterization of the level of spectral occupation in the frequency, time, and space dimensions. This can enable the formulation of models to describe the utilization and activity patterns of the different frequency bands with a high level of accuracy. When addressing the definition of spectrum-occupation models, there are three main elements to define. The first element is the set of parameters, characteristics, or properties of the spectrum occupation to be represented and reproduced through the model. This 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 modeling. It is then possible to distinguish among models based on Markov chains, or based on fitting curves to specific parameterized analytical expressions, or based 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 behavior 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 was done in [52] for the ISM band of 2.4 GHz using a vector signal analyzer over specific types of traffic, or in [53] using a spectrum analyzer. In the latter case, the target was to find out the statistical distributions that best fit the idle and busy periods for different technologies, and it was shown that a geometrical distribution can fit the actual measurements in a quite acceptable way for many of the considered technologies. It was also shown that in some cases, there exists a correlation between the durations of the idle and busy periods. Works such as [54] and [55] tried to qualitatively reproduce this. 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, the extension of existing models to reproduce at least two different levels of time resolution can be envisaged, one level for an instantaneous channel occupation using high-time-resolution models (e.g., using vector analyzers), and a second level able to reproduce the load variations in a longer-term time scale (e.g., using spectrum analyzers). The modeling 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 was used to identify periodicities in the spectral-occupation patterns that could be used to decide the appropriate sensing instants.

As for the modeling 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 large geographical areas, the generalization to other bands with smaller coverage areas and more variability in the occupation depending on the position was hardly feasible. In that sense, another model in the context of cognitive radio was developed in [60] and further extended in [53]. It analyzed 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 fit when applied to bands assigned to different technologies.

Finally, in the area of spatial-dimension modeling in [56], the spatial distribution of the spectral occupation in a real cellular system was analyzed 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 characterization of the spectrum occupancy through power-spectral-density measurements was carried out by making use of the random field theory. The procedure makes use of empirical power-spectral-density measurements at different points to adjust a semi-variogram model, which reproduces the statistical properties of the average power-spectral-density values observed in a certain geographical area.

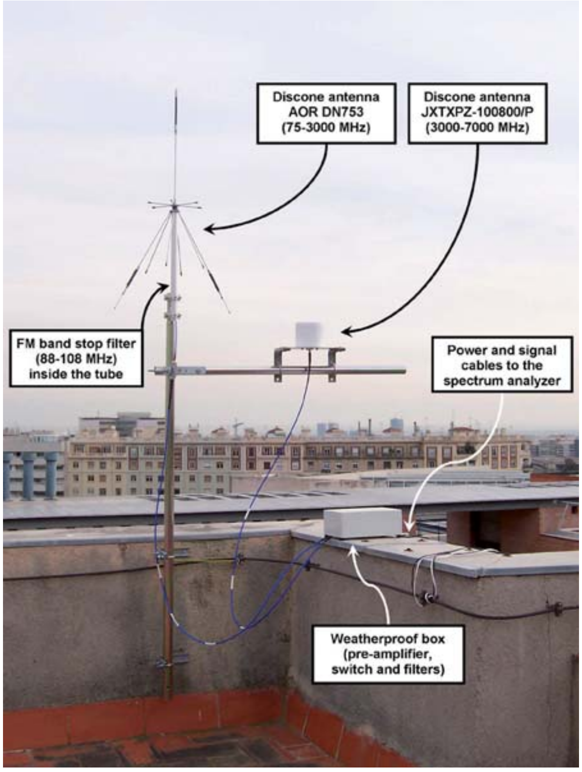

Figure 4. The measurement setup employed in this study (antenna subsystem).

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 of illustrating the methodologies described in the previous section with real measurements.

5.1 Measurement Setup and Configuration

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

The antenna subsystem is shown in Figure 4. Two wideband discone-type antennas were 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 polarization and an omnidirectional 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 omnidirectional feature (allowing the detection of primary signals coming for any direction) make discone antennas attractive in radio-scanning and monitoring applications. They have been a preferred option for many spectrum studies.

The radio-frequency (RF) subsystem performed antenna selection, filtering, and amplification. The desired antenna was selected by means of a single-pole double-throw (SPDT) switch, which enabled high isolation (90-100 dB) and low insertion loss (0.1-0.2 dB). In order to remove undesired signals, three filters were included. A band-stop filter blocked 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's 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, an FM band-stop filter was employed in order to remove

Parameter	Value	
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	

Table 1a. The spectrum analyzer configuration: frequency.

Parameter	Value	
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	

Table 1c. The spectrum analyzer configuration: amplitude.

FM signals and to avoid overload problems, improving the detection of weak signals at other frequencies. Low-pass and high-pass filters were used to remove out-of-band signals, and to reduce the potential creation of intermodulation products. To compensate for device and cable losses and increase the system's sensitivity, a low-noise preamplifier was included. The selected mid-gain amplifier provided significant sensitivity improvement, while guaranteeing the spurious-free dynamic range (SFDR) required by the measured signals.

An Anritsu Spectrum Master MS2721B high-performance handheld spectrum analyzer was used to provide power-spectrum measurements, and to record the spectral activity over the complete frequency range. It provided a measurement range from 9 kHz to 7.1 GHz, a low noise level, a built-in preamplifier that facilitated the detection of weak signals, an automatically adjusted fast sweep speed, and the possibility of connecting an external USB storage device to save measurements for later data post-processing.

Since the different operating modes of spectrum analyzers 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 analyzer were set according to the basic principles of spectrum analysis, as well as some particular considerations specific to cognitive radio. Table 1 shows the main spectrum-analyzer configuration parameters.

The measured frequency range (75-7075 MHz) was divided into 25 blocks, with variable sizes ranging from 45 MHz up to 600 MHz. The division was 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).

Parameter	Value
Measurement period	24 hours
Sweep time	Auto

Table 1b. The spectrum analyzer configuration: time.

The resolution bandwidth (RBW) played an important role in the measurements obtained. Narrowing the resolution bandwidth increased the ability to resolve signals in frequency and reduced 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 resolution bandwidth was selected as an adequate tradeoff between detection capabilities and required measurement time. The video bandwidth (VBW) is a smoothing function that dates to analog spectrum analyzers, but is now nearly obsolete. To eliminate this analog form of averaging, the video bandwidth was set equal to the resolution bandwidth.

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

For measurements below 3 GHz, where some overloading signals might have been present, only the external amplifier was used. For measurements above 3 GHz, where the received powers were lower, both the external and the spectrum analyzer's internal amplifier were 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 were equalized by adding a 20 dB offset to the power levels measured between 3000-7075 MHz (reference-level offset). The reference level (the maximum power of a signal that entered the spectrum analyzer and could be measured accurately) was then been adjusted according to the maximum power observed in each region, while the scale was adjusted according to the minimum signal level. No input attenuation was employed. An average-type detector was used. This detector averaged 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 were based on measurements performed in outdoor environments and, more particularly, on 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 cognitive-radio terminal in many other interesting practical situations where the secondary user is not placed on a static high point (e.g., a mobile cognitive-radio 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 on 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 41° 23’ 20” north; longitude 2° 6’ 43” east; altitude, 175 m). The selected place was 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 headquarters, as well as some maritime and aeronautical transmitters, due to the relative proximity to the harbor and the airport. For indoor experiments, the measurement equipment was placed inside the same building (location 2), on the middle floor. For measurements in narrow streets (locations 3 to 7), between buildings (locations 8 to 10), and open areas (locations 11 and 12), the measurement equipment was moved within the UPC’s campus.

5.3 Spectrum-Occupancy Results

The measurement results obtained are summarized in Table 2. As can be appreciated for the results of location 1, the spectrum experienced relatively moderate usage below 1 GHz and low usage between 1 GHz and 2 GHz, while remaining mostly underutilized between 2 and 7 GHz. In fact, while the average duty cycle between 75 and 2000 MHz was 31.02%, the value for this parameter between 2000 and 7075 MHz was only 2.75%. The overall average duty cycle over the whole frequency range considered in this study was only 17.78% for location 1, which revealed the existence of significant amounts of unused spectrum, which could potentially be exploited by future cognitive-radio networks. When considering other deployment scenarios, the results were even more promising. The comparison of

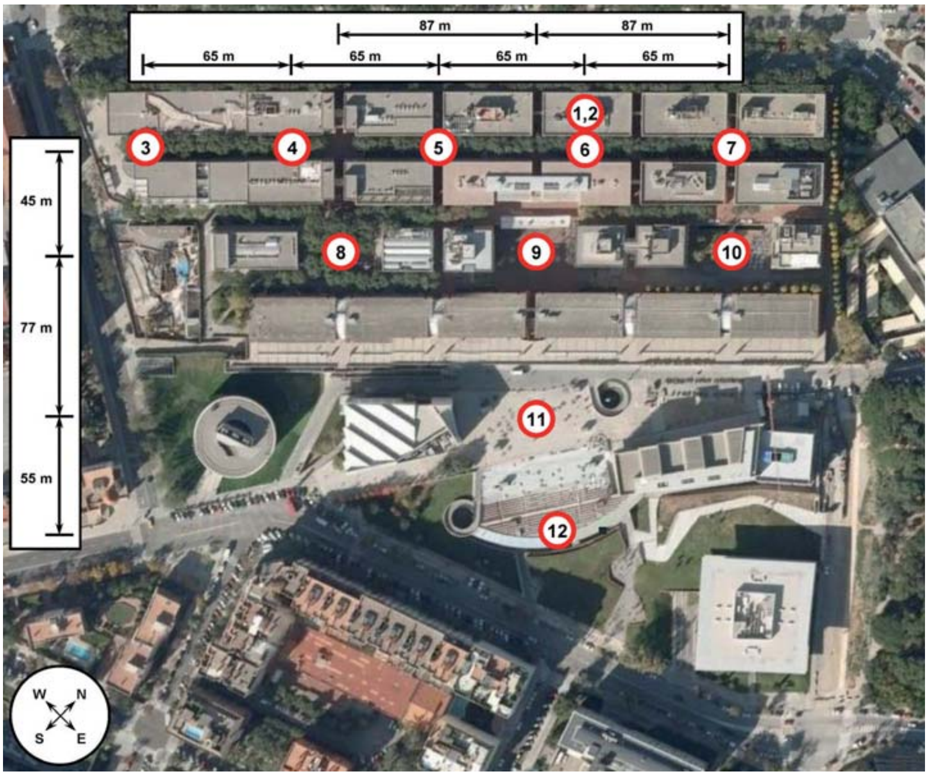

Figure 5. The measurement locations and scenarios in the urban environment.

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				

Table 2. The average duty-cycle statistics in locations 1 and 2.

the results obtained for locations 1 (outdoor) and 2 (indoor) constituted an illustrative example (see Table 2). From a qualitative point of view, the results obtained in location 2 followed the same trend as in location 1, with higher duty cycles at lower frequencies. As a matter of fact, the average spectrum occupancy was moderate below 1 GHz and very low above 1 GHz for location 2. However, significantly lower average occupancy rates were observed for the indoor location, which could be explained by the fact that most of the wireless transmitters were located outdoors, and the propagation loss due to outdoor-to-indoor signal penetration led to lower signal strengths in the indoor scenario, thus resulting in lower occupancy rates. The lower average duty cycles obtained for the indoor case suggested the existence of an even higher amount of free spectrum for cognitive radio in such environments.

The previous results indicated that the amount of spectrum opportunities could be related to the radio-propagation conditions. This could 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. The duty-cycle values were normalized with respect to the value at location 1. It could be appreciated that this normalized average duty cycle observed at each location was lower than one, meaning that the perceived spectrum occupancy was lower in closed regions. For example, in locations 4 and 6, where radio-propagation blocking caused by buildings was more intense, the normalized duty cycle was 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) exhibited the lowest normalized average duty cycle. Regarding the open areas (locations 11 and 12), the normalized duty cycle was in general higher than in the rest of the outdoor locations at the ground level. In this case, it was interesting to note that a higher spectral-activity level was recorded in location 11 with respect to the open region in location 12, despite the presence of some surrounding buildings. 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 was interesting to observe that the number of spectrum opportunities could be directly related to the radio-propagation conditions of the considered scenario, with lower occupancy rates observed in more-closed regions, and vice versa.

Although the previous results clearly indicated low spectrum-utilization levels, they did not provide a clear picture of how spectrum was 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 results obtained demonstrated that some spectrum bands were subject to intensive usage, while some others showed moderate utilization levels, some were sparsely used, and, in some cases, some were not used at all. The highest occupancy rates were observed for bands allocated to broadcast services (TV as well as analog 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, showed 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. This indicated that most of the spectrum offered possibilities for secondary cognitive-radio usage, even in those bands with the highest observed activity levels in terms of average duty cycle.

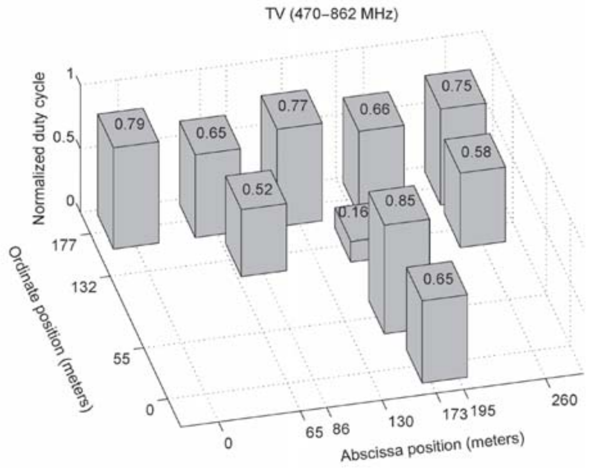

Figure 6. The normalized average duty-cycle statistics in locations 3 to 12 for the TV band (470-862 MHz). From left-to-right and up-to-down, the positions of the bars in each graph correspond to the physical locations of points 3 to 12. The duty cycle at each location was normalized to that of location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

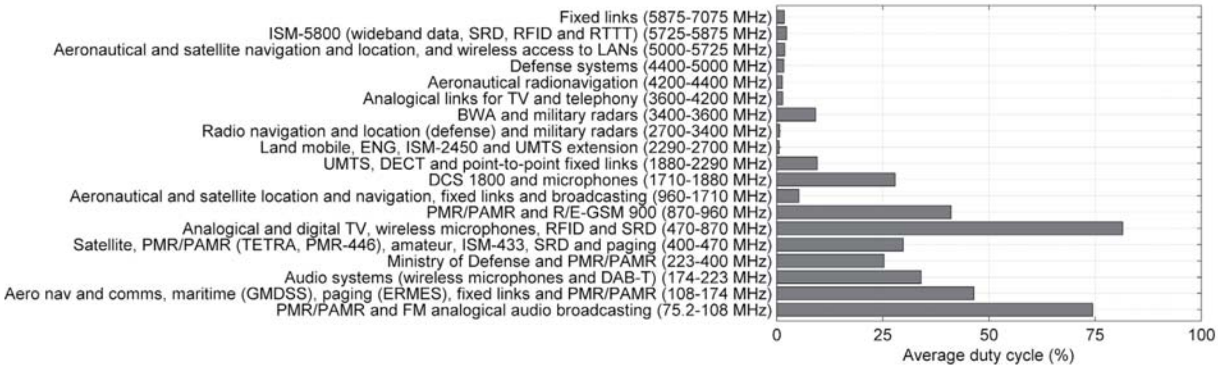

Figure 7. The band-by-band average duty cycle statistics.

6. Conclusions

Dynamic-spectrum-access networks are the topic of one of the current active research areas in the wireless community. They aim at enhancing spectrum efficiency by dynamically allocating underutilized spectrum. Regulation and etiquette implies that dynamic-spectrum-access networks can only operate provided that no harmful interference is caused to the other incumbents. One of the key enabling technologies for this paradigm is cognitive radio, envisaging a radio able to sense and be aware of its operational environment and to accordingly dynamically and autonomously adjust its parameters. Under this framework, this paper has 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 detection using cyclostationarity properties, has been given. The paper then presented a summary of the main standardization activities that have addressed the cognitive-radio network concept worldwide.

Measurements of the radio environment can provide valuable insights into how the spectrum is used in the different bands and locations. By a proper understanding of the primary-user behavior, it is possible to devise efficient mechanisms for cognitive-radio-network operation, for example by building databases in which different primary-user characteristics are stored and made available to the cognitive-radio 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 for defining a spectrum-occupancy measurement campaign, including the possible equipment, as well as some significant metrics. This was illustrated with a case study corresponding to an urban area, analyzing the primary-user occupation in different bands from 75 MHz to 7 GHz. Measurements revealed that the number of spectrum opportunities can be directly related to the radio-propagation conditions of the scenario considered, with lower occupancy rates observed in more closed regions, and vice versa.

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