Database-aided Sensing for Radar Bands

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Abstract—Radar bands have been suggested as one of the most promising candidates for spectrum sharing, as they occupy a considerable amount of spectrum, despite their usage efficiency being generally low. Although geo-location database and dynamic frequency selection were chosen by regulators as the preferred methods for enabling the coexistence between radar systems and low-power devices, these methods’ static nature and lack of flexibility may not enable an efficient utilization of this spectrum. In order to overcome this issue, we propose in this article a hybrid spectrum access technique, called database-aided sensing. We describe and test the ability of this technique to discern both spatial and temporal spectrum opportunities that arise from circularly and sector scanning radars. The obtained results were encouraging, taking into account the sensitivity levels required to protect radar systems, even when the database awareness about the radio environment is limited.

I. INTRODUCTION

With the intent to tackle the problem of scarcity of spectrum, regulators in the US and Europe have started to turn their attention to spectrum sharing in the radar bands, which would allow secondary users (SUs) to access spectrum opportunities, or so-called white spaces (WSs), in these licensed bands. Particularly promising candidates include the L, S and C bands, between 960-1400 MHz, 2.7-3.6 GHz and 5.0-5.850 GHz, respectively, as they occupy altogether more than 2 GHz of the spectrum that regulators consider the most attractive for sharing [1] [2] [3]. In addition to this, radio frequency (RF) measurements show that their occupancy is very low, usually under 5%, and reasonably static throughout a day period [4].

The appealing features of radar bands have already led some countries to open parts of the S and C bands for wireless broadband services [5]. The C band currently accommodates Wireless Local Area Network (WLAN) devices that coexist with radars on a co-primary basis. To avoid causing harmful interference, WLAN systems need to employ a rather simplistic Spectrum Sensing (SS) mechanism, called Dynamic Frequency Selection (DFS) [6] [7]. On the other hand, for the 3.5 GHz band, FCC suggested the deployment of a spectrum access authorization method that uses a geo-location database (GL-DB), as a primary WS detection technique [5].

Despite both DFS and GL-DB being able to provide adequate protection to radar systems, they leave a large percentage of the radar spectrum underutilized [1] [5]. For instance, they ignore the temporal WSs derived from radar mobility, highly directive antennas and predictable sweep patterns. To tackle this, more sophisticated spectrum access techniques should be designed. As an example, a cognitive radio (CR) could utilize the spectrum at a close distance from a radar station, by interrupting its transmissions whenever the radar antenna beam is pointing at it. This would require the CR to discern the main characteristics of the radar antenna radiation and scan patterns based on the signal level oscillations its constant motion creates. However, taking into account the wide diversity of features radar systems may display, and the fact that a CR may receive signals from more than one station at the same time, this temporal sharing mechanism may be technically challenging when relying solely on sensing. For this reason, we propose in this work a new spectrum access technique called database-aided sensing, where SU devices’ cognitive abilities are complemented with a priori incumbent-specific parameter information provided by a centralized database.

In Section II, we present the main types of radar systems deployed in the S, C and L bands, and we briefly analyse the main techniques proposed in the literature to detect WSs and identify radar emitters. Sections III, IV and V are dedicated to the database-aided sensing approach and, in particular, to the description of its main design features, scenarios of usage, and some of the techniques that it may incorporate to detect WSs. In Section VI, we provide initial simulation results to assess the proposed technique feasibility in some of the sharing scenarios encountered in radar bands. The main conclusions are drawn and the future work is proposed in Section VII.

II. STATE-OF-THE-ART OF DSA IN RADAR BANDS

A. Radar - The incumbents

Radar systems find application in almost any area or service that requires object detection, localization and recognition, in particular, in aeronautical and maritime radionavigation, weather forecast and radiolocation. Despite the basic operating principle being the same, this wide range of applications makes radar specifications very diverse, even for systems within the same band of operation [1].

In the L, S and C bands, the most prevalent types of radar are primary monostatic imaging systems, with pulsed waveform. These systems, with co-located transmitters and receivers, send directional pulses of electromagnetic energy and, through the returning echoes, detect the presence, position, and motion of objects. The emitted pulse trains (PT) can be mainly characterized based on Pulse Repetition Frequency (PRF) or Interval (PRI), Pulse Width (PW), Centre Frequency (CF), Intrapulse Modulation (IPM), and frequency hopping pattern in the case of frequency agile systems. Some examples of IPMs, namely, Pulsed Carrier (PC), Linear Frequency Modulation (LFM) and Phase Modulation (PM), are illustrated in figure 1. Radar systems, depending on their application, can also employ different beam and scanning patterns, as the ones shown in figure 2. With the exception of tracking systems, the
radar antenna constant motion creates a signal level oscillation pattern at the CR, whose repetition interval is constant over time and matches the radar antenna scanning period (ASP).

**B. Spectrum Sensing in radar bands**

Sensing as a way to avoid causing interference to radar systems has already been proposed and implemented in the 5 GHz band for WLAN devices, through DFS [6] [7]. Before initiating transmission, a system complying with DFS checks the channel availability by seeking pulses with peak power above -64 dBm in a time interval of 1 minute. This required sensing sensitivity level (-64 dBm or higher) or detection threshold (DT) is well above the noise floor, as a result of the radars’ typically high transmit powers and the absence of hidden node problems for the case of monostatic systems. As the channel availability check time (CACT) of 1 minute may not be enough to detect some helical rotating radars, the WLAN device has to keep performing RF measurements during its normal operation through an in-service monitoring scheme.

The main disadvantage of DFS is that it lacks the flexibility of modern CR techniques. First, it completely ignores the temporal aspect of spectrum sharing. Second, incumbent detection is accomplished using a one-size-fits-all DT and CACT, both dimensioned for worst case scenarios [1], which leads to unreasonably large exclusion zones and long sensing times.

**C. Geo-location database in radar bands**

The employment of GL-DB schemes as a dynamic spectrum access (DSA) enabling technology to protect military radar bands in the 3.5 GHz band from interference caused by small cells has been proposed by the FCC in 2012 [5]. Considering that most Navy systems, the main incumbents of this band in the US, have very long ranges and their positions are generally unknown to the public, a distance from the US shoreline of up to 450 km was proposed as exclusion zone [5]. This would only allow approximately 40% of the US population to benefit from WSs in that band.

**D. ELINT: what can be learned?**

Although temporal sharing in radar bands is a relatively unexplored research topic, some of its challenges are similar to the ones commonly found in Electronic Warfare (EW). Electronic Intelligence (ELINT), one of the key elements of EW, involves the interception and analysis of radar emissions to obtain information regarding enemy systems’ capabilities [8]. In ELINT, intercepted signals are characterized based on a wide range of parameters, such as pulse waveform, Angle of Arrival (AOA), and scan pattern, and then compared to the parameters of several radar models stored in a database, so the radar type can be recognized and the appropriate countermeasures of jamming and/or decoys can be initiated. A CR could adopt some of these parameter estimation techniques to distinguish and isolate PTs emitted by different stations, and discern the WSs each of them independently creates.

Figure 3 illustrates a typical architecture of an ELINT system. The pulses of the intercepted radar signals are detected and their respective parameters or pulse description words (PDW), namely AOA, PW, CF and time of arrival (TOA), measured. Pulse sorting is then initiated through a clustering algorithm that separates the detected pulses into clusters or classes according to their respective set of PDWs. The pulses of each cluster/class are then fit into sequential patterns, allowing the estimation of their PRF/PRI, a process called TOA deinterleaving. Ideally, at the end of the pulse sorting stage, each individual radar emitter’s PT and its respective PDWs have been successfully identified. Based on the variations over time of each PT’s amplitude, the ELINT estimates the radar antenna radiation pattern (ARP), ASAP and scan type. Finally, all the estimated parameters of each radar emitter are sent to the database to be analysed and the type of radar recognized.

In order to maximize the number of emitters identified, ELINT systems’ hardware is typically of very high complexity, designed to operate over very wide frequency ranges (e.g. 100 GHz) and dynamic ranges (e.g. 140 dB) and still able to detect signals at relatively low Signal-to-Noise Ratios (SNR) [8]. Although these capabilities are practically unachievable with a low-cost CR, the CR’s job is simpler than that of a typical ELINT system. Rather than focusing on classification and localization of all radars in a certain region, CRs’ main goal

![Fig. 1. Different types of pulse waveforms utilized by radar systems.](image1)

![Fig. 2. Types of antenna scan patterns and their signal level variation over time from a CR receiver’s point of view.](image2)

![Fig. 3. Possible architecture for an ELINT system adapted from [8].](image3)
consists in the protection of radars from potential interference, which can be achieved through spectrum sensing with a DT well above the noise floor (e.g. see the DFS case [6][7]), performed for a range of frequencies limited to the CR bandwidth of operation (e.g. 20 MHz).

III. DATABASE-AIDED SENSING

With the intent to solve the limitations of conventional DFS and GL-DB schemes in radar bands, we propose in this work the use of an hybrid spectrum access technique, called database-aided sensing. CRs, complying with this scheme, initiate their operation by first querying a centralized GL-DB about spectrum availability in their surroundings. The GL-DB, based on the reported CR’s location, band of operation, and transmit power, searches for radars within interference range, and sends their respective parameters back to the CR. These parameters may include each radar’s pulse waveform, ASP and required DT to protect it from interference. The CR then utilizes this information to configure its SS algorithm, optimizing its detection performance, and enabling a more efficient identification of WSs.

In military bands, there seems to be little motivation for incumbents to share their system-specific information with a GL-DB that targets the civil use of their spectrum. For these cases, the database-aided sensing method seems more suitable to spectrum sharing between radars and other military radio devices. Another possibility would be for the radar systems’ parameter information to be gathered through local sensing by CRs and sent back to the database to support other CRs in the identification of available WSs in a certain region.

A. CR operation modes

The centralized database will have a central role in SUs’ accreditation and spectrum access authorization, managing and limiting the aggregation of interference from multiple devices, and in defining in which manner, or CR mode of operation, the CR should detect and access WSs. Depending on the CRs’ hardware capabilities, the incumbents’ features and database’s awareness about the radio environment, we envision four main CR modes of operation. These are:

1. No exploitation of WSs allowed. This may happen when the CR is geographically deep inside one of the incumbents’ exclusion zones, or in exceptional scenarios, such as in emergency situations or system malfunction.
2. No exploitation of temporal WSs. Possible scenarios of occurrence may be when the radar displays unpredictable scanning patterns (e.g. tracking systems), there are passive incumbents nearby ( bistatic systems ), or the degree of support provided by the GL-DB is not enough for the CR to discern temporal WSs by itself.
3. Exploitation of the WSs provided by radar predictable sweep patterns. With the support of the database, the CR is able to identify temporal WSs.
4. Free exploitation of WSs. The CR is not located inside any radar exclusion zone and the band only accommodates systems with static position, making sensing redundant as the channel will always be free.

B. Degree of Database Support

Depending on the extent of the database’s awareness about the radio environment, we define three possible scenarios:

- Limited support: The database, in this scenario, will only be able to provide very limited non incumbent-specific information for a specific band and region, such as minimum and maximum values assumed by PW, PRF, and ASP, and minimum CACT. It will be the CR’s role to estimate through signal processing techniques the radar main parameters and to identify WSs.
- Moderate support: CRs receive data from the database regarding some of the operating parameters of the incumbents within interference range. This data could be each emitter’s ASP, PW, PRF, CF, bandwidth, and some considerations regarding the radar mobility and frequency agility. The CRs use this information to employ more advanced sensing techniques, based on autocorrelation or cyclostationarity. Moreover, the a priori knowledge about the ASP enables significant time savings, as the estimation of this parameter solely through sensing is usually time-consuming, requiring that the radar antenna’s main beam sweeps each CR receiver multiple times.
- Full support: The data received by the CR is enough to enable the employment of matched filtering techniques, achieving optimal sensing performance. On the other hand, it will also lead to higher overhead and complexity, as it requires the database to send large quantities of data and that the SU has highly reconfigurable circuitry to adapt to the type of signal to detect. In addition to the parameters provided in the moderate case, in this scenario, the database could also send each radar’s IPM, ARP, and scanning motion type.

In the following sections, we focus our analysis on WS detection for the third CR mode of operation, where temporal sharing is enabled, and for any of the previous database support scenarios. Spectrum sensing in any of these cases can be divided into two main stages: detection of radar PTs, and estimation of the respective scanning and radiation patterns. The first stage concerns the detection and identification of systems within interference range. In order to do so, the CR isolates the received PTs based on parameters, such as CF, IPM, PW, and PRF, estimated or provided by the database. Beam and scan analysis is then performed on each individual PT to identify, through the variations on its pulses’ amplitude (PA) over time, or equivalently through the obtained sensing test statistics (A[\text{}]), the respective radar’s ASP and ARP. Once the scanning patterns of all the incumbents in the radio environment are identified, the CR can then define the moments when interference may occur based on the intersection of the WSs provided by each individual emitter.

IV. DETECTION OF PULSE TRAINS

Contrarily to the TVWS case, spectrum sensing in radar bands is mainly based on the detection of very short pulses, with peak SNRs well above 0 dB, which reduces the impact of noise uncertainty. More emphasis is given, on the other hand, to the distinction of different radar emitters, whose transmitted PTs arrive superimposed to the CRs. Another important difference compared to the TVWS is the fact that the CRs receive the radar signals in short bursts, as a result of the radar antenna...
We propose employing the Generalized Likelihood Ratio Test (GLRT) approach, described in [10] for OFDM signals, using PRI as the sample value product lag parameter and as the interleaved average size, and PW as the sliding window size. In this work, we chose to implement the algorithm proposed in [8] [9].

A. Limited database support

With no a priori knowledge of the incumbent parameters, the CR distinguishes signals from different emitters through parameter estimation techniques similar to those employed in the context of ELINT. This procedure is done in three stages: pulse detection, pulse clustering and TOA deinterleaving. In general, in ELINT, only AOA, CF and TOA are used in most pulse sorting algorithms, as they can be much more reliably estimated. However, for a CR with an omnidirectional antenna, it is practically impossible to predict the AOA and, therefore, this parameter will not be used in the sorting algorithms analysed in this work.

1) Pulse Detection: For the limited database support scenario, an envelope detector that recognizes a rise(fall) of a pulse, when 4 contiguous samples are above(below) the threshold, \( \gamma_R(\gamma_F) \), is employed. To reduce the effect of sharp transitions caused by noise and multipath, we smooth the received signal a priori with an averaging window of size 3. The PW, PA and TOA are obtained by counting the number of samples, measuring the mean amplitude, and marking the start of each detected pulse. The PW is then compared with the \( PW_{\text{min}} \) and \( PW_{\text{max}} \) parameters, specified by the database, to check whether the pulse is valid. For a pulse with rise and fall times at the samples \( n_R \) and \( n_F \), the CF is obtained as follows,

\[
CF = \frac{f_s}{2\pi} \arg \left( \sum_{n=n_R}^{n_F-1} x[n] \cdot x[n+1]^* \right)
\]

where \( x[n] \) is the received signal and \( f_s \) is the sampling rate.  

2) Clustering: We employ a simple distance-based clustering algorithm that takes PW and CF as input PDWs. The test checks whether a pulse \( P_i \) belongs to a cluster \( C_k \), by calculating the distance between its \( PW_i \) to the mean \( PW_k \) of the cluster, and comparing it with a threshold.

3) TOA deinterleaving: A vast amount of work can be found in the literature regarding TOA deinterleaving for ELINT [8] [9]. TOA deinterleaving is initiated for each cluster of pulses \( C_k \), by first finding a PRI candidate based on the difference between pulses’ TOA. This step is then followed by sequence searching that looks for PTs that match the candidate PRI. Once a PT is successfully found, it is extracted from \( C_k \) and the TOA deinterleaving process is restarted for the remaining pulses in \( C_k \). This loop only stops when it is not possible to form a sequence with the remaining pulses.

In this work, we chose to implement the algorithm proposed in [9], as it can cope with staggered and jittered PRF signals, and has relatively low complexity, an appealing feature for CRs.

B. Moderate database support

As the CR does not receive information about the radar IPM, autocorrelation sensing methods are preferred for this scenario.

C. Full database support

When in the possession of the IPM data, the CR may employ matched filter techniques to optimize its sensing performance. Considering a radar with a normalized pulse shape \( p[n] \), the following parameter is calculated,

\[
R[n] = \sum_{k=0}^{K-1} |(x \ast h)(n + kPRI)|^2, \quad n = 0, ..., \text{PRI} - 1
\]

where \( x[n] \) is the received signal, \( T_W = K \cdot \text{PRI} \), the sensing window size, and \( h[n] = p[-n]^* \) the filter response. The final test statistic \( \Lambda[m] \) is obtained by calculating the maximum \( R[n] \) value and normalizing it by the energy of \( x[n] \).

For both the moderate and full support cases, a sequence of test statistics \( \Lambda[m] \) is obtained for each PT, whose PRI and \( p[n] \) are specified by the GL-DB. To avoid the need of perfect time-synchronization with the radar, the integration of pulses is performed in an incoherent manner, as shown in (2).

V. ANTENNA BEAM AND SCAN ANALYSIS

For each radar’s PT (\( PT_i \)), identified through any of the sensing techniques described in the previous section, a sequence of test statistics \( \Lambda_{PT_i}[m] \) is generated. The CR initiates temporal WS detection by first ensuring, through comparison of the peak \( \Lambda_{PT_i}[m] \) with a DT, that the emitter of the \( PT_i \) is within interference range. In case the result is positive, the CR proceeds to scan analysis, where it obtains a candidate ASP, that matches the \( \Lambda_{PT_i}[m] \) period. This step is then followed by beam analysis where the antenna radiation pattern \( ARP_i[\theta] \) is obtained by searching for bursts in \( \Lambda_{PT_i}[m] \) that fit into a sequence of period \( ASP_i \). For the moderate and full database support scenarios, some of these steps can be skipped, as the ASP and ARP information may be already provided by the GL-DB. The phases of potential interference within one single ASP with each emitter (\( \phi_i \)) can be calculated as follows,

\[
\phi_i = \arg_{\theta=0,...,\text{ASP}_i-1} \Phi \left( \text{ARP}_i[\theta] > \gamma \right)
\]

where \( \gamma \) is the DT specified by the GL-DB. The CR then schedules its transmissions in order to avoid the instants of time belonging to the union of the sets \( I_i \) obtained as follows,

\[
I_i = \left\{ m \in \mathbb{N} : |\phi_i + k\text{ASP}_i - m| < \xi \right\}, \quad k \in \mathbb{N}
\]

where \( \xi \) is a time interval margin defined to compensate the propagation delays or other uncertainties.

Considering its omnidirectional antenna, the CR is not able to distinguish azimuth from elevation scanning, which may hinder the estimation of both the ASP and ARP for radars with pencil-shaped beams. To address these scenarios without spending prohibitive amounts of time performing sensing, the ASP value should be provided by the database.

A. Scan analysis

The presence of side-lobe bursts or non-circular scan patterns may hinder the reliable estimation of the ASP. This issue is further exacerbated when several radar emitters, whose signal deinterleaving during pulse sorting was not successful, are contained in the same PT. With these challenges taken
into consideration, the period estimation technique suggested in [11], based on the average magnitude difference function (AMDF), was employed. In order to reduce its computational complexity, the AMDF values are only calculated for the lag parameters that match the time differences between the bursts in $A_{PT}[m]$ with the highest amplitude.

B. Beam Analysis

Contrarily to the ELINT case, beam analysis in CRs with fixed transmit power is not focused on the accurate identification of the ARP, but on the prediction and transmission interruption for periods of time, or angles, when the radar signal power crosses the DT specified by the database. The advantage of simple DT comparison over full ARP estimation is the fact that it can minimize the effect of limited dynamic range, as long as the DT is situated in the CR’s linear region of operation. The CR can estimate the ARP[$\theta$] for each PT$_i$ as follows,

$$\text{ARP}[\theta] = \frac{1}{M} \sum_{k=0}^{M-1} \sqrt{A[\theta + (k+1)\text{ASP}]A[\theta + k\text{ASP}]} \tag{5}$$

for $\theta = 0, ..., \text{ASP} - 1$ and $M = \left\lfloor \frac{\text{CACT}}{\text{ASP}} \right\rfloor - 1$, where CACT is the total time that the CR spends sensing, and $A[\cdot]$ the sequence of test statistics obtained for each detected PT.

VI. Simulation results

For our simulations, we considered a CR with an omnidirectional antenna, operating over a bandwidth of 20 MHz. For comparison purposes, for all the detectors, the sensing window size ($T_{dW}$) was set as 1.1 ms, equal to the dwell time of a fast rotating radar with an ASP of 4 seconds and beamwidth of 1°.

A. Scenarios of analysis

In this work, we focus our analysis on imaging primary monostatic radar systems, employing PC or LFM as IFs, with constant PRF, and with fan beams and circular and sector scanning patterns. This choice was based on the prevalence of this type of systems over the alternatives in the bands of interest for DSA (e.g. L, S and C), and on the simplicity their detection imposes on CRs, ideal as a first test for the database-aided method. In table I, the radar PTs used during the simulations are described.

<table>
<thead>
<tr>
<th>Scenario Separation</th>
<th>PTI type</th>
<th>PT2 type</th>
<th>baseband frequencies (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CF</td>
<td>II</td>
<td>[−4, 4]</td>
</tr>
<tr>
<td>2</td>
<td>PRI</td>
<td>II</td>
<td>[0, 0]</td>
</tr>
<tr>
<td>3</td>
<td>PW</td>
<td>I</td>
<td>[0, 0]</td>
</tr>
</tbody>
</table>

In figure 5, the ratio between the Root Mean Squared Error (RMSE) of PRI and PW and their actual values is displayed for each parameter’s worst case estimation scenario. It is clear that the RMSE does not tend to zero for the PW case, especially for the PT I, which has the shortest pulse. This is a direct consequence of the smoothing step taken during the pulse detection stage that alters the shape of the radar pulses. This error, however, is deterministic and can be compensated. The PRI estimator, in turn, has poor performance for PSNRs below 9 dB, which can be explained by the tendency conventional period identification algorithms have to detect sub-harmonics of the real signal’s period. In figure 6, the estimated CF for all
As shown, all the detectors managed to predict and avoid any interference, with a rate of wasted opportunities below 2%. In this article, we proposed database-aided sensing as a promising technique to exploit both temporal and spatial WSs in radar bands. For the case the database is able to provide data regarding radars’ pulse waveforms and ASPs, incumbent detection is possible at PSNR levels below the noise floor, and significant time savings are obtained to discern temporal opportunities. For the limited database support case, the bottleneck of the CR performance is the PT parameter estimation and deinterleaving technique, necessary to distinguish signals from different radar stations. Nevertheless, all the obtained results were still found adequate, considering the high DTs, specified for radar bands. Numerous challenges still remain to be addressed, regarding the deployment of the proposed technique. The architecture of the database, with all the functionalities described, needs yet to be designed and tested to prove its feasibility. Moreover, the assessment of spectrum sensing performance is still required for several other scenarios, such as for non-constant PRF and frequency hopping signals, and non-circular and non-sector antenna scan motions. Another possible research direction could be to complement the analysis made in this work with experimental results, to assess the performance degradation caused by limited dynamic range or propagation phenomena, such as multipath.

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