Is Spectrum Sharing in the Radar Bands Commercially Attractive? - A Regulatory and Business Overview

Evanny Obregon, Ki Won Sung, and Jens Zander

***Abstract*—The need to meet users' expectations in the "mobile data avalanche" represents a significant challenge for mobile network operators (MNOs). More spectrum is a natural way to meet these requirements in a cost and time-efficient way; but new, exclusively licensed, spectrum is increasingly hard to come by. Instead, vertical spectrum sharing has been discussed as a potential solution for finding additional spectrum. In this paper, we focus on vertical spectrum sharing in the radar bands for providing short-range wireless access, e.g. indoors and in hotspots that "offload" traffic demand. We propose a methodology for analyzing the technical, regulatory and business aspects of deploying large-scale wireless networks. Then, we identify the following criteria for achieving business success: spectrum availability, availability of low-cost end-user devices, system scalability in terms of number of concurrently used devices, and finally the ability to guarantee a quality of service for the users. Our technical availability assessment has identified geo-location database as the necessary technical enabler and detect-and-avoid mechanism as an auxiliary enabler for improving sharing conditions. Moreover, Licensed Shared Access (LSA) was found to be the suitable regulatory framework to support the proposed sharing mechanism and regulatory policies in real-life implementation. Our business feasibility assessment concludes that there is enough spectrum available for indoor and hotspots communication in urban areas in the radar bands to make a large scale system commercially viable. Service quality can be guaranteed and there is a strong potential to construct low-cost devices. Uncertainties do, however, remain regarding the spectrum access cost.**

I. Introduction

The unprecedented success of mobile services has resulted in the exponential growth of wireless data traffic. The substantial traffic increase is expected to continue in the coming years with the proliferation of high-end handsets [1]. There is a widespread concern about the shortage of available radio spectrum to fulfill the future demand, which is dubbed as spectrum deficit [2]. Secondary spectrum access or vertical spectrum sharing, referring to the sharing of already-licensed but under-utilized radio spectrum while protecting incumbent systems, has emerged as a practical means to address the perceived spectrum scarcity [3].

Although the concept of vertical spectrum sharing has been studied extensively from theory to practice in the last few years, most of the practical work has focused on a specific portion of spectrum, i.e., VHF/UHF band primarily allocated to digital terrestrial television (DTT) so-called TV white spaces (TVWS) [4]–[7]. This means that the vast amount of radio spectrum remains unexplored with regard to the potential of the vertical sharing. ITU spectrum allocation table indicates that the majority of frequency bands below 6 GHz are allocated currently to various systems such as aeronautical navigation, radar, satellite, and fixed link. Significant research efforts will have to be spent to investigate the viability of vertical sharing to those spectrum bands. Besides the studies on TVWS, only a handful can be found on radar and aeronautical spectrum. See, e.g., [8]–[11].

Our previous work showed that there are ample sharing opportunities for the deployment of ultra-dense networks (UDNs) in the radar bands, both above and below 10 GHz (e.g. S- and Ku-Bands) [12]. However, as claimed in [13], the fact that vertical spectrum sharing is technically feasible does not necessarily guarantee its commercial success. Whether the deployment of large-scale wireless networks employing vertical spectrum sharing in the radar bands can really happen or not is a multi-dimensional problem which includes technical, regulatory and business aspects. Therefore, we aim at answering the following research questions:

- *What are the main factors that would facilitate business success for mobile broadband communication in the radar bands?*
- *Is there a suitable regulatory framework that can ensure the protection of the incumbent system and still provide enough spectrum for vertical sharing to make it commercially interesting?*

In this work, we limit the scope of mobile broadband to indoor and outdoor hotspot communications providing high-capacity services in relatively short ranges where traffic demands are extremely high. UDNs consisting of low-power access points are of particular interest.

We can find substantial literature that studied individual aspects of vertical spectrum sharing: technical, regulatory, and business aspects. For example, fundamental limits of the vertical sharing were investigated in [14], [15], the regulatory and policy aspects were discussed in [16], [17], and the business side was looked into in [18], [19]. However, it is difficult to find a cross-boundary study. Thus, the main contribution of this paper is to establish a well-defined methodology for dealing with the technical, regulatory and business aspects of deploying large-scale wireless networks with vertical spectrum

E. Obregon, K.W. Sung (corresponding author), and J. Zander are with the Department of Communication Systems, KTH Royal Institute of Technology, Stockholm, Sweden, e-mail: ecog@kth.se, sungkw@kth.se, jenz@kth.se.

This article is accepted for publication at Transactions on Emerging Telecommunications Technologies (ETT) in June 2015.

sharing. Moreover, this methodology is tailored to the radar bands which has not been sufficiently addressed.

The remainder of the paper is organized as follows: the methodology for assessing technical, regulatory and business aspects that can make vertical spectrum sharing in the radar bands attractive is explained in Section II. Section III focuses on defining business cases and identifying key factors that impact its business success. In Section IV and Section V, we give a detailed technical description of the sharing usage scenario, sharing mechanism and technical enablers, which are essential inputs for selecting the regulatory framework in Section VI. Finally, the business feasibility analysis is provided in Section VII and our main findings are discussed and summarized in Section VIII.

II. Methodology

Towards assessing the commercial viability of sharing opportunities in the radar bands, we propose the methodology illustrated in Fig. 1. This methodology includes technical, regulatory and business aspects which are needed to make an assessment whether vertical spectrum sharing in the radar bands can take-off or not from the commercial point-of-view.

We first describe a business case by identifying the main actors, problems and value proposition. Based on a clearly defined business case, we establish the key factors that would facilitate business success. These factors are the evaluation criteria for the business feasibility analysis. Also, based on the characteristics of the business case, we model the vertical sharing scenario that will be employed for technical spectrum availability assessment. Another input to the technical assessment is the regulatory environment, such as sharing mechanism and spectrum etiquettes. Notice that the results of the assessment will depend strongly on the selected regulatory policies.

As a next step, we identify the most suitable regulatory framework (i.e. licensing regime) for enabling vertical spectrum sharing in the radar bands. This evaluation is made in a systematic manner by employing a spectrum sharing toolbox proposed within the EU FP7 METIS project, which allows to have a direct mapping between technical enablers, spectrum sharing scenarios and regulatory framework [20]. First, we start by defining the vertical sharing scenario and the sharing mechanism to then identify the tools or enablers that make this scenario feasible from the technical point-of-view. Later, the regulatory framework is chosen to bring the selected policies to real-life implementation. The selection of suitable regulatory policies are based on their impact on the exploitation of sharing opportunities. More detailed explanation on the the different components of the toolbox can be found in [20].

Finally, we proceed to qualitatively assess the business potential of the selected vertical sharing scenarios by employing the defined evaluation criteria and the results of the availability assessment, which includes technical and regulatory aspects.

III. Identifying Factors for Business Success

In this section, we identify and discuss different factors that would facilitate business success for UDNs for indoor and outdoor hotspot communications providing high-capacity broadband services in the radar bands. These factors will depend highly on a particular business case, which is defined by the type of actors that provides the service, their pains or problems and the specific value proposition. Here, we select a business case which is detailed in the following:

- Main Actors: An *existing MNO* who has a strong incentive to offer significantly higher capacity to satisfy *their customer's* demands in indoor and hotspots locations. We consider the MNO in this study based on the argument in [18] that a new entrant does not have a competitive edge over the existing MNO for deploying in shared spectrum.
- Problem: The MNO needs a solution that offers the best cost-performance trade-off since it has already been *challenged by the revenue gap* which refers to a discrepancy between soaring mobile data demand and dwindling revenue increase.
- Value Proposition: Mobile broadband communications in the radar bands *offloading traffic demands in indoor and hotspot* environments where the volume is extremely high.

In order to analyze the potential of the business case, we need to identify the different factors that could influence business success, or in other words *what the radar bands should offer.*

- **Enough Spectrum Availability** is required to alleviate the increasing data demand in current MNOs networks in indoor and hotspot locations.
- **Availability of affordable radio technology** is crucial for estimating when the solution can be deployed and how much cost it will generate. Particularly, the availability of low-cost end-user devices is important for reaching mass adoption. A plausible solution would be to utilize existing devices with minor modifications that will not have a significant impact on the total cost.
- **System Scalability** is also essential for motivating investments. Moreover, given that this solution is proposed for alleviating the high capacity demand, then system scalability is a must.
- **Guaranteed quality of service** should be provided in order to attract investments given that other best-effort alternatives, e.g. WiFi, are available for free of spectrum cost. Thus, there is a need to establish a regulatory framework that could guarantee quality of service in the radar bands.

IV. Sharing Usage Scenario

In this section, we provide a brief of description of the selected sharing usage scenario which is conformed by the characteristics of the incumbent system and the newcomer.

A. Radar systems as Incumbent

Radar is an acronym for radio detection and ranging. The basic operation principle of the radar consists of generating pulses of radio frequency energy and transmitting these pulses

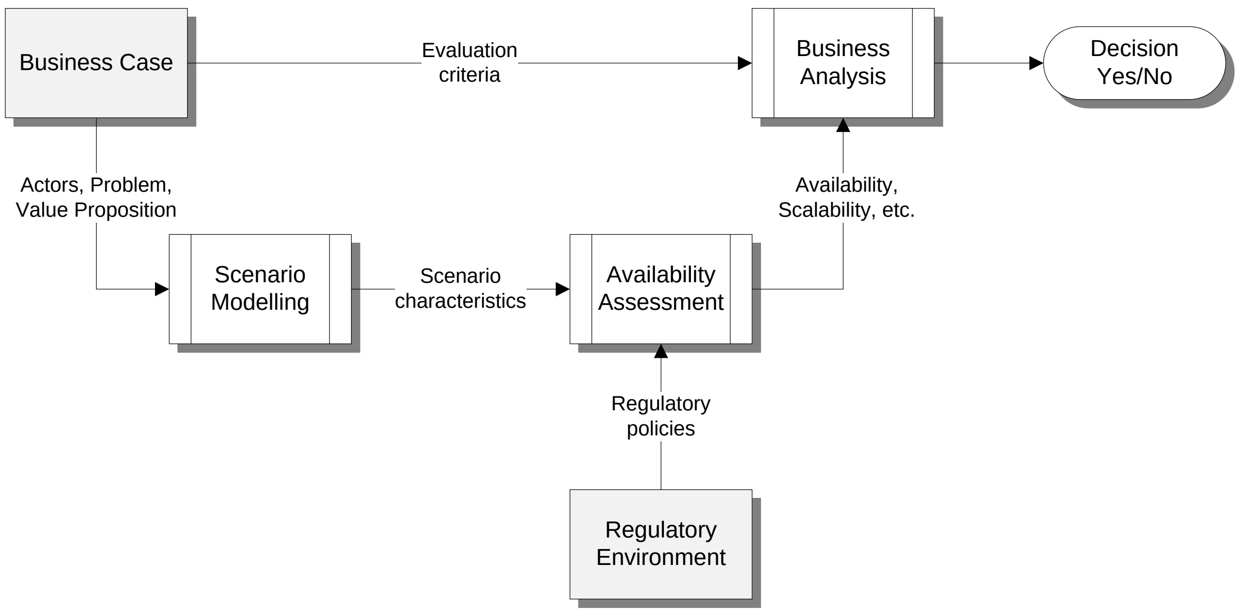

Fig. 1. Methodology for Assessing Sharing Opportunities

via a directional antenna. The radar indicates the range to the object of interest based on the elapsed time of the pulse traveling to the object and returning to the radar antenna. The most common uses of radar are aeronautical navigation, marine navigation, weather Detection and radio altimeters [21].

This paper focuses on the radar systems allocated below and above 10 GHz due to the good propagation characteristics for providing mobile broadband services. Specifically, we consider the ground-based rotating radars deployed in the S- and Ku-Bands: Air Traffic Control (ATC) radars in the 2.7-2.9 GHz band and surveillance radars such as Airport Surface Detection Equipment (ASDE) in the 15.7-17.2 GHz band, respectively. For the ATC radars, the 3 dB channel bandwidth can vary from 0.5 MHz to 15 MHz, depending on the radar type [22]. In contrast, for surveillance radars the 3 dB channel bandwidth could reach up to 100 MHz [21]. Notice that within 15.7-17.2 GHz, the precise allocation of surveillance radars could vary depending on the country or region.

Protection criteria

A maximum interference-to-noise ratio (INR) threshold is established to guarantee that the detection performance of radar systems is not degraded by harmful interference. The INR threshold defines the maximum allowable interference level relative to the noise floor at the radar receivers. In [22], International Telecommunication Union (ITU) recommended that INR of -10dB should be used to protect sensitive radars. This coincides with the result of extensive measurement campaign reported in [23]. Note that this threshold is very conservative for radars with up-to-date technologies. It is reported that multiple-antenna radars can mitigate the interference from communication systems almost completely [24]. Thus, we expect that the INR requirement will be much relaxed in the future. However, we stick to the threshold of -10dB in this study in order to take legacy radars into account.

Due to the random nature of the radio propagation, the protection of the radar is expressed as an interference probability which refers to maximum allowable probability that the aggregate interference exceeds the tolerable interference level. The interference probability is mathematically expressed as follows,

$$\Pr\left[I_a \geq A_{thr}\right] \leq \beta_{PU} \tag{1}$$

where I_a is the aggregate interference from the UDN or the newcomer, A_{thr} is the maximum tolerable interference at the radar and β_{PU} is the maximum permissible probability of harmful interference at the incumbent receiver. Due to the safety-related functionality of the radar, we applied conservative values for A_{thr} and β_{PU} which implies practically almost no interference violation. We adopt a very small value for β_{PU} that is used for air traffic control (ATC) radar in 2.7-2.9 GHz, $\beta_{PU} = 0.001\%$ [22]. We set A_{thr} based on the INR value, $A_{thr}(\text{dBm}) = INR + N$, which drops to $A_{thr} = -119$ dBm/MHz for co-channel vertical sharing for a noise figure (N) of 5 dB.

B. Ultra-Dense Networks as Newcomer

Various types of vertical sharing usage were described in [3]. The vertical spectrum sharing would be the most beneficial and attractive from the commercial point-of-view where we find the highest capacity needs taking into account that it has emerged as a solution to deal with the exploding mobile traffic demand. Approximately, 70% of the current data consumption is generated in indoor locations and ”hotspots” [25] followed by urban areas with high user density [26]. Thus, it is natural to assume that the spectrum sharing system provides high-capacity broadband services for customers located in these locations.

We envisage a scenario where an UDN as the newcomer in the radar bands is employed to expand the network capacity of a cellular network already operating in dedicated/licensed spectrum. The extremely high density of active UDN transmitters over a large geographical area raises the need of controlling the aggregate interference with very high reliability, which is a challenging task. Moreover, the UDN access points must be much cheaper than traditional outdoor base stations in order to make the massive deployment affordable. Thus, a simple interference control functionality is desired at the device level.

C. System Model

For a numerical evaluation of the sharing usage scenario, we consider a circular region with a highly populated urban area (hot zone) with density λ_H surrounded by a less populated sub-urban/rural area with density λ_B. Within the urban and rural area, UDN devices are spatially distributed according to a homogeneous Poisson point process in a two dimensional plane $\Re^2$. The radar is located at the center of the circular region limited by the radius R, which is the maximum distance from the radar. Given that we are considering a rotating radar with a predefined rotating pattern, UDN devices are also capable of exploiting sharing opportunities in the time domain. Thus, sharing opportunities for the UDN will depend on the distance r_j and on the angle θ_j from the radar.

Let us consider an arbitrary UDN device j, the interference that it would cause to the radar at a distance r_j and at an angle θ_j can be expressed as

$$\xi_j(r_j, \theta_j) = G_r(\theta_j) P_t^{eff} g(r_j) Y_j \tag{2}$$

where P_t^{eff} refers to the effective transmission power of the UDN device including antenna gains and bandwidth mismatch. Y_j is a random variable modeling the fading effect. The path loss between the primary receiver and the secondary user j is modeled as $g(r_j) = C r_j^{-\alpha}$ where C is a constant and α is the path loss exponent. $G_r(\theta_j)$ refers to the radar antenna gain dependent on the position of the UDN device and rotation of the antenna.

Let I_{thr} denote the interference threshold imposed on each UDN device. The value of I_{thr} is given by a central spectrum manager. Each UDN device accesses a particular channel or not by estimating the interference it will generate to the radar. This ensures that each UDN device makes its own decision without interacting with the others. The interference from a UDN device j is given by

$$I_j(r_j, \theta_j) = \begin{cases} \xi_j(r_j, \theta_j), & \text{if } \tilde{\xi}_j(r_j, \theta_j) \leq I_{thr} \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

where $\tilde{\xi}_j$ is the estimate of ξ_j by the UDN device j. Note that $\xi_j = \tilde{\xi}_j$ only when the UDN device has the perfect knowledge of the propagation loss. Considering that there are N UDN devices around the radar, the aggregate interference is

$$I_a = \sum_{j \in N_t} I_j \tag{4}$$

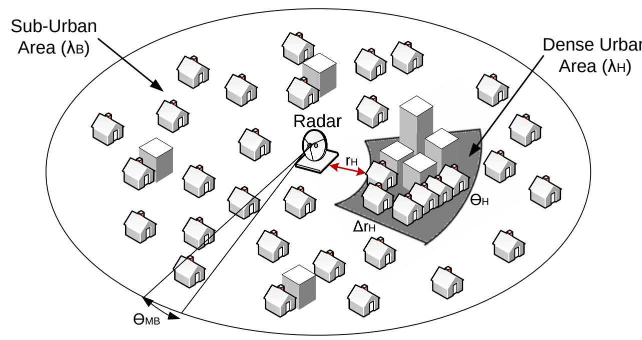

Fig. 2. Sharing Usage Scenario. The rotating radar with a beam width θ_{MB} surrounded by a rural and urban area.

where N_t is the set of transmitting UDN devices. The mathematical models employed to compute the aggregate interference can be found in [11], [12].

A detailed description of the sharing mechanism and functionality of the different involved entities will be provided in Section V.

V. Sharing Mechanism and Technical Enablers

A. Sharing Mechanism

In this section, we introduce a spectrum sharing mechanism that enables vertical spectrum sharing between the radar systems and the UDN. The key requirements for designing this mechanism are: guaranteed reliable protection of the incumbent system as well as good sharing opportunities for the newcomers. Moreover, it is desirable to implement a simple interference control functionality at the device level so the price of UDN APs can be kept below traditional outdoor base stations. Thus, large-scale investments can become attractive from the economic point-of-view. The design principles of the sharing mechanism are:

- *First principle: the aggregate interference should be controlled by a central spectrum manager*. This entity should be external and independent of the incumbent's and newcomer's interest, guaranteeing the fair enforcement of sharing rules. The central spectrum manager communicates and supervises constantly the correct operation of the geo-location databases, which collects all relevant information of the system. Given that the radar receiver can potentially receive interference from millions of UDN transmitters, each UDN user is unable to know whether its own transmission would cause a interference violation to the radar. Thus, it is essential that the central unit estimates aggregate interference and makes a decision on who can transmit with what power based on the information provided by the geo-location databases. A real-time execution of the decision (whether to transmit *now* or not) may be delegated to the individual users, but the guideline for the decision must be provided and updated constantly by the spectrum manager.
- *Second principle: geo-location database should be employed and can be combined with spectrum sensing for the interference estimation*. For the central spectrum

manager to calculate the aggregate interference, each user must be able to estimate the interference it would inflict to the radar and report it to the spectrum manager through the databases.

- *Third principle: a fast feedback loop between the radar and the spectrum manager should be established.* It requires that the radar be attached to the spectrum manager and provides a feedback when it receives the interference above a certain level. This feedback loop might turn out to be redundant most of time in practical sharing access situations because the application of the second principle is expected to produce an accurate estimation of the aggregate interference. However, it will contribute to the guaranteed protection to the safety-of-life functionality of the radar.

Our proposed spectrum sharing mechanism is illustrated in Fig. 3, which shows the basic architecture and communication links between the different entities, i.e. the incumbent system, the sharing system, the geo-location database and the regulatory entity. Communication links 1, 2 and 3 are employed to fulfill the first design principle. The second design principle is illustrated by the communication links 2 and 3, while communication link 1 illustrates the third design principle. Notice that the existing radars cannot measure the interference nor have a backhaul connection. Thus, an upgrade of incumbent equipment is necessary for establishing the feedback loop. Finally, communication link 4 shows the close collaboration between the geo-location database and the regulatory entity that aims at monitoring the correct operation of the geo-location database and enforcing the coexistence rules.

B. Technical Enablers

Based on the proposed sharing mechanism, we have identified technical enablers within the METIS spectrum toolbox [20] that would enable vertical spectrum sharing in the radar bands, which are the combination of geo-location database support and detect-and-avoid mechanisms. The support of geo-location databases is required to guarantee the reliable control of the aggregate interference, crucial for enabling vertical spectrum sharing in the radar bands. With the help of geo-location databases, the central unit can reliably estimate the aggregate interference from a huge number of spectrum sharing users deployed in a very large geographical area. Moreover, the central unit can make the decisions on who can transmit with what power and constantly update them based on the geo-location database information. It is important to notice that this database support is required mainly for the protection of the incumbent system. However, it could also be employed to manage interference between multiple newcomers.

We also consider the detect-and-avoid mechanisms (i.e. spectrum sensing) as a beneficial enabler that can be employed by the UDN devices for the interference estimation. Thus, each user must be able to estimate the interference it would inflict to the incumbent receiver and report it to the geo-location databases or spectrum manager. Spectrum sensing is not considered beneficial in many scenarios of commercial interest [13] since it does not tell us the whereabouts of the incumbent receivers which should be protected. A typical example is the DTT spectrum where thousands of passive TV receivers are kilometers away from a TV transmission tower. On the contrary, in sharing with radars the user can actually detect the presence of the incumbent receiver since the radar receiver is typically collocated with the transmitter. This will bring more reliability and precision for calculating the aggregate interference, making sharing conditions less rigid.

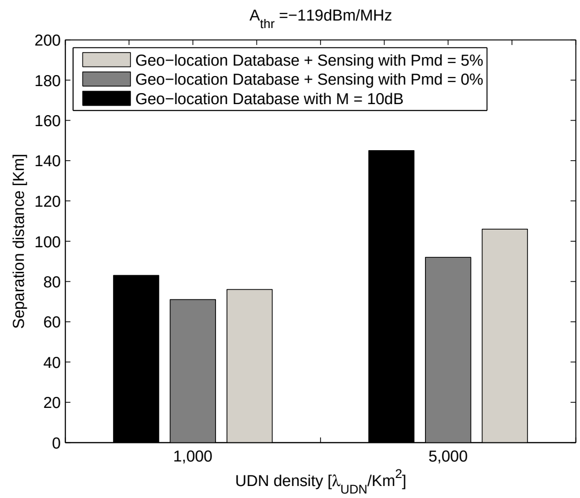

Fig. 4. Benefit of applying geo-location databases and spectrum sensing

For instance, if geo-location databases are onlyemployed, the need for additional interference margins (M) arises in order to cope with the uncertainty on the interference estimation. Thus, the protection criteria given in (1) would be modified as $\Pr[I_a \geq A_{thr} + M] \leq \beta_{PU}$, and also the decision rule for an arbitrary UDN device given by (3) should be rewritten as,

$$I_j(r_j, \theta_j) = \begin{cases} \xi_j(r_j, \theta_j), & \text{if } r_j(\theta_j) \geq r_{min}(\theta_j) \\ 0, & \text{otherwise} \end{cases} \quad (5)$$

where $r_{min}(\theta_j)$ is the minimum required separation distance from the radar in a given angle θ_j.

Supplementary use of spectrum sensing can enhance the performance of spectrum sharing significantly. In our spectrum sharing mechanism, UDN nodes are fed information about radar operational parameters such as center frequency, bandwidth, transmission power, and pulse repetition rate. It enables the UDN to detect radar reliably. Each UDN device can accurately estimate the radio propagation loss to the radar by means of the reliable detection of radar pulses and the knowledge of transmission power. Fig. 4 shows the gain of applying the combination of geo-location databases and spectrum sensing in terms of the required separation distance for protecting the radar. Notice that the gain is higher when the density of devices increases. Therefore, UDNs would particularly benefit from applying the combination of these two enablers. Fig. 4 also demonstrates that missed detection does not significantly impact the required separation distance or the gain of applying the combination of spectrum sensing and databases.

Notice that geo-location databases could potentially be

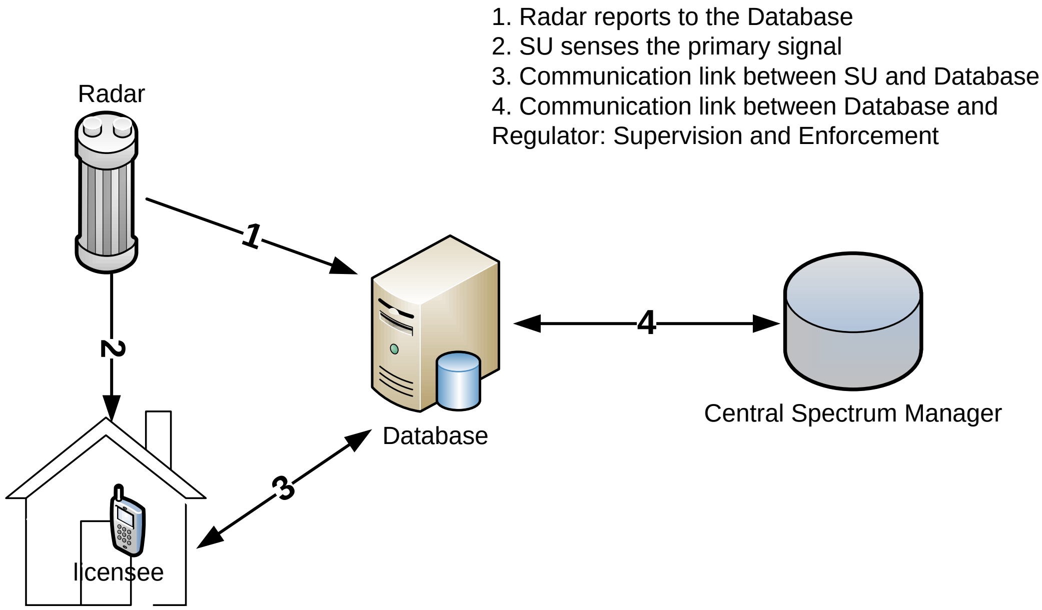

Fig. 3. Sharing mechanism

employed alone.This means that the combination of these two enablers is not necessary but beneficial for improving sharing conditions, as shown in Fig. 4. However, the spectrum sensing, no matter how accurate it is, cannot be used alone. A sensing-only decision cannot guarantee the protection of radar because individual device is not capable of controlling the aggregate interference.

VI. Regulatory Framework

The objective of this section is to identify the most suitable regulatory framework (i.e. licensing regime) that can support the above-discussed sharing mechanism in real life implementation. Various options can be envisaged under the umbrella of vertical spectrum sharing. Based on the METIS toolbox, two potential regulatory framework alternatives for vertical coexistence are license-exempt (countless licensees) and LSA (only a few licensees) [20]. One of the key factors that distinguishes these different frameworks is the number of entities who are granted usage rights.

From the incumbent point of view, reliable protection against harmful interference is essential. This is particularly important for the sharing of radar bands because radars are performing functionalities critical to safety in many cases. One of key questions is how to regulate the transmissions of UDN access points in order to keep the aggregate interference below the threshold while ensuring that UDNs in service fulfill the high capacity demand. In [12], we evaluated three regulatory policies: area power regulation, deployment location regulation and the combination of them as illustrated in Figure 5. Sharing opportunities were inversely proportional to the required time-averaged separation distance between the radar receiver and the UDN that guarantees a minimum transmission probability for the UDN user. Figure 6 indicates that applying any of the regulatory policies improves sharing conditions, particularly for radars allocated below 10 GHz. Overall, deployment location regulation turned out the most effective means to limit interference to the radar system and improve UDN's sharing opportunities, in particular when the difference in network density between urban and rural areas is significant. This means that it is better to allow the deployment of UDNs only in certain areas rather than letting devices transmit everywhere with a limited power. Naturally, the chosen areas would exhibit very high traffic demand.

Then, the next question is what type of licence can be given to the areas with transmission rights. License-exempt use of TVWS has been applied in the USA since 2008 [27], [28]. This model allows the white space devices (WSDs) to have access to the DTT spectrum without an individual license but subject to technical restrictions, allowing the access of an unlimited number of WSDs who provide different applications. However, the same approach does not make sense in radar spectrum bands because it is very difficult to guarantee that sharing conditions and regulatory policies are *enforced to all* the UDN devices without exception. Although it may look too conservative, the guarantee of harmful interference prevention is critical to the sharing of radar bands. Thus, we need to design a licensing scheme which makes sure the policies are enforced. As the number of licensees increases, it becomes more difficult to detect and punish the bleach of the rule. Therefore, it is recommended to keep a low number of licensees in radar bands. Less number of licensees can also be beneficial to the UDNs because the newcomer is willing to have guaranteed access to the available spectrum and manageable sharing conditions so that long-term investments can be justified.

Based on the above discussions, we consider that LSA is the most suitable regulatory framework that could allow the real-life implementation of the selected regulatory policies enabling

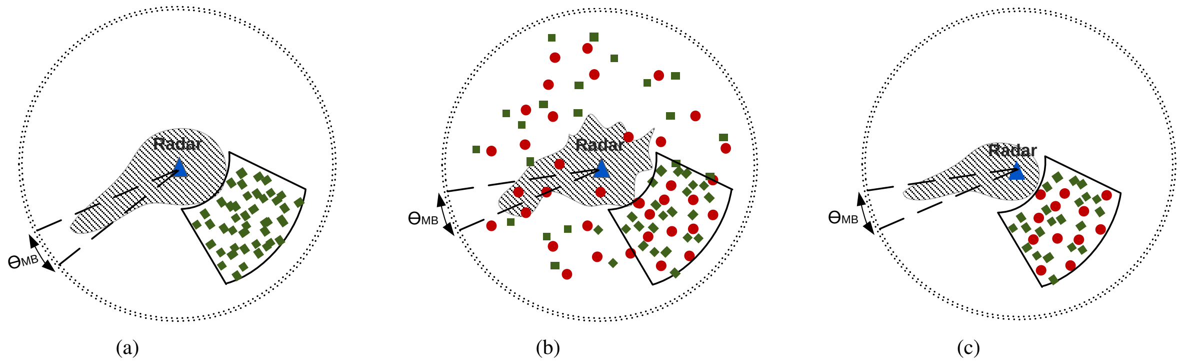

Fig. 5. Regulatory Policy Options: a)Deployment Location Regulation, b)Area Power Regulation and c)Combined Regulation. The radar (blue triangle) is surrounded by transmitting UDN users (green squared), not transmitting UDN users (red circles) and an irregular exclusion region (shadow area).

UDN deployment in the radar bands. We follow the definition of LSA by European radio spectrum policy group (RSPG): *"A regulatory approach aiming to facilitate the introduction of radio communication systems operated by a limited number of licensees under an individual licensing regime in a frequency band already assigned or expected to be assigned to one or more incumbent users. Under the LSA framework, the additional users are allowed to use the spectrum (or part of the spectrum) in accordance with sharing rules included in their rights of use of spectrum, thereby allowing all the authorized users, including incumbents, to provide a certain QoS"* [29]. According to [29], LSA excludes an opportunistic access of spectrum. Instead, it falls into an individual licensing regime which leverages contracts between the incumbents and licensees. Such contracts can ensure a protection of the incumbent (radar) against harmful interference as well as a predictable qualty of service for the licensees (UDNs).

Customizing the general LSA concept to the context of radar spectrum would be a challenge to be addressed. One of the most important aspects to be addressed is the terms of the LSA contract between the incumbent license holder and the licensees, which should contemplate mainly the following: the potential changes or variations in the radar system that could negatively impact the licensees and the technical and economic conditions in case of evacuation request from the incumbent system, e.g. request frequency, time period, time response, economic compensations, etc.

VII. Business Feasibility Analysis

In this section, we revisit the evaluation criteria and discuss what the radar bands offer with respect to them. Moreover, we identify the existing alternatives or competitors and analyze how indoor and hotspot communication in the radar bands is positioned compared to the other alternatives.

Enough Spectrum Availability can significantly impact business viability in the radar bands. However, there is not an universal answer because the availability can vary significantly between different countries. For instance, there is a single civilian ATC radar in Macedonia while there are around 77 ATC radars between civilians and military type in the UK. It is difficult to provide an accurate estimate of worldwide spectrum availability due to the lack of radar operations data. On the

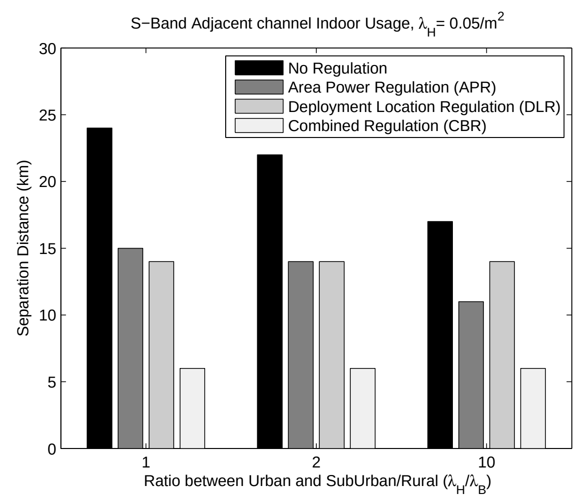

Fig. 6. Impact of spatial heterogeneity: S-Band Indoor Adjacent Channel Usage [12]

other hand, the operational facts about distance measuring equipment (DME), a widely used aeronautical navigation aid, are relatively well known. Since the radar and DME have similar technical characteristics and they are typically located in the vicinity, we can use the availability of DME spectrum as a rough estimate of the availability for radar spectrum. Results in [30] show that at least 30% of the DME band is available for indoor and hotspot mobile broadband usage. Recall that the regulation of deployment area can further improve the availability in the urban areas as shown in [12]. Considering that below 10 GHz there is around 1.2 GHz allocated to radar systems, it is reasonable to estimate that up to 400 MHz could be available for shared access in the radar bands. However, availability in the radar bands would be very much fragmented with a large separation in the frequency domain. This means that an advanced carrier aggregation capability is required to fully claim the available spectrum. An advantage of radar spectrum is that the usage pattern of radar bands has low spatial variance, which means that the available amount of spectrum is spatially uniform for large geographical areas. Therefore, the availability in a city will be most likely constant in space and time domain, which is a key difference from the availability in the TV bands.

Availability of affordable radio technology will depend on the selected radar band. Here, we are mainly discussing the bands below 10 GHz which are located close to already available radio technology dedicated to mobile communications. Moreover, filter characteristics, sensing capabilities and carrier aggregation functionalities, which are extremely relevant due to the noncontiguous availability, are already quite advanced in their development. Thus, adaptation of devices (i.e. access points and end-user devices) that are able to operate in the radar bands below 10 GHz can be done within a reasonable time period and cost. In contrast, the radar bands above 10 GHz would require much more time to make radio technology available since currently there is no radio technology for mobile communication in these bands.

System Scalability in the radar bands has been previously demonstrated in [12] where a system with a very high network density can share the radar bands with reasonable requirements (i.e. small exclusion region size), especially for adjacent channel access. Moreover, complex cross-layer interference management between the macro cellular network and indoor/hotspot networks will not be required in order to provide quality of service since they operate in different frequency bands.

Guaranteed quality of service is feasible in the radar bands due to the selected regulatory framework, i.e. LSA which allows access to few licensees so that the sharing rules are effectively enforced and quality of service can be guaranteed for all licensees.

As a next step, we identify the alternatives that are currently available in the market:

- **Unlicensed Option**: Indoor offloading in the license-exempt ISM bands (2.4 GHz or 5 GHz band) by employing WiFi technology.
- **Licensed Option**: Indoor offloading in frequency band exclusively licensed to the MNO by employing LTE technology.

We compare these options with our value proposition, mobile broadband services in the radar bands, which will be called **LSA option** given that this is the selected regulatory framework. Table I shows this comparison by identifying the advantages and disadvantages that the MNO will have if the LSA option is chosen. One of the main disadvantages is the location-based availability of the radar bands. However, applying the considered regulation on the deployment of spectrum sharing systems leads us to talk about area-based or city-based availability making this solution competitive with the existing alternatives in the areas with high capacity demand. The LSA option offers guaranteed quality of service and a level of system complexity that is perfectly manageable for traditional MNO that is used to complex systems. Also, the fact that only few licensees will access the available spectrum makes this option more valuable for competition with other players.

Finally, we identify that spectrum access cost is still an undefined parameters for the LSA option which will directly impact the business attractiveness of this solution for long-term investments. Thus, it should be set according to the potential benefits that could bring for the licensee, which will highly depend on the characteristics of the vertical sharing availability such as: the amount and the granularity of the available spectrum over space and time domain that strongly depend on the region or country where the evaluation is made. Establishing the right spectrum access cost or license fee is critical for motivating the MNOs to make long-term investments on this solution.

VIII. Concluding Remarks

This paper has provided a comprehensive qualitative assessment of the *commercial viability of vertical sharing in the radar bands* mainly focused on the case of indoor and hotspot communications in the radar bands offloading mobile traffic demand of MNO's cellular networks. For this, we have proposed a well-defined methodology for dealing with the technical, regulatory and business aspects of deploying large-scale wireless networks with vertical spectrum sharing in the radar bands.

By employing this methodology, we have identified the necessary conditions or *criteria for achieving business success* for the deployment of high-capacity wireless system with vertical spectrum sharing in the radar bands, which are the following: spectrum availability, radio technology availability (e.g. low-cost end-user devices), system scalability and guaranteed quality of service. In order to understand what radar bands can offer with respect to these criteria, we conducted a technical availability assessment where we proposed a sharing mechanism that enables vertical spectrum sharing between the radar systems and the UDN based on three design principles: aggregate interference control by a central spectrum manager, combined use of spectrum sensing and geo-location database for the interference estimation and fast feedback loop between the incumbent system and the central spectrum manager.

Based on the proposed sharing mechanism, we have identified the geo-location database support as the necessary technical enabler and detect-and-avoid mechanism as an auxiliary enabler. Notice that the combination of these two enablers is not mandatory but beneficial for improving sharing conditions. Moreover, we also identified that applying regulation on the deployment area of the UDN could also improve sharing conditions. LSA was found to be the suitable regulatory framework to support the above-discussed sharing mechanism and proposed regulatory policies in real-life implementation. License-exempt was ruled out since it cannot guarantee the enforcement of sharing conditions and regulatory policies to all UDN devices, which is critical for radar bands with many safety-related services.

Finally, we conducted a business feasibility assessment based on the devised technical and regulatory conditions. In this assessment, we compared mobile broadband service provisioning in the radar bands (LSA option) with two existing alternatives, Unlicensed and Licensed options, by employing the identified evaluation criteria for business success. We conclude that there is enough spectrum availability for indoor and hotspot communications in urban areas in the radar bands, thus meeting the MNO's needs where it is needed. This

TABLE I
COMPARISON BETWEEN THREE SOLUTIONS FOR INDOOR OFFLOADING

	Unlicensed	**Licensed**	**LSA**
Spectrum availability	Anywhere (538 MHz)	Anywhere (100 MHz)	Location-based (approx. 100 MHz)
Affordable Technology	Available	Available	Near-Term Available
System Scalability	Good	Good	Good
Quality of Service	Best-effort	Guaranteed	Guaranteed
Spectrum access cost	Free	Marginal	Undefined
Spectrum access	Open	Exclusive	Few Licensees

is a crucial characteristic for long-term investments as well as guaranteed quality of service, potential low-cost devices and proven system scalability that also favor the commercial viability of the LSA option. However, the commercial viability is still not clearly determined given the remaining uncertainties in the spectrum access cost. These uncertainties need to be resolved to proceed to quantitative evaluation of the business viability, leading to more explicit conclusions the commercial viability of indoor and hotspot communications in the radar bands.

ACKNOWLEDGMENT

Part of this work has been performed in the framework of the FP7 project ICT-317669 METIS, which is partly funded by the European Union.

REFERENCES

[1] Cisco, "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2012 - 2017," White Paper, Feb. 2013.

[2] FCC, "Mobile broadband: the benefits of additional spectrum," FCC Staff White Paper, Oct. 2010, http://www.fcc.gov/document/mobile-broadband-benefits-additional-spectrum.

[3] Y. Hwang, S.-L. Kim, K. W. Sung, and J. Zander, "Scenario making for assessment of secondary spectrum access," *IEEE Wireless Communications*, vol. 19, no. 4, pp. 25 –31, Aug. 2012.

[4] M. Nekovee, "Cognitive Radio Access to TV White Spaces: Spectrum Opportunities, Commercial Applications and Remaining Technology Challenges," in *Proc. IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN)*, Singapore, Apr. 6–9 2010.

[5] K. Harrison, S. Mishra, and A. Sahai, "How Much White-Space Capacity Is There?" in *Proc. IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN)*, Singapore, Apr. 6–9 2010.

[6] J. Van de Beek, J. Riihijarvi, A. Achtzehn, and P. Mahonen, "TV White Space in Europe," *IEEE Transactions on Mobile Computing*, vol. 11, no. 2, pp. 178–188, Feb. 2012.

[7] L. Shi, K. W. Sung, and J. Zander, "Secondary Spectrum Access in TV-Bands with Combined Co-Channel and Adjacent Channel Interference Constraints," in *Proc. IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN)*, Bellevue, Oct. 16–19 2012.

[8] R. Saruthirathanaworakun, J. Peha, and L. Correia, "Opportunistic sharing between rotating radar and cellular," *IEEE Journal on Selected Areas in Communications*, vol. 30, no. 10, pp. 1900 –1910, november 2012.

[9] M. Rahman and J. Karlsson, "Feasibility evaluations for secondary LTE usage in 2.7-2.9 GHz radar bands," in *IEEE 22nd International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC)*, Sept. 2011, pp. 1561 –1566.

[10] M. Tercero, K. W. Sung, and J. Zander, "Exploiting temporal secondary access opportunities in radar spectrum," *Wireless Personal Communications*, vol. 72, no. 3, pp. 1663–1674, 2013.

[11] E. Obregon, K. W. Sung, and J. Zander, "On the feasibility of indoor broadband secondary access to 960 -1215 MHz aeronautical spectrum," *Transactions on Emerging Telecommunications Technologies*, vol. 24, no. 7-8, pp. 724–733, 2013.

[12] ——, "On the Sharing Opportunities for Ultra-Dense Networks in the Radar Bands," in *2014 IEEE International Symposium on Dynamic Spectrum Access Networks (DYSPAN),*, April 2014, pp. 215–223.

[13] J. Zander, L. Rasmussen, K. W. Sung, P. Mahonen, M. Petrova, R. Jantti, and J. Kronander, "On the Scalability of Cognitive Radio: Assessing the Commercial Viability of Secondary Spectrum Access," *IEEE Wireless Communications*, vol. 20, no. 2, Apr. 2013.

[14] A. Ghasemi and E. S. Sousa, "Fundamental Limits of Spectrum-Sharing in Fading Environments," *IEEE Transactions on Wireless Communications*, vol. 6, no. 2, pp. 649–658, Feb. 2007.

[15] N. Devroye, P. Mitran, and V. Tarokh, "Achievable Rates in Cognitive Radio Channels," *IEEE Transactions on Information Theory*, vol. 52, no. 5, pp. 1813 –1827, May 2006.

[16] A. Medeisis and L. F. Minervini, "Stalling innovation of Cognitive Radio: The case for a dedicated frequency band ," *Telecommunications Policy*, vol. 37, no. 2-3, pp. 108 – 115, 2013.

[17] T. Forde and L. Doyle, "A TV Whitespace Ecosystem for Licensed Cognitive Radio ," *Telecommunications Policy*, vol. 37, no. 2-3, pp. 130 – 139, 2013.

[18] J. Markendahl, P. Gonzalez-Sanchez, and B. Molleryd, "Impact of deployment costs and spectrum prices on the business viability of mobile broadband using TV white space," in *7th International ICST Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM)*, Stockholm, June 2012, pp. 124–128.

[19] P. Gronsund, O. Grondalen, and M. Lahteenoja, "Business case evaluations for LTE network offloading with cognitive femtocells," *Telecommunications Policy*, vol. 37, no. 2-3, pp. 140 – 153, 2013.

[20] T. Irnich, J. Kronander, Y. Selen, and G. Li, "Spectrum sharing scenarios and resulting technical requirements for 5g systems," in *IEEE 24th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC Workshops)*, London, September 2013, pp. 127–132.

[21] Alenia Marconi Systems Limited, "The Report of an Investigation into the Characteristics, Operation and Protection Requirements of Civil Aeronautical and Civil Maritime Radar Systems," Report, 2002.

[22] International Telecommunication Union (ITU), "Characteristics of radiolocation radars, and characteristics and protection criteria for sharing studies for aeronautical radio navigation and meteorological radars in the radio determination service operating in the frequency band 2700-2900 MHz," ITU-R Recommendation M.1464-1, 2003.

[23] F. H. Sanders, R. L. Sole, B. L. Bedford, , D. Franc, and T. Pawlowitz, "Effects of RF Interference on Radar Receivers," NTIA Report TR-06-444, Sep. 2006.

[24] H. Deng and B. Himed, "Interference Mitigation Processing for Spectrum-Sharing Between Radar and Wireless Communications Systems," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 49, no. 3, pp. 1911–1919, Jul. 2013.

[25] Ericsson, "Heterogeneous Networks: Meeting Mobile Broadband Expectations with Maximum Efficiency," White Paper, 2012.

[26] J. Zander and P. Mahonen, "Riding the data tsunami in the cloud: myths and challenges in future wireless access," *IEEE Communications Magazine*, vol. 51, no. 3, pp. 145–151, 2013.

[27] FCC, "Second Report and Order Memorandum Opinion and Order," Tech. Rep. 08-260, Nov. 2008.

[28] ——, "In the Matter of Unlicensed Operation in the TV Broadcast Bands (ET Docket No 04-186), Additional Spectrum for Unlicensed Devices Below 900 MHZ and in the 3 GHz Band (ET Docket No. 02-380), Second Report and Order Memorandum Opinion and Order," 08-260, Nov. 2008.

[29] ECC, "Licensed Shared Access (LSA)," Available: http://www.cept.org, Feb. 2014, ECC Report 205.

[30] E. Obregon, K. W. Sung, and J. Zander, "Availability assessment of secondary usage in aeronautical spectrum," in *IEEE Wireless Communications and Networking Conference (WCNC),*, Shanghai, Apr. 2013, pp. 4510–4515.