Radar, TV and Cellular Bands: Which Spectrum Access Techniques for Which Bands?

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***Abstract*—Opportunistic access has been considered by regulators for a number of different spectrum bands. In this paper, we discuss and qualitatively evaluate techniques used in the discovery of spectrum opportunities, also called white spaces, in the radar, TV, and cellular bands. These techniques include spectrum sensing, cooperative spectrum sensing, geolocation databases, and the use of beacons. We make the case that each of the three bands considered calls for a different set of spectrum access techniques. While TV bands are well matched to the adoption of geolocation databases, a database-assisted spectrum sensing mechanism may represent the most efficient solution to exploit the spectrum holes in radar bands. We drew this conclusion based on a multitude of factors, such as the radar antennas' constant motion, and the absence of a hidden node problems in these bands. The unpredictability of cellular systems, on the other hand, calls for a more coordinated spectrum access approach, namely beacon signaling, that could be implemented using the already established cellular infrastructure and spare bits of its logical channels.**

***Index Terms*—Cognitive radio; spectrum sensing; geolocation database; beacon signaling; radar bands; TV White Spaces; cellular bands.**

I. Introduction

A COGNITIVE Radio (CR) is an intelligent wireless communication system capable of gathering knowledge of its radio environment, which it then uses to increase its communication channel reliability and to dynamically access underutilized spectrum resources. Opportunistic Spectrum Access (OSA) is currently one of the main applications of CR. In one of its many forms, OSA can be viewed as a new spectrum sharing paradigm that allows secondary users (SU) to opportunistically access spectrum holes, called white spaces (WS), in the bands for which the primary users (PUs) hold a license. Another form of dynamic spectrum access being currently discussed by regulators is Licensed Shared Access (LSA). The idea consists in authorizing the negotiation and sharing of spectrum resources between incumbents and a limited number of LSA licensees [1]. As it provides a large amount of control to spectrum license holders, the concept is appealing for incumbents such as mobile network operators (MNOs).

Although CR systems can be envisaged in any part of the radio spectrum, the frequency range considered more appropriate for their implementation is located between 100 MHz and 10 GHz. This includes the 300-3000 MHz range that the UK's Office of Communications (OFCOM) has dubbed the sweet spot for spectrum sharing [2]. Frequencies below 100 MHz present several challenges, including long-range interference caused by ionospheric effects and prohibitively large antenna sizes, as a consequence of the large wavelengths. Furthermore, the bandwidth provided is not large enough to make spectrum sharing economically attractive. As frequencies go beyond 10 GHz, advanced CR technology and spectrum sharing techniques become less appealing once again. At these frequencies, spectrum scarcity ceases to be a major issue due to not only the wide bandwidths available, but also the high atmospheric, rain, wall penetration and free-space losses, which provide extra spatial isolation to wireless communications and, consequently, allow greater frequency re-use.

For a specific secondary system, a spectrum resource is considered a WS if its utilization will not cause enough interference on incumbent communication systems to disrupt their communications at a given target performance level. Hence, WS availability must be assessed based on several operational, propagation and geographic parameters, namely systems' coverage area, occupied bandwidth, sensitivity to interference, adjacent channel filtering, center frequency, user location and density and the type of propagation environment (indoor/outdoor and urban/rural). The four main spectrum access (SA) techniques proposed in the literature for the identification of WSs are Spectrum Sensing (SS), Cooperative Spectrum Sensing (CSS), Geolocation Databases (GL-DB) and Beacon Signaling [3]. Spectrum sensing targets the detection of primary systems' activity during their regular operation. Its attractiveness lies in its simplicity, high flexibility, and low infrastructure requirements; one of its disadvantages is the inability to detect passive receivers, typically found in one-way communication systems, such as TV and wireless microphones. Cooperative spectrum sensing tackles the latter problem by allowing multiple CR devices to share their sensing results, which are then used to reach a conclusion about the presence/absence of a PU in a certain region and channel. In the GL-DB technique, each CR device estimates its position through GPS or another localization mechanism and queries a database for the nearby licensed channels' availability. Beacon signaling is a technique where the incumbent devices cooperate with SUs by informing them about the spectrum resources that are being utilized. Hybrid schemes such as GL-

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DB+SS are also attractive solutions, as they can overcome the limitations of each individual technique.

In May 2004, the FCC announced the TV White Space (TVWS) initiative, aiming at the opening of this part of the radio spectrum for unlicensed secondary use [4]. It was initially defined that the TV Band Devices (TVBD) must support spectrum sensing and geolocation, coupled with access to a database to ensure the protection of both TV and wireless microphone incumbent systems. Eventually, concerns with spectrum sensing viability made the FCC drop this requirement in 2010 [5]. These regulatory decisions have prompted discussion about the role of each different SA technique on the bands expected to be made available for opportunistic use in the future. To help answer this question, this paper analyses the adequacy of spectrum sensing, cooperative sensing, geolocation database and beacon signaling in three sets of bands: TV, cellular and radar. We chose the TV, radar, and cellular bands based on the economic attractiveness and diversity of technical challenges associated with their opportunistic use. To more clearly illustrate and compare the potential for the deployment of each specific spectrum access technique in each frequency band, we employ a coloring evaluation scheme where red, yellow and green indicate severe, moderate and low requirements, respectively.

While a large number of articles and reports concerning CR technology deployment have been published, its great majority is solely focused on the TVWS case [5]–[10]. Looking at the literature that goes beyond this particular scenario, we highlight the articles on PU exclusion zone size estimation [11]–[14], the spectrum occupancy measurement campaigns [15], [16], and the EU FP7 QUASAR project [17]–[20]. In these studies, the economic value for opportunistic use of several licensed bands is assessed, based on their occupancy and on the main characteristics of their incumbents. None of these works, however, focus on the actual implementation of each SA technique in the analysed contexts. In contrast, the authors in [21] address the intricacies of the GL-DB deployment in several distinct use cases. This study, however, is limited to one SA technique, and its discussion is centred on how the GL-DB architecture features may need to be adapted to accommodate different wireless applications, without focusing on any specific band other than the TV band. With respect to the previous works, the contribution of this paper, whose scope is illustrated in Figure 1, is to assess how CR technology deployment may need to be adapted to tackle the different technical challenges that the three analysed spectrum bands pose.

In Section II, we assess the main radio environment and incumbent systems' characteristics and the challenges they pose to CR devices. In Section III, we briefly describe the four main spectrum access techniques used for WS detection, highlighting the main aspects of their implementation and how these aspects vary with the radio environment in which a CR device operates. In sections IV, V, and VI, we conduct a qualitative assessment of the viability of each of these techniques for three different radio bands, considering the primary systems each band accommodates. In order to corroborate some of the affirmations made in section IV regarding the use of a hybrid database-aided sensing technique for radar bands, we provide in section VII a brief description and quantitative analysis of the performance of this technique. The main conclusions are drawn in Section VIII.

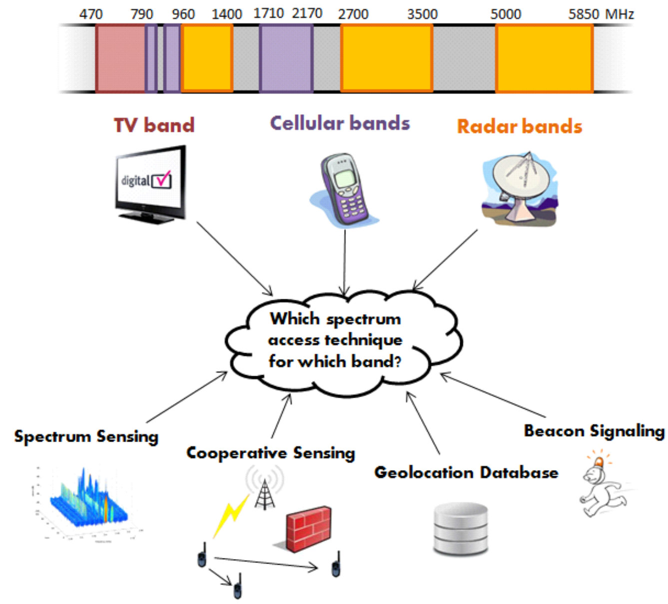

Fig. 1. Illustrative view of the article's scope.

II. Radio Environmental Factors

Depending on the scenario where OSA is applied, SS, cooperative sensing, GL-DB and beacon signaling techniques will have different specifications and requirements. For instance, the number of operations a GL-DB has to perform per second to be kept up-to-date will depend on the number of existing PU devices and how frequently their operating parameters change. SS complexity and detection times, on the other hand, will be related to the duty cycle of primary systems' transmissions and how easily their signals can be distinguished from noise. This section provides a list of the incumbent-dependent radio environmental (RE) factors considered relevant for defining the specifications of each SA technique:

a) **Uncertainty in PUs' parameters** – SA techniques require a certain amount of a priori knowledge about PUs' characteristics or whereabouts to ensure their protection against harmful interference. However, some of this information might not be always available, making the deployment of OSA a challenging task.
b) **Diversity of incumbent systems** – There is not a single beacon signaling, geolocation database or spectrum sensing mechanism capable of protecting all types of incumbent systems. In general, the spectrum access techniques' specifications need to match the characteristics each type of primary system displays. This can be especially difficult to implement in bands where several distinct primary communication technologies coexist at the same time.
c) **Number of devices** – The greater the number of incumbent devices operating in a certain region and band, the higher is the dynamicity and unpredictability of the spectrum utilization. The number of primary devices is also

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a relevant factor to determine whether it is economically viable to make alterations in their infrastructure.

d) **Planning** – SA techniques, namely geolocation databases, that do not check channel availability in real time are not able to avoid causing interference to licensed users, unless the incumbent systems' operation is planned and known in advance.

e) **Time dynamics and unpredictability** – The more unpredictable and dynamic the spectrum utilization by PUs, the more frequently CRs have to check channel availability.

f) **Mobility** – Incumbents' mobility contributes to the unpredictability of spectrum occupancy from the CR's point of view and is usually countered by applying more frequent channel availability checks or by increasing the size of PUs' exclusion zones (e.g. error regions [22]). Incumbents' mobility will, therefore, increase the complexity and energy consumption of CRs and reduce the efficiency of spatial spectrum sharing. In particular cases, the PU and SU mobility can benefit local spectrum sensing as it creates spatial diversity between the individual observations taken by a CR over time [23].

g) **Duty cycle (DC)** – The longer and more frequent the PUs' transmissions, the shorter the required sensing times and the lower the amount of available temporal spectrum opportunities.

h) **Resilience/Safety Margin (SM)** – This factor defines how much interference a PU should handle from unlicensed devices. It is, therefore, related to the robustness of incumbents to interference, the amount of interference caused by other PUs and the fact that some incumbent communications may concern safety-of-life operations.

i) **Susceptibility to fading** – A wireless signal is subject to multiple propagation phenomena, such as obstructions, reflections, diffractions, scattering, and refractions, that affect its power and shape, before reaching the receiver. The inability of a CR to accurately quantify the impact of all these factors limits its knowledge about the radio environment, and, consequently, its capacity to discern spectrum opportunities. In general, this issue is only overcome by employing more conservative incumbent exclusion zone sizes at the GL-DB or through more conservative detection thresholds when performing sensing.

j) **Hidden receiver** – CRs are only allowed to operate in licensed spectrum bands provided their transmission does not increase the interference at primary receivers beyond a certain maximum tolerable interference level [24]. However, this level is difficult to quantify by the SU in the presence of passive nodes or hidden receivers in the primary network, which is the case of TV and wireless microphone systems in TVWS [10]. A common practice to counter this problem is to add a margin to spectrum access techniques' detection thresholds or to increase the incumbent exclusion zones. The size of this margin will be proportional to the lack of knowledge the CR has about the position and antenna gain and orientation of the primary passive receivers.

k) **PUs' scale/range** – Uncertainty is also found in the derivation of the incumbents' exclusion zones as a result of the limited spatial resolution of the SA techniques employed when compared to the scale or range of PUs (e.g. limited database grid resolution or sparse distribution of cooperative sensing nodes across the space).

l) **Recognizable features/hidden periodicities** – Whenever PUs' signals display recognizable features in their structure that make them easily distinguishable from noise, such as pilots, coding sequences or cyclic prefixes, less powerful sensing mechanisms can be adopted to determine channel availability.

m) **UL/DL bands separation** – The allocation of primary systems uplink (UL) and downlink (DL) channels in separate frequency bands may influence CRs' hardware and sensing specifications, in particular whether more than one RF transceiver and in-band sensing are required to keep track of PUs' activity. Separate UL and DL bands also contribute to the loss of the reciprocity of the channel, since small-scale multipath affects the UL and DL differently, making sensing measurements less reliable, even in absence of hidden primary receivers.

n) **Aggregate interference margin (AIM)** – In order to account for the combined effect of multiple devices' interference, SA techniques may employ conservative propagation models or detection threshold values. This translates into the addition of a margin whose size will depend on the predominance of the aggregate interference in comparison to the interference caused by the closest secondary device to the primary receiver. In particular, this margin will be large for bands that accommodate primary systems of high coverage area, located at high altitudes, such as the ones employed in the satellite uplink bands. In cases spectrum sharing with SUs can be fully coordinated by PUs, the size of this margin may be set dynamically, improving sharing efficiency.

III. Spectrum Access Techniques

In this section, we provide a brief description of the main SA techniques, namely geolocation database, beacon signaling, spectrum sensing and cooperative sensing, proposed in the literature for the detection of WSs. We will then analyse how each of these techniques specifications will be affected by the RE factors we presented in the last section.

A. Spectrum Sensing

Local Spectrum Sensing is the SA technique that has received the most attention from the CR research community, due to its flexibility and the fact that it does not require any alterations to legacy systems or additional infrastructure. The ability to adapt in real time to changes in the radio environment, by periodically sensing the PUs' channels during their normal operation, has been one of the most appealing arguments in favor of spectrum sensing, as it allows efficient exploitation of the temporal spectrum opportunities provided by licensed users in each band.

The three standard spectrum sensing techniques are Matched Filter (MF), Energy Detection (ED) and Feature Detection (FD). When the primary signal structure is perfectly known, the optimal detector is the MF. This method, however, becomes overly complex as the number of different bands in which a CR operates increases, since it requires dedicated circuitry for each type of incumbent system. By contrast, ED is the simplest sensing scheme, does not require knowledge of the primary system and has optimal performance when signals are Gaussian. However, it is incapable of distinguishing interference from noise and its performance degrades rapidly when the noise power is not perfectly known. FD relies on the detection of the intrinsic periodicities embedded in modulated signals to distinguish them from Gaussian noise. However, it also requires knowing a priori the primary signal modulation scheme, and its complexity can sometimes become prohibitively high.

Spectrum Sensing Specifications:

a) **Detection threshold** – The detection threshold defines the sensitivity the SU's sensing algorithm should have to detect and avoid interfering with PUs. In the absence of hidden receivers, its value can be roughly deduced as shown in Appendix A. It depends not only on the ratio between transmit powers and bandwidths of PUs and SUs but also on several other factors, such as inter-PUs' interference, PUs' resilience, multipath and the aggregation of interference of multiple CRs. Since the impact of these factors is not completely known to the CR, they are traditionally overcome through the addition of a conservative PU Interference Margin (PUIM), a Safety Margin (SM), a multipath margin (Δ_{MP}), and an Aggregate Interference Margin (AIM), respectively, to the final threshold value. When some of the incumbent terminals are passive/hidden, the detection threshold must also include a hidden node margin (HNM) that accounts for shadow fading, misalignment of antennas, and receiver location uncertainty for worst-case scenarios. For the TVWS, SS seems unable to efficiently tackle this problem with reasonable sensitivity levels [8] [25].

b) **Sensing complexity** – Intuitively, as the detection threshold decreases, more complex sensing algorithms must be employed. There are, however, other important RE factors that affect the complexity and energy consumption of the sensing algorithm, such as the diversity of incumbents coexisting in the same band and the existence of clear, recognizable patterns in the PUs' signal structure. As pointed out earlier, sensing algorithms should be designed to match each different radio environment scenario in order to be efficient at recovering WSs. If the incumbent signals are too distinct from one another or do not have any special, recognizable feature, the deployment of powerful sensing schemes such as matched filter or feature detection becomes challenging or even impossible.

c) **Detection time/channel availability check time** – The channel availability check time (CACT) is the time it takes for a CR to detect the incumbent signal. Its value decreases with an increase in the detection threshold, with the incumbent signal's duty cycle and with the performance of the sensing technique employed. The main consequences of spending more time performing sensing is the reduction of the CRs' throughput in case of in-band sensing and an increase in power consumption.

d) **Sensing periodicity** – It defines how frequently sensing must be performed in order for the SU to be fully updated about its radio environment space-time-frequency variations that result from multipath, shadowing, mobility and alterations in the incumbent systems' operational parameters. Sensing periodicity should be high not only for CRs to adapt to dynamic scenarios but also to avoid causing long periods of interference on safety-critical systems. Like the sensing time requirement, an increase in sensing periodicity will reduce SUs' throughput and increase their energy consumption.

e) **In-band sensing** – Hardware limitations and the interference generated by the on-going SU's communication practically prevents the CR from performing sensing and transmitting/receiving data simultaneously in the same band. To address this issue, techniques such as quiet period (QP) scheduling, dynamic frequency hopping and self-signal suppression (SSS) are suggested in the literature [26]. Depending on their duration and periodicity, QPs, in particular, may significantly decrease CR devices' throughput and cause transmission interruptions. This problem is known as the sensing-throughput tradeoff [27]. With the separation of the incumbent uplink (UL) and incumbent downlink (DL) channel frequencies, however, in-band sensing might not be necessary. When frequency division duplexing (FDD) is adopted in a cellular network, for instance, a CR occupying the cellular UL band can check the presence of a Base Station (BS) nearby by (out-of-band) sensing the respective BS DL band. While this solves the sensing-throughput tradeoff, it also requires CRs to be equipped with two transceivers, which increases their complexity and power consumption.

f) **Ability to recognize spatial spectrum opportunities** – This factor defines how efficiently spectrum sensing can exploit the spatial aspect of spectrum sharing in a certain band. In other words, it will measure the amount of spatial spectrum opportunities (SO) a CR device can recover through this SA technique. This quantity is directly related to the conservativeness of the detection threshold employed, in particular if a margin is applied to counter the aggregation of interference, the hidden receiver, fading, incumbents' variable operational parameters (e.g. transmission power, band, or target signal to interference plus noise ratio), or to protect safety-critical systems.

g) **Ability to recognize temporal spectrum opportunities** – This factor is related to the ability of the CR to adapt in real time to the variations in the radio environment that surrounds it and, ultimately, to efficiently recover temporal WSs. It is, therefore, a consequence of the unpredictability and dynamicity of the radio environment, and of the sensitivity of the sensing techniques employed by the CR to these variations.

Table I summarizes the relation between the incumbent systems' characteristics and the consequences they have on spectrum sensing specifications and requirements.

B. Cooperative Sensing

Several propagation factors, such as multipath fading, shadowing and the hidden terminal problem may significantly

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TABLE I
DEPENDENCY OF THE SS SPECIFICATIONS ON THE PUS' CHARACTERISTICS

Requirements	RE Factors
Threshold	SM, AIM, HNM, Δ_{MP}, PUIM, uncertainty about PUs' parameters.
Complexity	Threshold, clear signal patterns, diversity of PUs.
Time	Threshold, duty cycle, clear signal features.
Periodicity	Mobility, time dynamics, number of PUs, environment, SM.
In-band sensing	UL/DL separation.
Spatial SOs	SM, AIM, HNM, uncertainty in PUs' parameters.
Temporal SOs	Number of PUs, mobility and time dynamics.

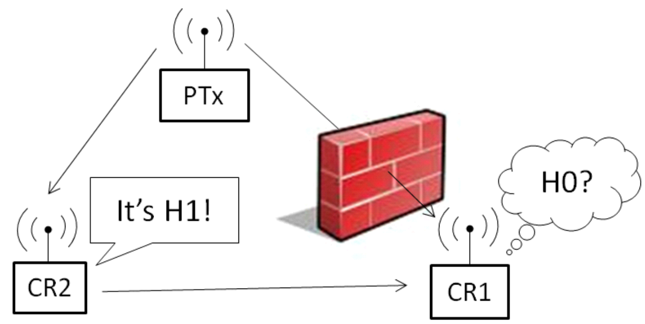

Fig. 2. Cooperative sensing between two CR devices where CR1 cannot detect the PTx (H0: PU absent) due to an obstruction in the propagation path.

affect a CR's ability to detect spectrum holes through local sensing. The impact of these phenomena could, however, be mitigated if individual SS results were shared between CR devices at different positions and turned into a combined decision regarding the availability of a specific channel. This mechanism, called cooperative spectrum sensing (CSS), is illustrated in Figure 2. Based on local spectrum sensing techniques alone, the attenuation caused by walls or other obstructions leads CR1 to draw an erroneous conclusion (H0 - PU absent) about the presence of a primary transmitter (PTx) nearby. If, on the other hand, CR1 utilizes CR2's sensing data, it will conclude that the channel is being occupied (H1) by a (hidden) PU. In addition to the contribution to the reduction of the hidden node effect, CSS may also decrease individual SUs' sensing time.

The cooperative process of combining the local sensing results from different CR nodes is named data fusion [28]. Depending on the bandwidth and energy available, three different combining techniques can be employed: (i) soft combining; (ii) quantized soft combining; (iii) hard combining. Soft combining has the highest performance of the three, as CRs exchange sensing data that have not been subject to any type of quantization process. However, the high overhead it incurs without significant advantages over the alternatives has led its applicability to DSA to be questioned in the literature [29]. At the other end of the spectrum, hard combining has the lowest detection performance and overhead, since it is based on applying simple linear fusion rules (e.g. OR, AND and majority) that only take one-bit local decision information from each different cooperative CR as input.

One of the main obstacles to CSS implementation has been the lack of performance guarantees it can provide, as its achievable detection level depends on the number of nodes involved in the cooperating process and on whether their individual samples are under the effect of spatially correlated shadowing [28]. CSS also adds significant overhead to CR networks for the exchange of the individual observations and often implies the use of a common control channel (CCC), not always a realistic assumption for DSA, considering the fact that this channel is also affected by PUs' activity and the potential a single CCC has to become saturated and a single point-of-failure [30].

Cooperative sensing specifications:

a) **Cooperative gain** – It refers to the improvement in detection performance and relaxed sensitivity requirements obtained when individual spectrum sensing samples from different CR users are combined. It depends not only on the data fusion techniques employed and the number of cooperating nodes, but also on other radio environment features such as:
   - **Hidden receiver and susceptibility to fading** – The gains obtained through the spatial diversity provided by cooperative sensing will be particularly high in the presence of hidden receivers and when the effects of reflection, refraction, diffraction and scattering are considerable (e.g. urban environments, high frequencies and low antenna heights).
   - **Spatially correlated fading** – The loss of spatial diversity between CRs' observations when blocked by the same obstacle can be detrimental to CSS [28]. The effect of this phenomenon is usually estimated based on the distance between cooperating SUs, the PUs' range, and the type of environment [31]. In cases where the correlation between users' observations is high (e.g. large-scale PUs), node selection mechanisms or fusion rules that predict how correlated different cooperating nodes' samples are may need to be employed.
   - **PU and SU mobility** – The spatial diversity between the observations taken by a CR in high mobility scenarios increases local sensing performance and, therefore, decreases the cooperative gain. It was shown in [23] that at high speeds, it can be more efficient for a CR to sense individually multiple times than to cooperate with other users.

b) **Density of SUs** – The unambiguous detection and protection of short-range PUs through CSS may require a SU network with a prohibitively high density of cooperating nodes, especially in the case of urban scenarios [32] [33].

c) **Overhead** – Sharing sensing samples may result in an increase in the overall sensing time, delay, energy consumption, number of operations and wasted bandwidth in CR networks (CRNs). This extra overhead will be particularly high if soft combining techniques are employed or

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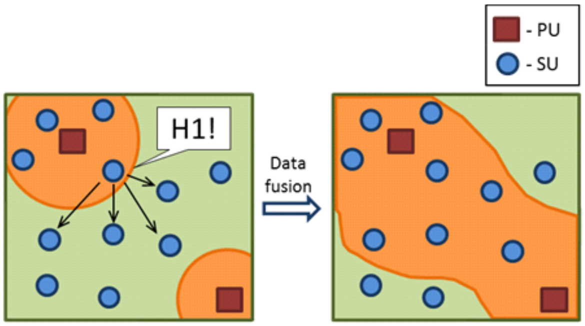

Fig. 3. Increase of PUs' exclusion zones from the SUs' point of view when CSS is employed. Exclusion zones and white spaces are represented in orange and green color, respectively.

in scenarios with a large number of short-range PUs with high mobility and unpredictable behavior. Node selection and censoring are mentioned in the literature as possible techniques to increase the energy efficiency and minimize the traffic on the CCC in CRNs without significantly affecting CSS performance [28], [34], [35]. By using node selection, some CRs are allowed to enter sleep mode, which leads to lower sensing and transmission costs for the overall network. Censoring results in a reduction of transmission costs, as it dictates, based on relevance, whether CRs' sensing observations should be sent to other nodes.

d) **Identification of spatial spectrum opportunities** – On the one hand, CSS allows a more efficient exploitation of the spectrum in the spatial domain, as it contributes to a reduction of the hidden node margins and, consequently, the relaxation of the sensing sensitivity requirements. On the other hand, CSS may raise a new issue known as the exposed node problem, which leads to significant under-utilization of the spectrum, in cases where the cooperating SUs' separation and PUs' ranges are comparable [33]. This phenomenon is illustrated in Figure 3. The exchange of sensing information close to the boundaries of PUs' exclusion zones can lead some SUs to erroneously assume that a channel is occupied and, therefore, reduce spatial sharing efficiency. The exposed node problem is a consequence of disregarding SUs' spatial diversity during data fusion. Possible ways to overcome this issue are to employ soft combining, less conservative fusion rules or more advanced data fusion techniques that consider the location or the correlation between sensing samples of different cooperating SUs. For instance, in [36], the authors propose a spatial diversity-aware clustering and data fusion technique where the cooperating nodes are grouped together based on the correlation of their local decisions.

e) **Identification of temporal spectrum opportunities** – No major differences when compared to SS except for the additional synchronization and sensing results reporting delays.

Table II describes the relation between the radio environment characteristics and the specifications of cooperative sensing.

TABLE II
DEPENDENCY OF THE CSS SPECIFICATIONS ON THE PUS' CHARACTERISTICS.

Requirements	**RE Factors**
Cooperative gain	HNM, PUs' range, susceptibility to fading and mobility.
Density of SUs	PUs' range.
Overhead	PUs' range, number, mobility, unpredictability.
Spatial SOs	Hidden receiver; PUs' susceptibility to fading; difference between PUs' range and cooperative nodes' separation.
Temporal SOs	Higher decision delays than SS.

C. Geolocation Database

In this spectrum access technique, a centralized database stores information about PUs' spectrum use and position, which it then uses to draw conclusions regarding spectrum occupancy in each region. Secondary devices estimate their position using a localization technology such as GPS and report the resulting coordinates to the database. The database then replies with a map of the channels which are available for use, considering the querying device's operating parameters and location [5], [8], [37], [38].

Distinctly from SS, GL-DB calculates the interference created between communication systems through theoretical propagation models rather than actual RF measurements. To avoid prohibitively high complexity, it first divides the terrain into squares with different latitude and longitude, each one representing a point or pixel on a geographical grid. Primary systems' operating parameters, such as equivalent isotropic radiated power (EIRP), center frequency, bandwidth, antenna height, location and expected duration of channel usage, also stored in the database, are then used to draw the incumbent systems' exclusion zones/keep-out regions, as shown in burgundy in Figure 4. The decision of whether a querying SU is authorized to transmit on a specific channel will depend on whether its coordinates are inside a grid pixel that belongs or is adjacent (to consider the inaccuracies of localization mechanisms, such as GPS) to one of these exclusion zones. The techniques used by a database to define WSs for SUs may significantly vary with the rules employed (e.g. FCC or ECC) [5], [37]. In [38], the authors compared the FCC and ECC approaches, demonstrating that the first was less protection-oriented, leading to increased throughput capacity for SUs.

The increased interest in the GL-DB method for TVWS mainly relates to the fact that it can grant higher protection to incumbent (hidden) receivers than SS, by using conservative propagation models, and to the fact that patterns of activity by most incumbents in the TV band are fairly static in time. As a downside, the GL-DB method requires TVWS devices to be equipped with localization mechanisms such as GPS to get their coordinates, and with out-of-band connectivity to access the database. There are also some concerns about how the database will be designed to support several radio bands with distinct characteristics, and its potential liability as a single point of failure. The GL-DB scheme is inadequate for the protection of dynamic incumbents, such as the ones found in cellular bands, not only because of the database

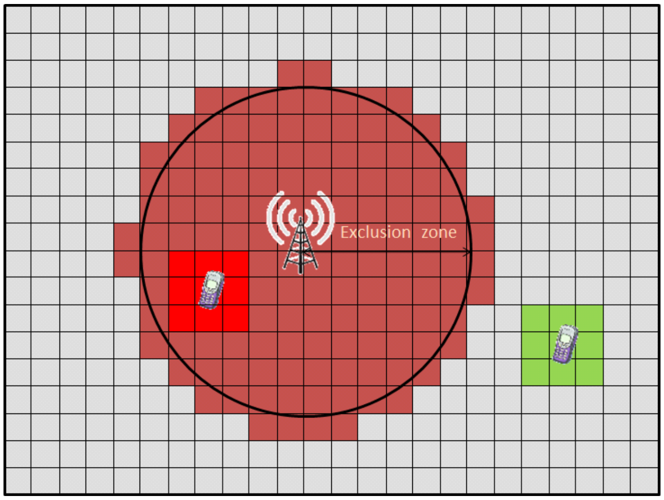

Fig. 4. Channel availability by region/database pixel. The secondary device on the left is not allowed to transmit since it is inside the incumbent base station's exclusion zone.

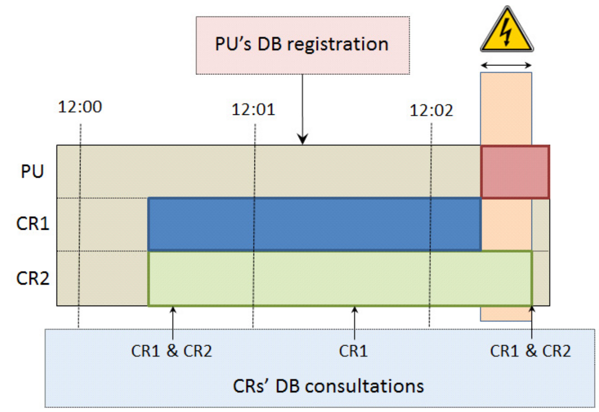

Fig. 5. PU, CR1 and CR2 operation and GL-DB consultations and updates over time in a specific channel.

complexity and delays, but also the complexity and energy consumption that the frequent GL-DB consultation would pose to CRs. Next, we describe the main requirements of GL-DBs.

Geolocation Database specifications:

a) **Registration of legacy systems** – The GL-DB requires a priori information about the incumbents' position and parameters (e.g. EIRP, frequency and expected period of channel usage) to be able to check channel spatial and temporal availability. When this information is not available, which is the case for unregistered devices, this spectrum access technique is not feasible.
b) **Complexity/processing power** – One of the factors that increase the implementation costs of a GL-DB is the number of terrain grid points it has to be able to update per second with information regarding the PUs' spectrum occupancy. This is not only related to the grid resolution employed, but also to the mobility, traffic dynamics, number and range of PUs. Even for very static scenarios such as TVWS, the update of a TV base station's exclusion zone with a radius of 150 km requires the computation of complex propagation models for millions of grid points (with a resolution of 100m x 100m). This issue is aggravated as higher grid resolutions start to be considered to accommodate short-range PU devices too. A GL-DB must also have the capability to answer a large number of SUs' queries with the lowest delays possible in order to give timely information about the radio environment and to avoid getting flooded. The implementation costs involved in providing this feature will increase as CR technology becomes more widespread.
c) **Consultation periodicity/maximum dissemination delay** – The CRs' database consultation periodicity is set based on how far in advance incumbents' spectrum utilization is planned. As illustrated in Figure 5, for instance, the protection of PUs that update their parameters in the database at least 1 minute before their actual operation requires CR devices with a database consultation periodicity below or equal to 1 minute. Since CR2 only consults the GL-DB every 2 minutes, there is a period of time when it causes interference to the PU. For the cases where PUs or SUs are not static, or PUs have unplanned transmitting patterns, the GL-DB must be consulted frequently. This will lead to a significant increase in the SUs' power consumption and GL-DB complexity, making its deployment unattractive from a business point of view.
d) **Ability to recognize spatial spectrum opportunities** – As GL-DBs do not rely on direct, real-time measurements to define incumbents' exclusion zones, they typically adopt conservative theoretical propagation models that seek to account for the impact of uncertain propagation phenomena such as ducting, obstructions, reflections and scattering [31], the aggregation of interference, the unknown primary receiver location (hidden receiver), and that are able to provide extra protection to safety-critical systems. Incumbents' exclusion zones must also account for database terrain grids with limited resolution or localization systems with limited accuracy, which can make this SA technique less adequate for the protection of small-scale PUs.
e) **Ability to recognize temporal spectrum opportunities** – The major GL-DB drawback is its high update and information dissemination latencies, lacking the flexibility to adapt to fast and unplanned variations in the radio environment. It is, therefore, expected that this method will not recover as many temporal spectrum opportunities as other SA techniques.
To recover the temporal SOs provided by mobile PUs with unplanned routes, a workaround has been proposed in the literature, which is illustrated in Figure 6 [22]. It consists in defining an error region around incumbent systems that is then used as an extra protection margin in the estimation of their exclusion zones. The area of this region is proportional to the product of the PUs' velocity and the database consultation periodicity. It should be stressed, however, that this feature is not yet envisaged for any GL-DB architecture operating in the TVWS or 3.5 GHz bands.

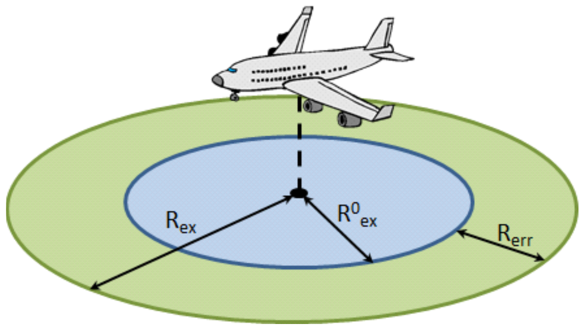

Fig. 6. The radius of the incumbent's exclusion zone (R_{ex}) is equal to the radius of the exclusion zone in case the incumbent was static (R^0_{ex}) plus an error distance (R_{err}).

The main aspects regarding the adoption of the GL-DB as an SA technique are summarized in Table III.

TABLE III
DEPENDENCY OF THE GL-DB SPECIFICATIONS ON THE PUS' CHARACTERISTICS.

Requirements	RE Factors
Registration	Uncertainty about PUs' parameters.
Complexity	PUs' scale/range, number of PUs, time dynamics and mobility and SU's consultation periodicity.
Consultation periodicity	PUs' activity planning, mobility.
Spatial SOs	PUs' scale, susceptibility to fading, AIM, SM and HNM.
Temporal SOs	PUs' activity planning, time dynamics and mobility and number of PUs.

D. Beacon Signaling

In this spectrum sharing approach, primary licensed devices cooperate with secondary devices by transmitting information regarding their spectrum resources utilization through beacons. Although an attractive solution for efficient spectrum sharing, it raises several implementation issues, one of them being that its deployment usually requires significant changes to legacy systems' infrastructure [8]. These changes are not only unattractive to incumbent users, but also infeasible to implement when the technology is too widespread (e.g. cellular and WLAN). The lack of a global consensus on what band the beacons should use to transmit also represents a barrier to the deployment of this method in the near future.

Beacon information can be modulated through carrier tones or through direct sequence spreading codes. Although more complex, the latter is considered more reliable, as it usually inflicts less interference on licensed operation and it is not so easily mistaken for spurious signals or harmonics from other bands.

Beacon devices can be of four different types, depending on the entity that manages and emits their radio environment information [3]: per-transmitter, receiver, unlicensed, and area beacon. Throughout this work, special emphasis will be given to the receiver and area beacons, which have clear advantages when compared to the other two.

- **Receiver beacon (RB)** – This device is integrated in the primary system receiver. Its main advantage comes from the fact it mitigates the hidden node problem.
- **Area beacon (AB)** – The area beacon is a dedicated radio device that disseminates channel availability information, previously stored in a database, valid within a certain region. This method offers standardized access to GL-DB information without the need for CRs to directly query the database. It also makes the GL-DB less costly, more secure and less predisposed to jams and floods of queries, as it would only be accessed by the ABs, far less numerous than individual secondary devices. Nonetheless, the AB solution is still less dynamic than infrastructure-independent spectrum access techniques, due to the update delays of the centralized database.

Beacon signaling specifications:

a) **Design limitations –** Beacons are communication devices and, therefore, they must respect the regulations and policies imposed for each radio band, including bandwidth and power limitations, and avoid causing interference to other PUs. Since there is not a universal beacon design capable of meeting these two requirements for all radio bands, these devices' parameters and transmission channels must be defined based on the characteristics displayed by the PUs with which they co-exist.

b) **Infrastructure costs** – Contrarily to SS, this spectrum access technique in general requires changes to the incumbent systems' infrastructure. Therefore, its deployment cost varies with the cost of each single beacon device and with the number of beacons that need to be installed to protect the PUs of a specific band from harmful interference.

c) **Ability to recognize spatial spectrum opportunities** – The number of spatial opportunities recovered by a CR system is maximized when beacon devices are placed next to the primary receiver, avoiding the hidden node problem. Beacons may also carry additional data regarding PUs' parameters, such as transmit power, bandwidth and maximum interference before service disruption, which assists SUs in defining a detection threshold. If completely integrated with the PU, the beacon can adjust in real time the information it transmits to SUs, avoiding issues related with aggregate interference and reducing the required safety margins.

d) **Ability to recognize temporal spectrum opportunities** – In order to exploit the temporal aspect of spectrum sharing, the beacon devices may be only turned on slightly before and during PUs' operation. This would ensure that CR devices detect primary systems far enough in advance and, as a result, do not cause any interference. Beacons may also carry data in their signal structure related to the expected period of utilization of the spectrum by the incumbent.

Due to the fact that it also relies on a centralized database, the AB also has several implementation aspects in common with the GL-DB, namely: the database processing complexity,

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TABLE IV
DEPENDENCY OF THE BEACON SIGNALING SPECIFICATIONS ON THE PUS' CHARACTERISTICS.

Requirements	RE Factors
Design limitations	Regulations, PUs' diversity, required dedicated channel for signaling.
Infrastructure costs	Number of PUs, beacon devices' cost.
Spatial SO	HNM, AIM and SM, depending on how and where the beacon device is deployed.
Temporal SO	Beacons may emit information regarding PUs' expected period of operation.

the conservativeness of the propagation models, and high update and information dissemination delays.

Table IV illustrates the relation between the radio environment characteristics and the requirements of beacon signaling.

The next three sections present an analysis of the four techniques used to recognize spectrum opportunities, in the context of the radar, TV, and cellular bands.

IV. RADAR BANDS

Radars are object detection systems with application in several areas such as aeronautical and maritime radionavigation, weather forecast and radiolocation. Although they occupy a significant portion of the international radio spectrum, their spectrum occupancy is usually under 5 % and does not vary significantly throughout a day [15]. For this reason, radar bands are nowadays seen as promising candidates for opportunistic access [39] [14].

The most adequate radar bands for secondary use are the L, S and C bands between 960-1400 MHz, 2.7-3.6 GHz and 5.0-5.850 GHz, respectively. These frequencies are sufficiently low to avoid high power consumption and the usage of highly directional antennas, and sufficiently high to offer considerable bandwidths when compared to VHF, for example. Furthermore, they are close to the cellular and ISM bands used for 2G/3G/4G and WiFi, respectively, facilitating the production of devices capable of using all these frequencies.

Several interference studies for the radar bands have already been conducted [13], [14], [19], [20]. In [14] both co-channel and adjacent channel interference generated by a single secondary device are studied for the L, C and S bands. The author considers the C band to be the one with the best sharing conditions where, according to the tests, co-channel and adjacent channel coexistence is possible at a distance equal to or higher than 45 km and 17 km, respectively. In [19], the authors study the impact of aggregate interference from multiple, uniformly distributed devices on the meteorological radar band at 5.6 GHz. Their findings highlight the technical difficulties associated to the measurement of the aggregate interference on the PU, since its value hugely depends on the propagation environment and, in particular, the path loss exponent. This work was further extended in [20], where non-uniform user distribution scenarios were considered.

Spatial sharing is an attractive aspect of radar bands, due to the limited number and usually fixed and well known position of their incumbents. However, the radars' high transmission power and heavy deployment in coastal regions and close to airports can block a large percentage of the world population from accessing this spectrum. For this reason, other sharing scenarios have also been assessed in the literature [13], [17], [40], [41]. Let us take, as an example, primary radar systems with highly directional rotating antennas. From a temporal sharing perspective, a considerable amount of spectrum opportunities can be exploited in this scenario by allowing CRs inside exclusion zones to transmit when the radar antenna's main beam is pointing in another direction. However, this requires some kind of synchronization of the CRs with these antennas' sweep patterns, which might be technically challenging considering the diversity of incumbents operating in these bands and the fact that CRs may overhear signals from more than one radar station at the same time.

To provide a qualitative evaluation of the opportunities and challenges of DSA in radar bands, we start by discussing RE factors of particular relevance to these bands. We then consider how applicable each spectrum access technique is, given the operational characteristics of incumbent systems. We follow the same methodology when discussing each of the other bands analyzed in this article.

A. Radio Environmental Factors

a) **Uncertainty in PUs' parameters** – Information regarding radar stations' position, EIRP, frequency and expected period of operation is usually available. Some military radiolocation information may, however, be classified.

b) **Diversity of incumbent systems** – Despite the same operating principle, radar systems display very distinct features, dimensioned according to their application. Overall, radars can be classified as:

- Imaging / Non-imaging: Imaging radars form a picture or map, whereas non-imaging radars make a one-dimensional representation of the observed object or area;
- Primary / Secondary: In primary radar systems, the picture of an object or area is formed using the echoes of the transmitted signal, while in secondary systems, it is formed through the two-way communication between an interrogator and a transponder;
- Monostatic / Bistatic: In monostatic primary systems, the transmitter and receiver are co-located, whereas in the bistatic case, they are separated.

From the waveform perspective, a radar signal can, in turn, be classified based on:

- Constant Wave (CW) / Pulse Radar (PR): CW radar signals are continuous in time, while PR signals are formed by a train of short pulses;
- Intrapulse Modulation (IPM): Pulses can be simple or compressed, for instance, through frequency modulation (FM) or phase modulation (PM);
- Pulse Repetition Frequency (PRF): The PRF values of PR systems are generally around 1000 Hz for the S, C, and L bands. The PRF or pulse repetition interval (PRI) may not remain constant in some cases, e.g. in staggered and jittered PRF systems;
- Pulse width (PW) - PR systems' pulse durations can range from $0.1\mu s$ to several milliseconds;

- Frequency agility: To avoid enemy jamming, a radar may hop from channel to channel in a pseudo-random manner.

Radar beams can be divided into two general types according to their shape: fan and pencil-shaped. Fan beams are characterized for being very wide in one direction and very narrow in the orthogonal direction, whereas pencil-shaped beams are directional in both elevation and azimuth. Radar scan patterns, that define the path the antenna beam takes to scan its environment, can be of several types, such as, circular, sector, raster, conical, helical, and spiral.

c) **Number of devices** – The number of radar systems is generally low due to their long ranges, with heavier deployment close to coastal regions and airports.

d) **Planning** – Radar systems' positions and parameters tend to be planned ahead of time. There are, however, some exceptions, such as systems placed on airborne and shipborne platforms, which may not have pre-planned routes;

e) **Time dynamics and unpredictability** – Most radar systems have fixed and predictable transmitting parameters, such as transmit power, scan patterns, PRF, center frequency and position, for long periods of time. There are some exceptions, such as:

- Military radiolocation systems that employ frequency hopping techniques such as Electronic Counter-Countermeasures (ECCM) when subject to enemy jamming.
- Secondary radar transponders, whose emissions are not periodic and only occur after the reception of an interrogation message. CR devices might be able to predict these systems' reply channel utilization by sensing activity in the respective interrogation channels.
- Some tracking systems that have irregular antenna scan patterns, designed to focus on specific targets.

f) **Mobility** – Some radar antennas are placed on mobile platforms, such as ships and airplanes.

g) **Duty cycle (DC)** – Radar systems, with the exception of CW systems, emit signals of very low duty cycles, which can be less than 0.1%, depending on the pulse width and PRF employed. The directional antennas and long rotation periods also contribute to the reduction of radar signals' duty cycle, from the CR device's point of view.

h) **Resilience/Safety Margin (SM)** – The importance of radar systems to public safety significantly varies with their application. Aeronautical radionavigation systems (ARNS), in particular, are safety-of-life services, so every possible precaution must be taken to ensure their protection [18]. Nevertheless, radar systems also employ interference mitigation techniques such as low duty cycle suppression techniques of asynchronous signals, Side Lobe Suppression (SLS), and Electronic Counter-Counter-Measures (ECCM). These mechanisms should be considered in the dimensioning of a safety margin.

i) **Susceptibility to fading** – Radar systems operate outdoors, most of them close to coastal areas and airports. Considering their highly directive antennas, and very high peak transmit powers, they can reach CRs at very long distances, sometimes even beyond the horizon. For instance, a radar station with 10 kW of transmit power, and 35 dBi and 500 meters of antenna gain and height, respectively, has a -64 dBm free space range of approximately 2240 Km, which is well above its horizon of around 25 Km. Taking these systems' long ranges into account, it is possible to infer that spatial sharing with CRs will normally occur in non-line-of-sight (NLOS) scenarios, i.e. with Rayleigh fading and very high path loss exponents. As depicted in [42], the exclusion zone of an established weather radar in the 5 GHz band is highly irregular, as a result of the attenuations caused by buildings and the terrain elevation. For systems with lower centre frequencies, a more circular exclusion zone would be expected. Due to its beam's constant motion, the radar signal will also suffer fast fading, with a coherence time proportional to the radar antenna's rotation period and beamwidth.

j) **Hidden receiver** – Most primary radar systems are monostatic, and, therefore, have co-located transmitters (Tx) and receivers (Rx). For the case of secondary radar systems, both interrogators and transponders can be detected by sensing the interrogation and reply bands, respectively. Systems placed aboard aircraft usually operate at lower transmit power, making them harder to detect.

k) **PUs' scale/range** – Radar systems have very large coverage areas, in some cases with a radius over 200 km, as a result of the high radiated powers in the order of KiloWatts or MegaWatts and the high antenna directivities.

l) **Recognizable features/hidden periodicities** – The intrinsic periodicities created by virtue of constant PRFs, IPM, pulse widths and antenna rotation periods can be recognized through feature or matched filter detection. There are, however, some systems that, to make their emissions unrecognizable to enemies, utilize complex or irregular scan motions, centre frequencies, or pulse waveforms.

m) **UL/DL bands separation** – Primary radar systems use the same channel for transmission and reception. On the other hand, secondary radar systems such as Secondary Surveillance Radar (SSR) and DME use two separate bands, one for the transponder and another for the interrogator.

n) **Aggregate interference margin (AIM)** – Radar systems have long ranges and are usually deployed close to areas of high population density, such as coastal regions and airports, which make them more prone to be affected by a large number of SUs at the same time. On the other hand, the authors in [19] show the positive effect that the high path loss exponent of an urban environment has on the reduction of the aggregate interference caused by a specific density of SUs. In addition to this, the high directivity of most radar systems' antennas, with some few exceptions (e.g. DME), makes the interference

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TABLE V
RADAR SYSTEMS' RADIO ENVIRONMENTAL FACTORS

RE Factors	Commentaries	
PUs' parameters	Licensed with well-defined ownership. Military systems' parameters are classified.	
Diversity	Distinct signal patterns or parameters.	
Number of devices	Very low.	
Planning	Planned, with some exceptions.	
Time Dynamics	Parameters are constant, with some exceptions.	
Mobility	Fixed position, with some exceptions.	
DC	Low duty cycles and highly directional antennas with long rotation periods. Some exceptions.	
SM	Robust against interference; ARNS concern safety-of-life.	
Susceptibility to fading	NLOS, fast fading, highly irregular exclusion zones, especially at high frequencies.	
Hidden receiver	Non-existent for monostatic and secondary radar systems.	
PUs' range	Very long ranges.	
Recognizable features	Intrinsic periodicities in signal structure.	
UL/DL separation	Only some secondary radar systems.	
AIM	High directivity of antennas. Some exceptions.	

caused to them to be dominated by the closest CR device inside their main lobe.

Table V summarizes the radar bands characteristics considered relevant for DSA.

B. Spectrum Sensing

Spectrum sharing has been authorized in the 5 GHz radar bands (5150-5350 MHz and 5470-5725 MHz) opening up new spectrum for wireless access systems (WAS) and, in particular, wireless local area networks (WLAN) devices [42] [6]. To protect radars from harmful interference, IEEE 802.11h WLAN devices employ a channel allocation mechanism, based on spectrum sensing, called Dynamic Frequency Selection (DFS). The stipulated DFS detection thresholds (-62 dBm and -64 dBm) are well above the noise floor (approximately -100 dBm) of WLAN receivers operating in this band. On the other hand, the radar's low duty cycles and directional rotating antenna require that WLAN devices employ very long Channel Availability Check Times (60 s). This duration might even not be enough for very slowly rotating radars, as noted by the ITU-R, so an in-service monitoring scheme, consisting of interleaving data transmission with in-band sensing during devices' normal operation, has also to be employed [6].

The DFS functionality, as initially developed, was incapable of ensuring the protection of terminal Doppler weather radar (TDWR) systems [43]. Interference investigations carried out by the FCC concluded that the considerations for the WAS systems' adjacent-channel interference were not adequate and some modes of operation of TDWR systems were overlooked in the dimensioning of the DFS certification requirements. Despite most of the DFS interference issues having been addressed in further recommendations, this episode serves as an example of the potential risks that spectrum sharing can bring to radar systems that concern safety-of-life applications, such as the ones operating at 5350-5470 MHz, if an inappropriate interference and coexistence assessment is used. It also demonstrates the importance of making radio systems reconfigurable, as an efficient way to make them adaptive to dynamic policies, standards and protocols.

Although the DFS mechanism is now capable of protecting incumbents from low powerWLAN devices' harmful interference, its one-size-fits-all detection threshold and availability check times, dimensioned for the worst case scenarios, lack the flexibility and intelligence of modern DSA techniques. In order to fully exploit the spatial and temporal aspects of radar bands, CR devices should be able to identify radar systems through their distinct transmitting features, namely scan period, transmit power, antenna gain, pulse duration, and PRF and, then, apply the appropriate sensing algorithms and detection thresholds and efficiently schedule the quiet intervals devoted to sensing.

Spectrum Sensing Specifications:

a) **Detection threshold** – As shown in [6], the required detection thresholds for the protection of primary radar systems in the 5 GHz band are very high (from -61.7 dBm to -36.4 dBm). The main reasons behind these large values are these incumbent systems' high transmit power and the absence of the hidden receiver problem. A similar conclusion can also be drawn for secondary radar systems. The protection of DME systems in the 960-1215 MHz band, for instance, would require sensing thresholds of -61 dBm for the interrogation and reply bands, as estimated in Appendix A. However, additional safety and aggregate interference margins can further reduce this value.

b) **Sensing complexity** – To detect and distinguish radar signals from other communication systems' interference or from different radar stations, CRs' sensing algorithms should rely on peak detection techniques that are able to identify the sparse nature of radar signals, and estimate their respective parameters, such as PRF, pulse width, and scan period. However, identifying these parameters can be particularly complex in case of incumbent systems with very long antenna rotation periods, with random PRFs, or that employ frequency hopping techniques.
The radar systems' high transmit power ($\sim$1 MW) and short pulse lengths (as low as 0.4 μs) also add to the complexity of the CR receiver, as they require analogue-to-digital converters (ADC) of high sampling rates and amplifiers of very large dynamic ranges.

c) **Detection time/channel availability check time** – The radar low duty cycles and very long antenna rotation periods might significantly increase the channel availability check times (e.g. 60 seconds for DFS) [6]. The sensing time can be reduced through the synchronization between the CR's sensing intervals and the instants of time when the radar antenna beam points at it.

d) **Sensing periodicity** – Radar channels' occupation is usually constant over time and space, thus spectrum sensing only needs to be performed occasionally. There are, however, some exceptions such as military radiolocation systems that employ frequency hopping techniques, tracking systems, and systems placed on mobile platforms. Safety-of-life applications, such as ARNS, also require lower maximum interference times and, therefore, for their bands, SS must be performed more often.

e) **In-band sensing** – CR devices need to interleave their transmissions with periods devoted to spectrum sensing in order to detect PU activity in the occupied radar channel [6]. Considering radar systems' high transmit power, sensing can still be performed by the CR during normal packet reception mode. Quiet periods might not be required for secondary radar systems if the interrogation and reply channels are located in separate frequencies (e.g. DME).

f) **Ability to recognize spatial spectrum opportunities** – Not being affected by the hidden receiver problem, sensing can be an efficient way to exploit the spatial SOs of radar bands. However, the diversity of radiolocation systems coexisting in the same frequencies makes the one-size-fits-all detection threshold adopted for DFS in the 5 GHz band inadequate, as it leads to exclusion zones unnecessarily large for some PUs. In order to circumvent this issue, a CR has to somehow identify the thresholds and transmit power levels necessary to protect each of the radar systems within its interference range. Although distinguishing signals with origin in different radar stations is technically possible through parameter estimation techniques, knowing the level of protection each of the detected stations requires is impossible without a priori information regarding their transmit power and maximum interference-to-noise ratio (INR).
The several techniques employed by a radar system to cancel interference, and its relatively low susceptibility to the effect of the aggregation of interference from multiple CRs, make the safety margins and aggregate interference margins added to the CRs' detection thresholds small and, consequently, increase the number of recoverable WSs.

g) **Ability to recognize temporal spectrum opportunities** – SS can ensure the protection of radar systems placed on mobile platforms or that operate on an intermittent basis, usually employed in radionavigation. In the case of secondary radar systems that operate on an ask-reply basis, CR devices might be able to opportunistically access these systems' reply channels as long as they do not detect any signal in the respective interrogation channels. The complexity involved in the exploitation of temporal spectrum opportunities that stem from the radars' predictable sweep patterns is high, due to the fact that radars may also receive interference from sidelobes and the challenges associated to the synchronization between CRs and radars' sweep patterns, when the CR has no a priori information about the PU parameters. Some types of radar do not have predictable scan patterns, or may include receive-only periods used for noise calibration that should not be affected by CRs' operation.

TABLE VI
SS SPECIFICATIONS FOR RADAR SYSTEMS

Requirements	Cons	Pros	
Threshold	Diversity; safety-critical	No hidden receiver; high EIRP; resilient	🙂
Complexity	Diversity; low DC; high dynamic range	High threshold	😐
Time	Low DC and high rotation period	High threshold	🙁
Periodicity	High SM; mobile systems	Predictability of most radar systems	😐
In-band sensing	No UL/DL separation	Some exceptions (e.g. secondary radar)	😐
Spatial SOs	High SM; diversity	No hidden receiver; radar robustness	😐
Temporal SOs	Complexity; diversity	Predictability; protects mobile and intermittent systems	😐

The discussion regarding the adequacy of spectrum sensing in radar bands is summarized in table VI.

C. *Cooperative Sensing*

Cooperative sensing is not envisaged to be as attractive for radar bands as it is for TVWS, due to the absence of the hidden node problem in these bands. However, it can still bring some benefits, such as a reduction the local sensing time and periodicity of each CR node or providing an extra margin of protection to safety-critical systems, namely ARNS.

The discussion regarding CSS specifications in radar bands is provided next, and summarized in table VII.

a) **Cooperative gain** – The cooperative gain is low in radar bands due to the absence of the hidden receiver problem. The fast fading caused by the constant radar beam motion creates temporal diversity between local sensing samples and reduces the gains obtained through cooperation.

b) **Density of SUs** – Considering radar stations' long ranges, the required density of SUs to perform cooperative sensing is not high.

c) **Overhead** – Radar bands' radio environment is fairly static, due to these systems' fixed positions and parameters and low density of deployment. There are, however, some exceptions such as airborne radionavigation or frequency hopping systems. The time spent sensing could be significantly lower if CRs shared some of the information obtained through sensing. For instance, a CR through cooperation could get information from other SUs, regarding the antenna scan periods of the radars in its surroundings, and schedule its sensing intervals to match the instants when their main beams point at it.

d) **Identification of spatial spectrum opportunities** – As individual SS results are not affected by the hidden node problem in the radar bands, the use of hard combining rules (e.g. AND and counting rules) would increase the occurrence of the exposed node problem, leading to waste of spatial spectrum opportunities. CSS would also not address some of the SS limitations, such as the determination of the required threshold to protect each different radar system a CR might coexist with.

TABLE VII
COOPERATIVE SENSING SPECIFICATIONS FOR RADAR BANDS

Requirements	Cons	Pros	
Cooperative gain	No hidden receiver, fast fading	-	☹
Density of SUs	-	Large-scale PUs	☺
Overhead	High for mobile and frequency hopping systems	Predictability; low number; reduction of sensing time	😐
Spatial SOs	Exposed node; SS limitations remain unsolved	-	😐
Temporal SOs	-	Shorter sensing intervals	😐

e) **Identification of temporal spectrum opportunities** – By sharing sensing samples, the time spent by each CR performing sensing would be significantly reduced, which would allow a more efficient utilization of the spectrum.

D. Geolocation Database

Geolocation database represents an attractive spectrum access technique for the identification of spectrum opportunities in radar bands. In fact, it was proposed in the FCC's NPRM 2012 as the primary technique to protect military and Fixed Satellite Services (FSS) communications in the 3550-3650 MHz band from small cells operating on an opportunistic basis [44]. The FCC, in this report, proposed the division of this band into three tiers of services: (i) Incumbent Access; (ii) Priority Access; and (iii) General Authorized Access (GAA). The Incumbent Access tier would consist of authorized federal and legacy fixed satellite services, which would be guaranteed full protection from the remaining users. The Priority Access tier would be assigned to critical use facilities such as hospitals, utilities, government facilities and public safety entities with stringent QoS requirements. The GAA tier would accommodate users operating on an opportunistic basis in zones where their operation would not interfere with incumbent and priority access systems. Both the Priority Access and GAA users would be required to register in a Spectrum Access System (SAS), crucial to define this hierarchical three-tier spectrum use structure. This system would delimitate the incumbent and priority access users' exclusion zones based primarily on geolocation-enabled dynamic database techniques. The FCC is currently considering the implementation of these rules in the neighboring 3650-3700 MHz band, already used for commercial broadband services [45].

It is estimated that spectrum access techniques solely based on GL-DB will only allow approximately 40 % of the US population to benefit from the 3550-3650 MHz band [44]. The reason behind this low percentage is the fact that conservative exclusion zones of up to 450 km from the US shoreline will have to be defined to compensate for the Navy radar systems' long transmit ranges and unknown/unplanned locations. As also stated in [44], [46], the adoption of more agile spectrum access techniques, namely spectrum sensing, in conjunction with GL-DBs could significantly reduce this waste of spatial white spaces and, therefore, its deployment should be also considered.

Geolocation Database specifications:

a) **Registration of legacy systems** – Radar systems' position and relevant operational parameters can be available to the database. However, there might be strong opposition from some military systems to provide information to the database about their position or other classified information that make them more prone to be affected by enemy jammers.

b) **Complexity/processing power** – Most radar systems have fixed position and operating parameters. Radar systems placed on airborne and shipborne platforms, however, may not have pre-planned routes and, therefore, an error region has to be defined for such cases. Military radiolocation systems may also employ random frequency hopping techniques (ECCM), making their protection infeasible or inefficient using only the GL-DB technique. Radar systems usually have very long ranges, which reduces the required database grid resolution. From a security perspective, the database must be designed in a way that ensures that the classified information of, for example, military systems does not reach the general public.

c) **Consultation periodicity/maximum dissemination delay** – For the less dynamic and unpredictable scenarios, CR devices would only need to access the database a few times per year to be fully updated regarding changes in radar systems' parameters and positions. On the other hand, in the case of radar systems placed on mobile platforms, that operate on an intermittent basis or that employ frequency hopping techniques, the database would need to be consulted frequently in order for CR devices to check whether their emissions will cause harmful interference.

d) **Ability to recognize spatial spectrum opportunities** – The position and parameters of radar systems are usually fixed, well known and can be made available to the database. Depending on its capabilities, the database can receive information in real-time regarding the aggregate interference SUs' activity is inflicting on radar receivers and adapt the exclusion zones' size accordingly [13]. The limited database grid resolution does not represent an issue in radar bands due to these systems' very long ranges. However, conservative propagation models may need to be used in case of systems that concern safety-of-life (e.g. radionavigation). There might be also an interest, for security reasons, for military systems to not report accurate information about their position and operating parameters, which will reduce the efficiency of spatial sharing.
From a propagation perspective, it is challenging to set exclusion zones efficiently in these bands, due to the fact that radar systems' very long ranges make the path between them and CRs likely to be obstructed by buildings, terrain elevation or even as a result of the Earth's curvature. As shown in [42], a radar exclusion zone at 5 GHz is still far from being circular and is not easily

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TABLE VIII
GL-DB SPECIFICATIONS FOR RADAR SYSTEMS

Requirements	Cons	Pros	
Registration	Classified information	No uncertainty about PUs' parameters	😐
Complexity	ECCM, mobile radar, security	Planned, predictable; low grid resolution; low number	😐
Consultation periodicity	Mobile radars, ECCM: constantly	Fixed: few times per year	😐
Spatial SOs	High penetration losses; safety-critical; classified information	Low uncertainty about PUs' parameters	😐
Temporal SOs	Mobile radars; time dynamics; classified information	-	☹

predictable through theoretical propagation models if no considerations are made regarding the terrain elevation or other possible obstructions.

e) **Ability to recognize temporal spectrum opportunities** – Exploiting the radar antennas' predictable sweep patterns is infeasible using only GL-DB, due to the relatively fast rotation. To account for the mobility of radar systems placed aboard aircraft or ships, an error region must be defined. For example, in the case of a radar antenna aboard an airplane flying at 900 km/h and with a database consultation periodicity of 5 min., the error region radius would be

$$R_{err} = 900\frac{5}{60} = 75\ km. \tag{1}$$

Adding 75 km to the aircraft exclusion zones' radius would greatly reduce the amount of recoverable white spaces in ARNS bands in every country.

The previous discussion is summarized in table VIII, where it is evident the inability of a GL-DB to protect mobile PUs and its inefficiency at exploiting temporal spectrum opportunities.

E. Geolocation Database + Spectrum Sensing

An SU with SS capability can more efficiently exploit the spatial and temporal aspects of secondary access in radar bands than with a GL-DB, because it relies on real-time RF measurements of the signal path loss to infer the interference it causes to PUs, without being affected by the hidden receiver problem like in TVWS. However, it is technically challenging and complex for CR devices to extract information about radars' EIRP, sweep periodicity, main-beam to side-lobe ratio and modulation, based solely on SS results. A database-aided SS scheme, where information about the incumbents' technical parameters is provided to SUs by a centralized database, combines the best aspects of both techniques. Knowing in advance what types of radars are operating nearby, CR devices could adapt their detection thresholds, sensing intervals and algorithms and schedule transmissions when the radar main beam is not pointed at them. Some of this information, however, may not be open to the public when it concerns military radiolocation systems. The effect of the aggregation of interference could also be mitigated if radars reported to the database, in real-time, the level of interference they are being subject to and the database, based on these values, adapted the detection thresholds CRs should use [13].

A hybrid GL-DB+SS scheme could also be appealing in "low risk" regions, that is, areas sufficiently far away from any radar, where the chance of CR operation inflicting any harmful interference is pratically zero. A CR device located in one of these regions could be authorized by the database to not employ spectrum sensing, which would translate into higher throughput and reduced battery consumption, which is especially important for handheld devices.

F. Beacon Signaling

The deployment of the beacon signalling approach in radar bands has not yet received much attention in the literature, mainly due to the focus on GL-DB and DFS for these bands by regulatory entities [44] [42] [6]. Nonetheless, beacon signalling can still be employed in support of SS in the identification of radar systems' transmitting parameters and temporal spectrum opportunities, avoiding significant increases in CR devices' complexity.

Through some alterations in their structure, radar signals could carry information regarding their transmit power, gain, rotation period, modulation, pulse rate frequency, beam width, etc. Alternatively, radar systems could also send Channel Allocation Frames (CAF) between pulses that would be detected and used by opportunistic secondary systems to avoid transmission when the radar main beam is pointing towards them [47], [48]. If these data were transmitted at a power somewhat similar to the traditional radar pulse, they could be easily decoded outside these systems' exclusion zone (e.g. at a received power below -64 dBm for the 5 GHz band).

The description of how a beacon device would be designed and its costs and performance is described next and in table IX.

Beacon signaling specifications:

a) **Design limitations** – The beacons could be co-located with radar systems and transmit at a similarly high power. In order not to affect incumbents' operation, they could employ interference mitigation techniques based on:

- frequency separation using a dedicated channel;
- an additional antenna with non-intersecting pattern [39], which would ask CRs to interrupt their communications before being swept by the radar main beam;
- transmission between radar pulses inside the inter-measuring gap (IMG) [47], [48]; or
- transmission of low duty cycle asynchronous signals easily suppressed by radar systems through Interference Rejection (IR) techniques.

A beacon employing any of these techniques, on the other hand, would be complex, placing a significant burden on the incumbents. Furthermore, it would be challenging to design a beacon signaling mechanism compatible with all types of radar, so it could be unambiguously detected and decoded by CR devices, without the use of a separate control channel.

TABLE IX
BEACON SPECIFICATIONS FOR RADAR BANDS

Requirements	Cons	Pros	
Design limitations	High complexity design; diversity of incumbents	-	☹
Infrastructure costs	Complexity of radar systems	Few systems	😐
Spatial and temporal SOs	-	No hidden receiver; PU's information available; efficient control of aggregate interference	☺

b) **Infrastructure costs** – The number of radar systems is generally low. However, radar systems are expensive and highly complex systems, so changes in their infrastructure should be avoided.

c) **Identification of temporal and spatial spectrum opportunities** – CR devices would discern both spatial and temporal spectrum opportunities based on the energy and the coded data incorporated in the beacon signals. Considering that the beacon would be co-located with the radar system antenna, the hidden receiver problem would not be an issue. The main advantage of this SA technique, however, is that it enables a constant monitoring and control of the aggregate interference by the incumbents.

V. CELLULAR BANDS

Cellular networks offer to mobile phones in any location a wide range of services such as telephony, text messaging and Internet access, by virtue of an infrastructure of strategically located base stations or cell sites. These systems currently occupy a considerable portion of the spectrum, with a tendency to increase as new mobile standards are introduced into the market. Despite the large number of customers, studies reveal that cellular systems' spectrum occupancy is low in rural areas and during night time periods [16]. The studies in [11], [12], [16] also point out the underutilization of cellular uplink bands as a result of Internet traffic asymmetry and the base station's higher transmit powers and continuous transmission on the logical channels in the DL band.

In the long term, as the percentage of spectrum occupied by cellular networks increases and more technologies are introduced in the market, it becomes more challenging for operators to maintain the costly exclusive access to their spectrum [49]. On the other hand, conventional OSA in cellular bands is not as conceivable as it is in the TVWS and radar bands due to technical difficulties associated with the pervasive coverage, dynamic traffic patterns, the presence of different services with different QoS requirements and the fast adaptive power control of cellular systems [50]. In order for spectrum owners to keep control of the access to their spectrum and, simultaneously, ensure the maximum exploitation of their resources with no considerable service degradation, a more coordinated DSA approach, accomplished with the assistance of operators acting through spectrum brokers, has been suggested in the literature [51] [52] [53]. This would enable spectrum sharing between multiple operators and radio access networks and facilitate regulators' control of spectrum usage by providing support to SUs in the identification of spectrum opportunities.

According to this spectrum sharing framework, the unused frequencies inherent to cellular bands can be exploited by cognitive radio technology not just for the deployment of small-scale secondary networks, such as ad-hoc emergency networks or Machine to Machine (M2M) communication, but also for spectrum sharing among operators, to facilitate the repurpose and switchover (i.e. refarming) between different radio access technologies (RAT) (e.g. 2G to 4G), inter-band carrier aggregation, multi-hop relay and the deployment of low-power, self-configuring small cells [54] [50]. The concept of cognitive M2M (CM2M) communication in cellular bands has already been proposed in the literature, as a way to cope with the large amount of traffic generated by this type of services [55]. For intermittent, delay tolerant networks employed in group-based operations, with applications, for instance, in home multimedia distribution and sharing and healthcare remote monitoring, a CM2M network architecture, where the traffic of nodes, operating on a low-power DSA basis, is aggregated by a cluster head and forwarded to a cellular network, could provide an appealing solution to reduce the number of machines directly accessing the cellular access points, resolving most of the congestion issues inherent to this type of technology.

A. Radio Environmental Factors

a) **Uncertainty in PUs' parameters** – All cellular base stations (BS) are registered and the information about their locations and allocated carriers are usually public. Cellular networks also keep information regarding BSs and user equipment (UE) identification and resource allocation stored in database subsystems.

b) **Diversity of incumbent systems** – Cellular systems have well standardized features, namely maximum transmit power, channel bandwidth, modulations and carrier frequencies. Different technologies (2G, 3G and 4G) tend to operate in separate dedicated bands. On the other hand, some of these technologies employ adaptive modulation order and power control and may provide services with different quality constraints.

c) **Number of devices** – It is estimated that there are over 6 billion mobile phone users and 5 million mobile base station sites worldwide [56] [57]. The number of base station sites is expected to grow to more than 11 million by 2020.

d) **Planning** – Macro-cell base stations' center position, coverage and allocated carriers are usually planned ahead of time (although user-deployed femtocells are not). It is practically impossible to know in advance the spreading codes, carriers and timeslots in use by BSs and UEs due to the unpredictability of cellular traffic demand.

e) **Time dynamics and unpredictability** – Macro-cell BSs' allocated carriers remain unaltered for long periods of time. The BS and UE transmit powers, modulation and resource allocations, namely the spreading codes, carriers and timeslots in use at a certain instant of time in a certain cell vary rapidly and according to instantaneous demand.

f) **Mobility** – Macro-cell BSs locations remain unaltered for long periods of time. On the other hand, UEs' position varies in an unpredictable manner.

g) **Duty cycle (DC)** – The duty cycle is highly dependent on the user density and on the standard and, in particular, on the duration of each timeslot and frame. As shown in [16], BSs transmit more frequently due to the asymmetric nature of Internet data traffic, broadcast of signaling/control messages on a periodic basis and the fact that BSs may serve multiple UEs simultaneously.

h) **Resilience/Safety Margin (SM)** – The protection of commercial cellular bands from harmful interference is usually not crucial for public safety. There is, however, an increased interest in using 4G technologies for public safety applications [58]. Spread spectrum schemes employed in 3G networks, power control and frequency hopping techniques make cellular systems robust against interference.

i) **Susceptibility to fading** – Cellular site coverage is extensively studied by operators during the network planning stage. The wall penetration losses or other types of attenuation are highly dependent on the center frequency used and the environment where these systems operate. UEs are usually located at street level (at a height of approximately 1.5 meters), making their operation or detection very susceptible to fading in urban scenarios.

j) **Hidden receiver** – Relying on two-way communication, both the BSs and UEs can be detected in the downlink and uplink bands respectively. However, BSs have much higher transmit powers and transmit more frequently than UEs.

k) **PUs' scale/range** – As a base station can only serve a limited number of users, a cell's coverage radius drastically varies with the environment, going from more than 10 km in rural areas to 100 m in shopping malls and downtown streets.

l) **Recognizable features/hidden periodicities** – Signal features vary with the cellular technology. 3G technologies, in particular, employ direct-sequence spread spectrum (DSSS) schemes, making their signals decodable below the noise floor.

m) **UL/DL bands separation** – Most cellular systems employ Frequency Division Duplex (FDD) schemes to separate DL and UL traffic. Time-Division Long-Term Evolution (TD-LTE) is also a solution being currently considered by several providers.

n) **Aggregate interference margin (AIM)** – Base stations' and user equipment's isotropic antennas and large ranges in low fading rural environments make the aggregation of interference a relevant issue.

A summary of the cellular bands characteristics relevant to DSA is provided in table X.

TABLE X
RADIO ENVIRONMENTAL FACTORS OF CELLULAR BANDS

RE Factors	Commentaries	
PUs' parameters	BS information is available; UEs' ID and resource allocation is kept up-to-date in the cellular network infrastructure.	🙂
Diversity	Standardized features; systems may employ adaptive power control and modulation order schemes and provide services with different QoS constraints.	😐
Number of devices	Very widespread technology.	☹️
Planning, mobility and dynamics	BSs' carriers, position and coverage are fixed and planned in advance; UEs' operational parameters, position and allocated resources are not.	😐
DC	Dependent on the technology, user density and type of traffic; BS signals have higher duty cycles.	😐
SM	Usually not safety-critical; robust against interference.	🙂
Susceptibility to fading	High fading due to UEs' low altitudes; cellular site coverage is extensively studied by operators during network planning.	😐
Hidden receiver	Two-way communication; BSs more easily detected.	🙂
PUs' range	Cell size dependent on the density of users.	😐
Recognizable features	Dependent on the standard.	😐
UL/DL separation	FDD typically employed.	🙂
AIM	Isotropic antennas with reasonably high coverage.	😐

B. Beacon Signaling

There are several beaconing mechanisms proposed in the literature that facilitate CRs' process of getting knowledge about their radio environment with help from a ubiquitous infrastructure. These mechanisms include a Common Spectrum Coordination Channel (CSCC) [59], a Resource Awareness Channel (RAC) [60] and the Cognitive Pilot Channel (CPC) [53]. We highlight in this section the CPC approach not only for the many applications it can have, such as operator and RAT discovery and selection, identification of unused frequencies and reconfigurability of terminals' operational parameters, but also due to its attractiveness to operators, since it enables spectrum license holders to control the access to their spectrum [61]. Moreover, it can make spectrum sharing lucrative to operators by enabling them to dynamically lease their spectrum [61].

CPCs can be classified into two types: in-band CPC and out-of-band CPC. The out-of-band architecture is a physical channel outside the RATs' spectrum that transmits detailed information regarding existing operators, RATs and frequencies in a certain region to assist end-users in the selection of the most appropriate network to join [53]. Its main drawback is the fact that it requires an infrastructure of ubiquitous coverage and a worldwide harmonized frequency channel. While the regulatory issues concerning the implementation of an out-of-band CPC remain unsolved, [61] suggests the repurposing of the already established cellular infrastructure and the spare bits of their respective logical channels for the implementation of a operator-aided in-band CPC, referred to in this article as a Cognitive Beacon Channel (CBC). This approach would allow efficient spectrum coordination among primary and secondary users utilizing cellular bands, avoiding complications related to the CPC infrastructure cost, how this channel would retrieve information about the radio environment, and scalability issues, which affect more independent decision-making architectures [62]. CR devices would demodulate CBC signals on a periodic basis to obtain knowledge about their

TABLE XI
BEACON SPECIFICATIONS FOR CELLULAR BANDS

Requirements	Type	Cons	Pros	
Design limitations	In-band CPC	Slow network discovery	No dedicated band or infrastructure	😐
	Out-band CPC	Channel allocation; scalability issues without in-band CPC	Heterogeneous scenarios	😐
Infrastructure costs	Indepen-dent	Costly	-	☹
	Operator-aided	-	Repurposing cellular network infrastructure	🙂
Spatial and temporal SOs	-	-	Real-time coordination	🙂

radio environment and, in particular, which timeslots and carriers are available for secondary use in a certain region. In the long run, a worldwide out-of-band CPC will eventually be required in order for end-users to avoid the employment of time-demanding *rendez-vous* algorithms to detect in-band CPCs in heterogeneous scenarios (i.e. several operators and RATs in the same region) [53].

Beacon signaling specifications:

a) **Design limitations** – The operator-aided in-band CPC, also called CBC, does not require new regulation, dedicated infrastructure or worldwide harmonized frequencies, provided it is implemented and managed by the already established cellular systems. However, it would require that CRs be compatible with the RAT of the cellular system coordinating the access to its spectrum, which may only be possible with the market adoption of software-defined radio technology. As the environment becomes more heterogeneous (i.e. more operators, radio access and cognitive networks in the same spectrum), a worldwide harmonized out-of-band CPC may eventually be required to reduce the complexity, time and energy spent performing network discovery.

b) **Infrastructure costs** – The CPCs/CBCs, if managed by operators, can be implemented through the repurposing of cellular systems' ubiquitous infrastructure. This task is further facilitated by the mobile infrastructure market adoption of software-defined radio technology for BSs [63].

c) **Identification of temporal and spatial spectrum opportunities** – Although cellular traffic is very dynamic, a DSA scheme based on an operator-aided beacon channel would be able to perform efficient resource allocation to distribute spectrum opportunities between BSs, UEs and secondary devices. Information regarding the interference caused by each node to others in the network can also be obtained both through reported spectrum sensing results and geolocation information.

The specifications of a beacon channel in cellular bands that were previously discussed are summarized in table XI.

In order to efficiently assess the interference caused on PUs, CRs could not only use information regarding PUs' resource allocation in a certain cell, provided by a beacon channel, but also spectrum sensing or geolocation data to draw accurate UEs' and BSs' exclusion zones. In the following sub-sections, we analyze the adequacy of SS, CSS and GL-DB techniques with the assistance of a beacon channel (e.g. CPC), as a means to assess and mitigate the interference caused by SUs on PUs in cellular bands.

C. Spectrum sensing + beacon channel

Although conventional OSA is not envisioned in cellular bands due to the incumbents' ubiquitous coverage, and unpredictability of subscribers' traffic patterns, with the support of a beacon channel (e.g. CPC), spectrum sensing may still be a valuable tool since it provides real time information about the path loss between PUs and SUs. The CRs' sensing samples can also be utilized for spectrum management and resource allocation procedures, maximizing spectrum efficiency. The main aspects related to spectrum sensing deployment, using this more coordinated approach in cellular bands, are summarized in Table XII.

An estimation of the detection threshold for the protection of GSM, UMTS and LTE systems without the assistance of a beacon channel is provided in Appendix A. As shown, the employment of power control techniques makes the detection of UMTS UEs' signals challenging to perform in real-time. A more viable approach for sensing would be to adapt the CR's transmitted power and detection threshold on a regular basis, depending on the SINR values experienced by the PU receivers. To monitor these SINR values, the CRs need to overhear the primary BSs' periodic beacon and scheduling frames, transmitted through their logical channels [64]. With this knowledge about PUs' operational parameters, and experienced quality of service, CRs can then accurately estimate how much interference they cause to BSs and UEs.

There is no purpose in performing sensing for discerning the available subcarriers, timeslots and spreading codes at each cell in each instant of time, not only due to the technical difficulties associated with the detection of rapid, almost unpredictable oscillations in cellular traffic, but also because this information can be available to CRs through a CPC or the primary BS' logical channels.

D. Cooperative Sensing

The main benefits and drawbacks that stem from combining individual spectrum sensing samples are summarized in Table XIII. The UEs' short-ranges in urban environments, the absence of hidden receivers, and the spatial diversity created by UEs' mobility increases the exposed node occurrence and overhead and reduces the cooperative gain obtained through cooperative sensing algorithms. Hence, joint decision combining is not envisioned as an attractive technique in cellular bands. A better alternative would be to employ cooperative sensing to facilitate multiband or wideband sensing and, consequently, reduce the sensing time of each individual CR node [28].

TABLE XII
SS+CPC SPECIFICATIONS FOR CELLULAR BANDS

Requirements	Cons	Pros	
Threshold	Power and modulation order control; AIM; inter-cell interference	No hidden receiver; low SM; BSs' high EIRP; UEs' mobility	😐
Complexity	Time dynamics; power and modulation control	Low diversity of standards; high threshold for DL detection	😐
Time	Time dynamics; power control	Significantly lower for DL due to higher thresholds and DCs	😐
Periodicity	PUs' high density, unpredictability and mobility	-	☹️
In-band sensing	-	UL/DL separation	🙂
Spatial SOs	Power and modulation control; AIM and inter-cell interference	No hidden receiver; support from a CBC; low SM	😐
Temporal SOs	Time dynamics, mobility	Low diversity, support from the CBC	😐

TABLE XIII
COOPERATIVE SENSING SPECIFICATIONS FOR CELLULAR BANDS

Requirements	Cons	Pros	
Cooperative gain	UE mobility; no PU hidden receivers	BSs are static	☹️
Density of SUs	Small-scale PUs	-	☹️
Overhead	PUs' high number, unpredictability and mobility	Individual sensing periodicity can be reduced	😐
Spatial SOs	Small-scale PUs; no hidden receiver	-	☹️
Temporal SOs	PUs' high number, unpredictability and mobility; cooperative delay	-	☹️

E. Geolocation database

Geolocation capability coupled with database access does not represent a likely solution for opportunistic spectrum sharing in cellular bands for the reasons described in Table XIV, namely the unpredictability of cellular traffic, the ubiquitous coverage, the cell radius, which can be as low as 100 meters in urban scenarios, requiring a database of very high grid resolution, and the unavailability of information about UEs' location. Moreover, the information about BSs' resource allocation, position and identification is already managed in real time and stored in the operators' cellular database subsystems. Hence, it would be a more attractive option for PUs, SUs and regulatory bodies if the operators coordinated entirely the access to their bands instead of providing information about BSs' and UEs' parameters to a quasi-static centralized database. It is also still unclear whether geolocation databases will emerge as part of LSA in cellular bands. One possible application could be to exploit the underutilization of cellular spectrum during night periods to back-up data from customer premises to a secure location on a peer-to-peer link basis. These over night back-up systems or LSA licensees, by means of a GL-DB, would agree with the incumbents on sharing a certain frequency and bandwidth in a certain location and over a certain period of time. The incumbent, in turn, would ensure that the reliability of the licensee's service would be preserved.

TABLE XIV
GL-DB SPECIFICATIONS FOR CELLULAR BANDS

Requirements	Cons	Pros	
Registration	No information about UEs' coordinates	Aggregated data stored in cellular database subsystems	🙂
Complexity	Unplanned and dynamic traffic; high grid resolution requirements	BSs' static carrier allocation; data retrieved from cellular database subsystems	☹️
Consultation periodicity	UEs' resource allocation: continuously	BS carrier allocation and position: fixed	☹️
Spatial SOs	Limited database grid resolution and high fading in urban scenarios; no information about UEs' position	Low uncertainty about users' parameters and resource allocation; not safety-critical	😐
Temporal SOs	Unplanned, dynamic traffic; UEs' position not known to the DB	-	☹️

VI. TV BAND

In May 2004, the FCC announced the TVWS initiative, aiming to open some of the broadcast TV bands (470 MHz to 790 MHz) for license-exempt secondary use [4]. Several companies have shown their interest in this part of the spectrum for its exceptional propagation characteristics, suitable for the delivery of new communication services such as wireless broadband to underserved rural areas, enhanced Wi-Fi and Machine-to-machine (M2M) communications [5]. Studies estimated that up to 250 MHz of this band is available in most rural areas [65]. In more dense urban scenarios, multiple unoccupied 6 MHz channels can still be found.

A. Radio Environmental Factors

The two main incumbent systems operating in the broadcast band are Digital Terrestrial Television (DTT) and Wireless Microphone (WM) systems. There are several Digital Television standards, Digital Video Broadcasting-Terrestrial (DVB-T) being the most prevalent one. DTT signals are OFDM modulated with a 6 MHz and an 8 MHz channel bandwidth. Wireless microphones do not follow a single, common standard, but usually employ FM with a maximum of 200 kHz of bandwidth. Both these two incumbent systems and their characteristics that are relevant for assessing the feasibility of each SA technique are described next and summarized in tables XV and XVI.

TV systems:

a) **Uncertainty in PUs' parameters** – Information regarding TV stations' operation and position is available and open to the public. As for the receivers, in several countries, TV sets do not require a TV license and, therefore, it is impossible to know their whereabouts.
b) **Diversity of incumbent systems** – All DTT signals use OFDM, but they may employ different sets of pilot carriers, guard intervals and symbol sizes.

c) **Number of devices** – According to the FCC, as of December 31, 2010, there were a total of 1781 full-power, 522 Class A and 2191 low power TV stations on the air in the US [66]. The estimated percentage of U.S. homes with a television set (TV penetration) was around 96.7 % in 2011, according to Nielsen estimations [67]. By extrapolating these results to the rest of the world, it can be inferred that in general the number of TV sets per country is in the same order of magnitude as the number of homes.

d) **Planning** – TV stations' coverage area is intensively studied during network planning and deployment, and TV channel occupation is usually scheduled several hours, days or weeks in advance.

e) **Time dynamics and unpredictability** – TV stations in general have fixed operating parameters and their channels' utilization is also constant throughout a day, with the possible exception of switch on/off transitions at day/night periods. Information regarding TV channels' occupation schedule typically remains valid for more than one day.

f) **Mobility** – TV stations have fixed positions. DTT receivers, on the other hand, may be installed on mobile platforms.

g) **Duty cycle (DC)** – DTT signals are continuous.

h) **Resilience/Safety Margin (SM)** – TV systems usually do not concern safety-of-life applications.

i) **Susceptibility to fading** – The TV stations' low frequencies of operation and antenna placements at high altitudes (approximately 500 meters) lead to reduced wall penetration loss and fading effects.

j) **Hidden receiver** – It is practically impossible to identify the position of the TV receivers and the channels their respective owners are watching at a certain instant of time. The hidden node margin calculation for DTT has been exemplified in [8] [25]. The main factors considered in this margin are the misalignment of antennas (~7 dB), different indoor locations (~14 dB), wall penetration losses (~7 dB) and height losses between the DTT signal at the rooftop and at street level (~12 dB).

k) **PUs' scale/range** – Full-power TV stations have a transmit range of approximately 135 km.

l) **Recognizable features/hidden periodicities** – OFDM signals can be detected at very low SNRs through pilot-based or cyclic prefix-based detection.

m) **UL/DL bands separation** – No UL band.

n) **Aggregate interference margin (AIM)** – Considering TV stations' isotropic antennas and large coverage area, the aggregation of interference is considered a relevant factor in the TV broadcast band. The ECC has defined an aggregate interference margin between 3-6 dB depending on the number of White Space Devices (WSD) operating in a given area at the same time [10].

TABLE XV
TV SYSTEMS RADIO ENVIRONMENTAL FACTORS

RE Factors	Commentaries	
PUs' parameters	TV stations' position and parameters are known and open to the public; TV sets' ownership and location is not registered in several countries.	😐
Diversity	OFDM; different modes of operation.	😐
Number of devices	Receivers are widespread.	😐
Planning	Channel occupation is scheduled in advance.	🙂
Time Dynamics	Channel occupation is constant over time with a switch on/off period per day.	🙂
Mobility	TV stations have fixed positions.	🙂
DC	No signal interruptions.	🙂
SM	Do not concern safety-of-life applications.	🙂
Susceptibility to fading	Reduced fading and wall penetration loss effects; high ranges.	🙂
Hidden receiver	One-way communication; high range; height loss; antenna misalignment.	☹
PUs' range	High range.	🙂
Recognizable features	OFDM cyclic prefix and pilots.	🙂
UL/DL separation	No UL band.	☹
AIM	Isotropic antenna and large coverage area. AIM=3-6 dB.	😐

WM systems:

a) **Uncertainty in PUs' parameters** – It is estimated that the vast majority (around 3.5 million) of WM systems in the US are unlicensed [68]. Information regarding these systems' position, EIRP, channel and expected period of operation is generally not available.

b) **Diversity of incumbent systems** – There is no globally followed specification for the generation of WM signals, but they are usually frequency modulated (FM) with a maximum bandwidth of 200 kHz. The same WM may also emit signals with different transmit power levels and features depending on the profile in use (silent, soft or loud speaker).

c) **Number of devices** – WM systems are widespread, with around 1 million licensed users and 3.5 million unlicensed users in the US in 2011 [68]. Multiple WM transmitters tend to be present at the same venue.

d) **Planning** – While a large percentage of WMs are used at planned events such as concerts, conferences and sports events, the occurrence of unplanned program changes or breaking news events where WM use cannot be predicted ahead of time is not uncommon.

e) **Time dynamics and unpredictability** – Although WMs can operate intermittently [9], there is a common practice of leaving wireless microphones turned on throughout performances [69]. Updates in WM channel utilization schedule usually occur on a daily basis when used at planned events.

f) **Mobility** – WMs are less static than TV stations over a period of minutes; e.g. actors can enter and leave the stage several times during the same event. WM receivers, on the other hand, usually have fixed positions.

g) **Duty cycle (DC)** – WM signals are continuous.

TABLE XVI
WM SYSTEMS RADIO ENVIRONMENTAL FACTORS

RE Factors	Commentaries	
PUs' parameters	Several users have not registered their WM systems.	☹
Diversity	No standard specification; usually FM; several modes of operation.	😐
Number of devices	Widespread.	😐
Planning	Some WMs are used in an unplanned manner.	😐
Time Dynamics	Might be used intermittently. Updates occur on a daily basis for planned events.	😐
Mobility	WM receivers usually have fixed positions but transmitters do not.	😐
DC	Continuous carrier.	☺
SM	Do not concern safety-of-life applications.	☺
Susceptibility to fading	Reduced wall penetration loss effects due to low frequency. Highly susceptible to fading.	😐
Hidden receiver	One-way communication; short range; high body absorptions.	☹
PUs' range	Short range.	☹
Recognizable features	WM signals are easily mistaken for manmade noise.	☹
UL/DL separation	One-way communication.	☹
AIM	Low coverage.	☺

h) **Resilience/Safety Margin (SM)** – WM systems usually do not concern safety-of-life applications.

i) **Susceptibility to fading** – The low frequencies of the TV band lead to reduced wall penetration losses. On the other hand, WM systems can be deployed in several distinct environments (e.g. indoor/outdoor, urban/rural) and usually at relatively low heights, which makes their signals' propagation highly susceptible to fading phenomena.

j) **Hidden receiver** – Being a one-way communication system, the WM system receiver is not detectable through SS. From the fact that WMs have lower coverage areas than TV systems, one would suspect that the required hidden node margin considered for their detection would be lower. However, WMs are usually attached to humans and, therefore, their transmitted signals suffer high body absorptions (~20 dB) [8].

k) **PUs' scale/range** – Despite their maximum transmit power being 250 mW in UHF and 50 mW in VHF, due to battery life concerns, the transmit power levels typically used are around 10-50 mW. This leads, as a result, to a coverage area of approximately 100-150 meters.

l) **Recognizable features/hidden periodicities** – WM signals are easily mistaken for spurious tones originated by man-made noise.

m) **UL/DL bands separation** – One-way communication.

n) **Aggregate interference margin (AIM)** – WMs' low coverage does not make the aggregation of interference of multiple devices a critical factor.

B. Spectrum Sensing

The initial interest in spectrum sensing for the TVWSs stemmed from the fact that it would enable the protection of unregistered WM users whose operating parameters are not planned ahead of time or not available to a GL-DB. SS would also be an attractive solution for low-cost unlicensed devices as a way to avoid the need for an Internet connection or localization mechanism (e.g. GPS) to access the GL-DB. However, the conservative hidden node margins initially proposed by several regulators (~35 dB for DVB-T by OFCOM) not only made the deployment of this technique almost infeasible but also highly inefficient at recovering spectrum opportunities [8] [70].

Spectrum Sensing specifications for TV systems:

a) **Detection threshold** – The hidden node margins defined by regulators, despite all the other less conservative considerations regarding the amount of interference TV receivers could handle, have reduced the DTT detection thresholds to -114 dBm and -120 dBm for the FCC and OFCOM, respectively [8]. Other factors such as the cleanliness of the spectrum, receivers' noise figure or the aggregation of interference might hinder even further the detection of these systems at these threshold values.

b) **Sensing complexity** – DTT signals are well standardized and have intrinsic periodicities, namely pilot carriers and cyclic prefix, that are unambiguously detected through pilot-based or autocorrelation algorithms at low SNRs [71].

c) **Detection time/channel availability check time** – The high duty cycles and recognizable features of DTT signals can offset the required low detection thresholds, making these signals detectable in few seconds for the case of the FCC threshold (-114 dBm).

d) **Sensing periodicity** – TV channels' occupation is almost constant over time and space and, therefore, spectrum sensing only needs to be performed occasionally.

e) **Time dynamics and unpredictability** – To check TV channels' availability, CR devices need to interleave their normal operation with quiet periods devoted to in-band sensing or perform other techniques such as dynamic frequency hopping techniques, as suggested in [26].

f) **Ability to recognize spatial spectrum opportunities** – The fixed thresholds proposed by the FCC, OFCOM and ECC are very conservative and defined for worst case scenarios and, as a result, SS can only recover a limited amount of white spaces, especially when adjacent channels are also protected [70].

g) **Ability to recognize temporal spectrum opportunities** – TV signals are static and predictable and, therefore, this band's temporal spectrum opportunities can be efficiently exploited by a sensing device. There would be less temporal waste if CR devices were also able to detect which channels are actually being watched by primary users at close range. However, due to the fact that TV sets do not emit any easily detectable signal, this information cannot be gathered through sensing.

The main specifications of spectrum sensing for detecting digital TV systems are summarized in table XVII.

TABLE XVII
SS SPECIFICATIONS FOR TV SYSTEMS

Requirements	Cons	Pros	
Threshold	Hidden node and aggregate interference	No safety margin	☹
Complexity	Low threshold	Clear signal features, low diversity	😐
Time	Low threshold	DC=100%; clear features	😐
Periodicity	-	≈1 min	☺
In-band sensing	Only DL band	-	☹
Spatial SOs	Hidden receiver; aggregate interference	Low safety margin	☹
Temporal SOs	Hidden receiver	Predictability	😐

TABLE XVIII
SS SPECIFICATIONS FOR WM SYSTEMS

Requirements	Cons	Pros	
Threshold	Hidden receiver	No significant safety margins, low aggregate interference	☹
Complexity	Diversity; low threshold; not clear features	-	☹
Time	Low threshold	DC=100%	😐
Periodicity	≈1 to 60 seconds	-	😐
In-band sensing	UL/DL	-	☹
Spatial SOs	Hidden node margin, different EIRPs	Low safety and aggregate margins	☹
Temporal SOs	-	Generally not very dynamic	😐

Spectrum Sensing specifications for WM systems:

a) **Detection threshold** – The large hidden node margins defined for the protection of WMs by the FCC and OFCOM reduced their detection threshold to -114 dBm and -126 dBm, respectively, which is well below the noise floor [8].
b) **Sensing complexity** – The WMs' low detection threshold and diverse, not easily recognizable signal patterns hinders the design of sensing algorithms of low complexity.
c) **Detection time/channel availability check time** – Despite the low threshold, it is expected that WM detection will take some seconds, in general, due to their high duty cycle.
d) **Sensing periodicity** – There is disagreement in the literature about the time between scans for the detection of WMs. Some groups suggest an interval of 1-2 seconds to protect microphones that were just turned on, while others specify 60 seconds, considering the practice of leaving microphones turned on throughout performances [10] [8] [69] [9].
e) **In-band sensing** – In-band sensing is required.
f) **Ability to recognize spatial spectrum opportunities** – The conservative thresholds proposed for protecting WMs, that consider not only fading and the hidden node factors but also the undefined EIRPs of these devices, can lead to a large percentage of wasted spatial WSs.
g) **Ability to recognize temporal spectrum opportunities** – Spectrum sensing is a sufficiently agile mechanism to detect changes in WMs spectrum utilization, in case these systems are left on for several minutes or hours. For a more intermittent use of these devices, sensing may create some interference if not employed every second.

The main specifications of spectrum sensing for protecting WM systems are summarized in table XVIII.

C. Cooperative Sensing

Cooperative sensing specifications for TV systems:

a) **Cooperative gain** – Usually high, since CSS can significantly reduce the hidden node margins (~35 dB) defined for DTT detection. On the other hand, CSS fusion rules and censoring mechanisms may have to consider the impact of correlated shadow fading, significant in the detection of large-scale systems such as DTT.
b) **Density of SUs** – Considering TV stations' long ranges, the required density of SUs is not prohibitively high.
c) **Overhead** – TV stations' low number, lack of mobility, and predictability implies a low overhead incurred by cooperative sensing for the protection of these systems.
d) **Identification of spatial spectrum opportunities** – Cooperative sensing allows a reduction of the sensing hidden node margins, and taking into account the large-scale of TV systems, without making CRs' ability to discern spectrum opportunities being severely affected by the exposed node problem. A more efficient exploitation of the spectrum from a spatial perspective could be possible if the location and channel of TV sets was known to the CRs. However, it is impossible to gather this information solely based on CSS.
e) **Identification of temporal spectrum opportunities** – The CSS technique is agile enough to adapt to TV systems' spectrum occupancy changes over time. However, it cannot detect the channels each TV user is watching in a certain instant and location.

TABLE XIX
COOPERATIVE SENSING SPECIFICATIONS FOR TV BANDS

Requirements	Cons	Pros	
Cooperative gain	Correlated shadowing	Reduction of hidden node margin	😐
Density of SUs	-	Large-scale PUs	☺
Overhead	-	Predictability, static behavior; low number	☺
Spatial SOs	Hidden receivers	Large-scale PUs; reduction of the hidden node margin	☺
Temporal SOs	-	The same as SS	😐

In table XIX, the main specifications of CSS for the protection of TV systems are summarized.

Cooperative sensing specifications for WM systems:

a) **Cooperative gain** – WMs' slow mobility in specific

TABLE XX
COOPERATIVE SENSING SPECIFICATIONS FOR WM BANDS

Requirements	Cons	Pros	
Cooperative gain	PUs' mobility compensates for temporal fading	Low correlated shadowing, reduction of hidden node margin	☺
Density of SUs	Low-scale PUs	-	☹
Overhead	Considerable PU number and unpredictability	Low mobility	😐
Spatial SOs	Small-scale PUs	Reduction of the hidden node margin	😐
Temporal SOs	-	The same as SS	☺

applications creates spatial diversity between individual sensing samples taken by a CR over time, reducing the impact of multipath and making the gains obtained through CSS less attractive. On the other hand, CSS can be an efficient way to address the hidden receiver problem.

b) **Density of SUs** – Considering WMs' short ranges, the required density of SUs for their detection with significant cooperative gains would be high.
c) **Overhead** – The mobility of WM users, in general, is low enough to not require frequent channel availability checks. The large number of WMs and unpredictability of their spectrum use, however, can increase the number of cooperative operations (e.g. SS samples reports) and, consequently, the energy consumption of CRs.
d) **Identification of spatial spectrum opportunities** – CSS can lead to a reduction in the WMs' detection threshold hidden node margins. However, WMs' short ranges (e.g. 100-150 m) require high densities of cooperative CR users to avoid the exposed node problem [33].
e) **Identification of temporal spectrum opportunities** – Similar to SS.

In table XX, the main specifications of CSS for the protection of WM systems are summarized.

D. Geolocation Database

The inability of SS to overcome the large hidden node margins imposed for detecting both DTT and WM systems made the FCC drop its requirement in 2010 and focus solely on GL-DB [5]. Everything seems to suggest that GL-DB will also be the preferred interference avoidance mechanism for the TV band in the rest of the world [8] [10]. With the intent to promote competition in the delivery of this new service, several entities have been designated as TV band database administrators in the US - Comsearch, Frequency Finder Inc., Google Inc., KB Enterprises LLC and LS Telcom, Key Bridge Global LLC, Neustar Inc., Spectrum Bridge Inc., Telcordia Technologies, and WSdb LLC [72]. This multitude of database administrators may, however, raise some technical challenges, since it is required for all databases to be coordinated and provide the same information regarding channel availability. In order not to prevent low-cost systems from exploiting the TVWS, the FCC classified White Space devices (WSD) into three categories: fixed and Mode II devices, with location awareness and direct access to the centralized database through Internet connection, and Mode I devices, which get information about their radio environment from devices of the other two types. The specifications of a GL-DB in the TV band is described next and summarized in tables XXI and XXII.

Geolocation Database specifications for TV systems:

a) **Registration of legacy systems** – Information regarding TV stations' position and parameters is usually open to the public and, therefore, employing GL-DB does not require changes to DTT infrastructure.
b) **Complexity/processing power** – The number of TV stations per country is low and updates in their channel utilization schedule occur sporadically and are planned ahead of time. Considering TV stations' long ranges, several regulators have decided that a reasonably low database grid resolution of 100 m x 100 m would be sufficient to enable efficient spatial sharing. As a counterpoint, these long ranges also contribute to a significant increase in the number of computations and the number of grid points updated by the GL-DB, every time an alteration is made to a TV station's operation. For instance, for a station with an exclusion zone radius of 155 km and a GL-DB grid resolution of 100 m x 100 m, the spectrum occupancy would have to be computed for more than 7.5 million GL-DB grid points.
c) **Consultation periodicity/maximum dissemination delay** – WSDs do not need to consult the database more than once per day to check for updates in TV channel usage.
d) **Ability to recognize spatial spectrum opportunities** – The GL-DB technique is relatively reliable at predicting TV systems' coverage areas as a result of these systems' low susceptibility to fading and long ranges, when compared to the database grid resolution employed (e.g. 100 m x 100 m). The exclusion zone around each TV station must be large enough to compensate for the unknown location of TV receivers (hidden receivers).
e) **Ability to recognize temporal spectrum opportunities** – There would be less temporal waste of WSs if TV sets had the capability to report to the GL-DB their position, the channel they are currently tuned to and the interference they are being subject to. Based on this information, the database would then draw exclusion zones around the TV receivers to protect them from interference. It would be, however, impossible for the GL-DB and SUs to cope with the fast transition between channels of most users. The GL-DB architecture should, therefore, focus on the TV broadcasters' channel occupation, as this data is available, planned in advance and has slow variations over time.

Geolocation Database specifications for WM systems:

a) **Registration of legacy systems** – The major obstacle to the deployment of GL-DB methods to protect WMs is the fact that several users of this service have not yet

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

TABLE XXI
GL-DB SPECIFICATIONS FOR TV SYSTEMS

Requirements	Cons	Pros	
Registration	-	TV stations are registered	🙂
Complexity	Long range	Planned; not dynamic; low number; low grid resolution	😐
Consultation periodicity	-	Planned: ≤1x per day	🙂
Spatial SOs	No information about TV sets' location (hidden receivers)	Low uncertainty on BSs' parameters; low penetration losses; large scale; not safety-critical	😐
Temporal SOs	TV receivers' channel usage unplanned and unknown	TV stations' spectrum utilization planned and not dynamic	😐

TABLE XXII
GL-DB SPECIFICATIONS FOR WM SYSTEMS

Requirements	Cons	Pros	
Registration	Majority of WMs are unregistered	-	☹
Complexity	Dynamic	Short range; planned events; low number; low DB resolution	🙂
Consultation periodicity	Unplanned: minute by minute basis	Planned: 1x per day	😐
Spatial SOs	Short range; low antenna height; deployed in different environments	Low wall penetration losses; not safety critical	😐
Temporal SOs	Time dynamics	Sometimes used at planned events	😐

registered their devices. The solutions proposed to solve this impasse are to complement geolocation with other spectrum access techniques such as spectrum sensing and beacon signaling or to allocate a safe harbor channel dedicated to unregistered WM operation [73]. Registered WM systems, on the other hand, can register their operation in the database in advance to guarantee their protection from harmful interference.

b) **Complexity/processing power** – By virtue of a safe harbour, the registration in the GL-DB is only reserved to a relatively low number of registered WMs whose spectrum utilization schedule is planned in advance. Furthermore, the WMs' short ranges make computing WMs' exclusion zones a less significant burden to the database, compared to the TV systems case. However, updates in their channel utilization also occur more frequently.

c) **Consultation periodicity/maximum dissemination delay** – WSDs will need to consult the database at least once per day to check for updates in WM channel usage. This update frequency is not adequate, however, to protect WMs in case of casual or unplanned use. In order to cover these scenarios, other more agile techniques such as SS or a safe harbour channel may be necessary.

d) **Ability to recognize spatial spectrum opportunities** – The derived WM systems' exclusion zones are conservative to compensate for these systems' high susceptibility to fading and their small scale as compared to the database grid resolution proposed for this band (100 m x 100 m [10]). However, WM systems do not require large safety and aggregate interference margins.

e) **Ability to recognize temporal spectrum opportunities** – WM spectrum usage can be usually planned ahead of time. However, in contrast to TV systems, their operation is more dynamic and unpredictable.

E. Beacon Signaling

Beaconing specifications for TV systems:
To protect TV systems, the authors in [3] suggest placing a receiver beacon device (RB) connected to each TV receiving antenna. The RB would emit a carrier tone signaling the channel that is currently being watched by the PU. At the cost of increased primary systems' complexity, the TV band spectrum efficiency could be increased since secondary devices would be able to operate in occupied TV channels in the absence of TV users watching these channels nearby.

TABLE XXIII
BEACON SPECIFICATIONS FOR TV SYSTEMS

Requirements	Cons	Pros	
Design limitations	Dedicated channel for transmission, EIRP<0.25 mW	-	😐
Infrastructure costs	Widespread, unregistered sets and legal issues	-	☹
Spatial SO	-	No hidden receiver	🙂
Temporal SO	-	Signals the channels being watched	🙂

a) **Design limitations** – The beacon would operate as a Part 74 device, at a maximum transmit power of 250 mW. A dedicated channel might be required for beacon transmission. In case the beacon device operates as an area beacon (AB), it must access the GL-DB to get information regarding TV channel utilization.

b) **Infrastructure costs** – TV systems are widespread, so the deployment of receiver beacons in every receiving TV set antenna would be too costly. Furthermore, the placement of a beacon device in each household would require authorization by the owner.

c) **Ability to recognize spatial spectrum opportunities** – Beacons placed close to TV receiver antennas would solve the hidden receiver problem that affects the detection of these systems.

d) **Ability to recognize temporal spectrum opportunities** – Beacons placed close to TV receiving antennas would enable CR devices to detect which TV channels are being watched around them at a given time.

The challenges to the design of the beacon devices previously described are summarized in table XXIII.

Beacon specifications for WM systems:
Several groups have proposed the use of a beacon device as a way to overcome the difficulties associated with the detection of WM systems through either spectrum sensing or geolocation in the case of unplanned events [74] [75].

a) **Design limitations** – The beacon would operate as a Part 74 device, at a maximum transmit power of 250 mW

TABLE XXIV
BEACON SPECIFICATIONS FOR WM SYSTEMS

Requirements	Cons	Pros	
Design limitations	EIRP<0.25 mW; as an AB, the beacon must access the GL-DB	Does not need a dedicated TV channel	😐
Infrastructure costs	Widespread, unregistered WMs	Solution: Safe harbor channel	😐
Spatial SO	-	No hidden receiver	🙂
Temporal SO	-	Only turned on during WM utilization	🙂

[75]. The beacon can operate both as a receiver beacon, signaling the presence of a WM receiver nearby, and as an area beacon, also transmitting information regarding the occupancy of other TV channels in the region. The latter would require an Internet connection and localization mechanism to access the GL-DB. Decoding the AB signal information would also increase CRs' overhead and, therefore, should be left at the discretion of the SU [75]. The beacon signal can be transmitted in the TV channel occupied by the WM it protects, since each WM only occupies a very small portion of this channel. In Appendix A, the required beacon signal detection threshold for a CR with transmit power of 1 W and bandwidth of 8 MHz to avoid WM service degradation is estimated to be around -103 dBm. An additional margin still needs to be considered to account for the impact of small-scale fading. The size of this margin, however, will also depend on how frequently sensing is performed.

b) **Infrastructure costs** – WM systems are widespread, so the deployment of receiver beacons in every WM receiver would be costly. Furthermore, several users have not registered their WM systems and, therefore, need to be protected through spectrum sensing or need a safe harbor channel for operation.
c) **Ability to recognize spatial spectrum opportunities** – Beacons placed close to WM receivers would solve the hidden receiver problem.
d) **Ability to recognize temporal spectrum opportunities** – Beacons would be turned on before and during WMs' operation in order to ensure that CR devices detect the presence of these systems ahead of time.

In table XXIV, the specifications of a beacon device for the protection of WM users are briefly summarized.

VII. SIMULATION ANALYSIS: THE RADAR CASE

From the previous band by band analysis, we consider that the radar spectrum displays numerous features that make it one of the most appealing bands for regulators, in their goal to establish OSA. Differently than for the TVWS, an efficient exploitation of radar white spaces with limited impact on the incumbents' infrastructure and operation may only be achieved through a hybrid database-aided sensing scheme. In this section, we summarize the results of an initial simulation analysis of the combined use of GL-DB and SS in these bands.

A CR complying with this scheme schedules its operation time as shown in figure 7. During the initial sensing stage, the CR searches for radar emitters within interference range through threshold comparison, and discerns their antenna motion and radiation patterns. Considering the periodicity of the detected scan patterns, the CR can then predict the available temporal opportunities, and allocate them for transmission/reception (Tx/Rx). SS still needs to be performed at the instants of potential interference, such as when the radar main beam is pointing at the CR receiver, to keep the SU updated and synchronized with the radar antenna rotation.

Depending on the amount of a priori information CRs will get about their environment from the database, we can define three different scenarios: limited, moderate and full database support. For the first case, the CR applies a simple envelope detector that identifies radar pulses through sudden variations in the received signal level. The algorithm then groups the detected pulses based on their centre frequency and width, and fits them into a pulse train sequence of constant PRF. For the moderate database support case, the CR employs an autocorrelation detector algorithm, requiring a priori knowledge about every radar emitter's centre frequency, bandwidth, PRF and pulse width, within range. For the full support scenario, the CR detects radar pulses through a matched filter, shaped to the exact waveform of the received radar's pulses.

In figure 8, we show the performance of the three detectors, for a linearly frequency modulated radar signal with a PRF of 1000 Hz, and pulse width of 28 μs, using a CR receiver bandwidth of 20 MHz, and a sensing window of 11 ms of duration. The probability of detection was simulated for different pulse powers (P_{Rx}) in dBm, and their respective pulse peak SNRs ($PSNR_{Rx}$), measured at 20 MHz, and considering only thermal noise. As can be seen, with a priori incumbent data, the performance of spectrum sensing has considerably improved. There are two main reasons why such a discrepancy was observed. First, matched filter and autocorrelation are much more sophisticated than envelope detection based algorithms. Second, for the limited database support case, the CR does not know a priori within which frequencies the radar signal is contained, and, therefore, it has to sense for its whole bandwidth of operation.

For both the moderate and full database support cases, the database may also provide information regarding the radar antenna scan type (e.g. circular, sector, helical, raster), scan period, and radiation pattern. This will significantly reduce the number of times the CR needs to be swept by the radar main beam to be able to discern future temporal opportunities, i.e., it will lead to reductions in the sensing times.

VIII. CONCLUSIONS AND FUTURE WORK

The choice between spectrum sensing, geolocation database and beacon signaling techniques for exploiting WSs is closely interlinked with the radio environment where a CR device operates. Despite the clear preference for geolocation database over other methods in the TV band, spectrum sensing with the assistance of a database may represent the most efficient solution to exploit the spectrum holes in radar bands, considering radar systems' high predictability and transmit power and the absence of a hidden node problem in these bands. Beacon signaling, on the other hand, seems more appropriate for the

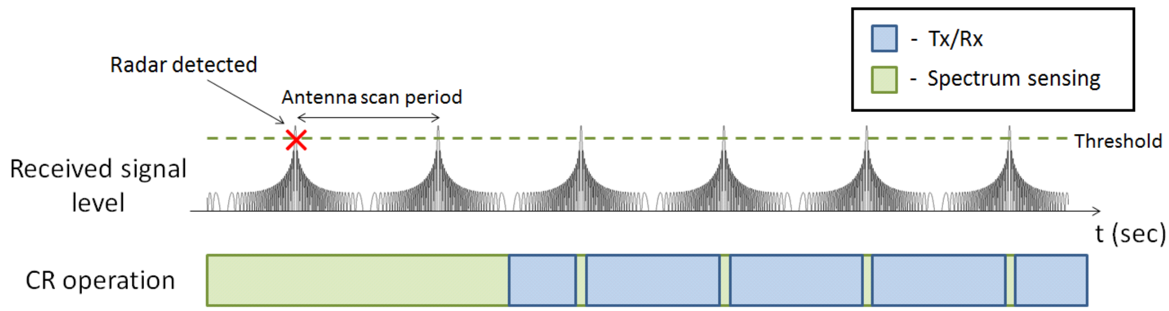

Fig. 7. Illustrative view of the exploitation of temporal opportunities derived from a radar antenna rotation.

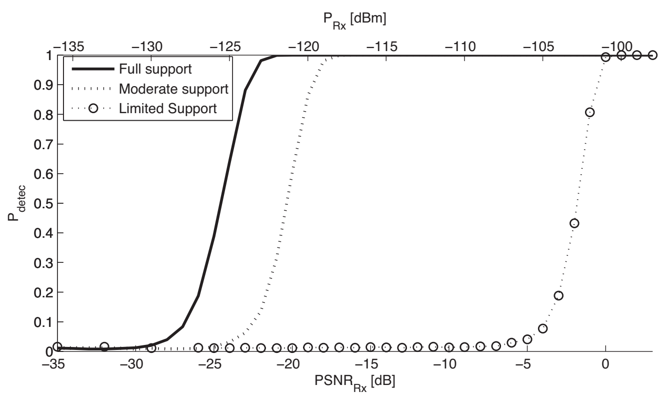

Fig. 8. Probability of detection vs PSNR for a linear frequency modulated radar signal, for the cases of full, moderate and limited database support.

cellular bands, as it provides enhanced spectrum coordination between devices and can be implemented using the already established cellular infrastructure and the spare bits of the logical channels of such systems.

We analyzed three of the bands where DSA is considered most promising: radar, cellular, and TV. Taking into account that radar systems inefficiently utilize almost fifty percent of the spectrum deemed relevant for spectrum sharing, we conclude that, as future work, further studies should be made regarding the implementation of a database-aided spectrum sensing scheme and the exploitation of temporal spectrum opportunities in these bands. We also expect the methodology followed in this paper to be extended to other parts of the spectrum, such as satellite bands, to evaluate whether their characteristics are adequate for CR deployment.

Appendix A

In this section, we calculate some of the required thresholds to be adopted by CRs to protect PUs from interference. It should be stressed that the values obtained here are just rough estimations with the intent to provide a more quantitative view of the CRs' required sensitivity. The detection threshold required to avoid interfering with primary systems can be determined based on the two following equations [8]:

- **Interfering link** – The level of interference the CR device can cause on the primary receiver without service degradation ($I_{max}|_{PU}$):

$$I_{max}|_{PU} > P_{CR} G_{PURx} G_{CRTx} \frac{B_{PU}}{B_{CR}} A_{PURx} \tag{2}$$

  where P_{CR}, G_{CRTx} and B_{CR} are the power, gain and bandwidth of the CR, G_{PURx} and B_{PU} the gain and bandwidth of the primary receiver and A_{PURx} the path loss from the CR to the primary receiver, due to many effects, such as free-space loss, refraction, diffraction, reflection and absorption. The ratio B_{PU}/B_{CR}, in Eq. 2 is employed as an approximation of the percentage of the CR's transmission power that is contained in the PU's channel and that, in effect, causes interference to this user.
- **Detection link** – The PU signal received at the CR must be above the threshold T^0_{min} to be detected.

$$T^0_{min} < P_{PU} G_{PUTx} G_{CRRx} A_{PUTx}. \tag{3}$$

  where P_{PU} and G_{PUTx} are the power and gain of the primary transmitter, G_{CRRx} the antenna gain of the CR receiver and A_{PUTx} the path loss between the primary transmitter and the CR device.

For the case of PUs that transmit and receive (i.e., in the absence of hidden receivers), the assumption of reciprocity of the path loss between CR and PUs can be made (i.e., A_{PUTx}=A_{PURx}, G_{PUTx}=G_{PURx} and G_{CRTx}=G_{CRRx}). Combining the interference and detection link equations, the threshold (T^0_{min}) can be then expressed as follows,

$$T^0_{min} < I_{max}|_{PU} \frac{P_{PU} B_{CR}}{P_{CR} B_{PU}} \tag{4}$$

In Table XXV, the detection threshold (T^0_{min}) is estimated for some of the incumbent systems analyzed throughout this work using equation (4). Additional margins have yet to be considered to provide extra protection to safety-critical systems (SM) and to account for other factors, such as the inter-PU's interference (PUIM), the aggregation of interference of multiple CR users (AIM), antennas losses or any parameter in equation (4) that is not perfectly known by the CR user. For Frequency Division Duplex (FDD) and low mobility systems, it may be also important to consider the impact of small-scale fading or multipath (Δ_{MP}) that affect the PUs' transmitted and received signals differently, i.e., when the channel reciprocity assumption $A_{PUTx} = A_{PURx}$ is no longer accurate. Based on these margins, which are represented in Table XXV as low (L) or high (H), the final threshold for the CR device (T_{min}) would be obtained.

TABLE XXV
THRESHOLD CALCULATION FOR SEVERAL COMMUNICATION SYSTEMS

Parameter	WM Beacon	DME		UMTS		GSM		LTE	
		RB	IB	UL	DL	UL	DL	UL	DL
$I_{max}\|_{PU}(dBm)$	-115	-99	-107	-110	-102	-123	-111	-116.4	-97.5
$P_{PU}(dBm)$	26	54.8	63	[33, 43]	[-50, 21]	[37, 46]	[5, 39]	[26, 46]	[-40, 23]
$B_{PU}(MHz)$	0.2	1		5		0.2		[1.4, 20]	
$P_{CR}(dBm)$	30								
$B_{CR}(MHz)$	8	20							
$T^0_{min}(dBm)$	-103	-61	-61	[-102, -92]	[-176, -105]	[-96, -87]	[-116, -82]	[-109, -89]	[-162, -102]
Δ_{MP}	H	L	L-H	L-H	L-H	L-H	L-H	L-H	L-H
SM	L	H		L		L		L	
$PUIM$	L	H	L	H		L-H		L-H	
AIM	L	H	L-H	L-H		L-H		L-H	

A. Examples of Incumbent systems

- **WM Beacon** – The main WMs' specifications were taken from [10]. Considering the beacon's static and non-line-of-sight position, a considerable margin has to be defined to compensate for multipath fading.
- **DME** – The authors of [76] suggested a margin of 12 dB for the DME interrogators and transponders, to account for the fact that DME is a life-critical system (SM) and for the potential interference caused by other systems such as UMTS that operate close to this band (PUIM). Considering the fixed positions of the DME transponders, which, in turn, increases the impact of fading in their detection through SS, and the fact that DME interrogators are more prone to aggregate interference as a consequence of their altitude, the final threshold values T_{min} for the DME reply (RB) and interrogation bands (IB) need then to be significantly reduced compared to T^0_{min}.
- **Cellular systems:**
  - **GSM** - The required thresholds were measured for a macro-BS receiver and mobile station with a sensitivity of -114 dBm and -102 dBm, respectively, and a minimum carrier to interference ratio (CIR) of 9 dB before service degradation [11].
  - **UMTS** - In [12], the authors estimated that a 1 dB increase in the noise floor at the UMTS receivers causes a negligible degradation in the capacity and coverage of UMTS cells. This value was deduced considering the underutilization of the cellular uplink bands (half-load) and the impact of inter-cell interference. The maximum interference caused by CR users at PUs can then be derived from this value through the following equation,

$$I_{max} = 10^{\frac{N_0+1}{10}} - 10^{\frac{N_0}{10}} \quad (5)$$

    where N_0 represents the noise floor of the PU receiver.
  - **LTE** - The required thresholds were measured for a macro-BS receiver and mobile station with a sensitivity of -123.4 dBm and -106.4 dBm, respectively, and a minimum SINR of -7 and -9 dB before service degradation [77] [78].

As seen in Table XXV, the threshold for cellular bands highly depends on whether a power control scheme is employed. For instance, a UMTS UE transmitting at the minimum power of -50 dBm would require a detection threshold of -176 dBm, which is practically impossible to apply using modern CR technology. Additional margins need yet to be added to this value to account for the inter-cell interference, aggregate interference of multiple SUs and multipath that may affect differently the uplink and downlink bands.

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