24TH EUROPEAN REGIONAL CONFERENCE OF THE INTERNATIONAL TELECOMMUNICATIONS SOCIETY, FLORENCE, ITALY, 2013

# Secondary Access to the Radar Spectrum Bands: Regulatory and Business Implications

**Evanny Obregon, Ki Won Sung and Jens Zander**
Email: {ecog, sungkw, jenz}@kth.se
Wireless@KTH, KTH Royal Institute of Technology
Electrum 229, SE-164 40 Kista, Sweden

## Abstract

The large expected increase in the capacity requirements raises not only technical issues but also regulatory and business challenges. One of the key methods to increase the capacity of mobile networks in a cost efficient way is to find additional frequency spectrum. However, it is a difficult task since most of the spectrum is already allocated in long-term basis. Therefore, innovation in the technical and regulatory domain is needed to make additional spectrum available for mobile communications that not only improve spectrum utilization but also to make long-term investments feasible. Secondary spectrum access was proposed as a technical solution to improve spectrum utilization. However, uncertainties on the regulatory regime have been the main “show-stopper” for long-term investments. This paper has devised techno-regulatory conditions for making large-scale secondary access to the "radar bands" an attractive business scenario from the MNO's perspective. Our numerical results showed that applying regulation on the deployment of secondary users can significantly improve sharing opportunities, especially in lower frequency bands (S-band) where the impact of interference aggregation is higher. We also identified Licensed Shared Access (LSA) as suitable authorization model for secondary access to the "radar bands" since it provides the level of reliability on the protection against harmful interference and it could also motivate long-term investments. Finally, establishing the right spectrum access cost or license fee for secondary access to the "radar bands" is crucial for achieving competitive edge over alternatives indoor solutions.

*Index terms – radar bands, secondary spectrum access, secondary access availability, spectrum opportunities.*

## 1. Introduction

The "data avalanche" in mobile networks caused by the proliferation of high-end handsets and the large expected increase in the average traffic per device brings new capacity requirements to current wireless networks [1]. This does not only give rise to technical issues but also regulatory and business challenges. One of the key methods to increase the capacity of mobile networks in a cost efficient way is to find additional frequency spectrum. Current long-term, exclusive licensing regimes are preferred by Mobile Network Operators (MNOs) since they are guaranteed access to spectrum over long periods of time to match their long-term investments. Finding spectrum for exclusive allocation, however, is a difficult task since most of the spectrum is already allocated existing services on a long-term basis. Therefore, other ways of making additional spectrum available for mobile communications are being investigated, that require innovation in the technical and regulatory domain to not only improve spectrum utilization but also to make long-term investments feasible.

Secondary spectrum access has been proposed as a technical solution to improve spectrum utilization [2]. Extensive previous work has proved that secondary access is technically possible. However, uncertainties on the regulatory regime (i.e. cost, liability, etc.) have been the main “show-stopper” for the MNOs to invest on the commercial roll-out secondary networks. Recently, some of these uncertainties has been addressed for enabling secondary access to the TV broadcasting band, so called TV white spaces (TVWS) [3, 4]. However, these uncertainties have not been investigated in other frequency bands, such as the radar band. In Europe, the spectrum allocated to radars (here denoted the “radar bands”) represents a significant portion (approx. 1GHz) of the allocated spectrum below 6GHz and exhibits low spectrum utilization [5]. Previous studies showed that large-scale secondary access to some portions of this band is technically feasible [6, 7]. Therefore, it is worthwhile investigating the regulatory regime and economic potential of secondary access to this band.

Secondary access to the radar band faces different technical challenges from the ones in the TVWS, leading to different regulatory policies to enable large-scale secondary access to the radar bands. In this investigation, we aim at *devising the regulatory policies to make large-scale secondary access to the radar band an attractive business scenario.* Particularly, we consider an incumbent MNO as potential operator because results in [8, 9] showed that it is type of operator which obtains the largest benefits from secondary spectrum access.

Previous works on secondary spectrum access have addressed diverse technical, regulatory and business challenges, mostly related to the TV broadcasting band [3, 10]. The link between technical and regulatory solutions is, however, frequently unclear. A coherent techno-regulatory proposal is needed to minimize uncertainty on business scenarios for operators that could retard the commercial deployment of secondary networks. In [7], the authors identified policy reforms needed to facilitate the implementation of proposed technical solutions for hierarchical spectrum sharing, highlighting the relationship between technical and regulatory challenges. In this paper, we will also analyze the techno-regulatory conditions in the radar band and their impact on the business attractiveness for existing MNOs. Firstly, the key technical characteristics of secondary access to the different radar bands will be identified. Secondly, the technical findings will be employed to qualitatively evaluate a suitable authorization scheme. Finally, we analyze how the authorization scheme and proposed regulatory policies could benefit the business scenario of the incumbent MNO.

## 2. Spectrum sharing in the “radar bands”

### 2.1. Description and basic operation of radar systems

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 via a directional antenna. When a pulse imposes on an object in its path, a small portion of the energy is reflected back to the antenna. The radar is in the receiving mode in between the transmitted pulses, and receives the reflected pulse if it is strong enough. The radar indicates the range to the object as a function of the elapsed time of the pulse traveling to the object and returning. In general, the most common uses of radar are: Ground based Aeronautical Navigation, Marine Navigation, Weather Detection and Radio Altimeters. Radar stations may be fixed or mobile, and some are mounted on ships. Mobile radars are often military [11].

Some radar applications such as Air Traffic Control (ATC), Secondary Surveillance Radar (SSR) and Maritime Surveillance are clearly identified as "Safety of Life" services. Other radar applications, such as ground based weather radars, provide a safety-related function. Long range systems (up to 250nm) use L-Band with large antenna rotating at 5 rpm Medium range systems (50 to 100 nm) use S-Band with medium sized antennas rotating at 12 to 15 rpm and short range systems (< 20 nm) use X or Ku-Band and tend to have much smaller antennas and faster rotation (20 to 60 rpm) rates [11]. Therefore, above 10GHz might be challenging to exploit time-domain sharing opportunities.

It is common to define a maximum interference-to-noise ratio (INR) threshold at the radar that defines the maximum allowable interference level relative to the noise floor, such that detection performance of the primary radar system is not unduly compromised. Large INR thresholds mean that the radar has a better interference tolerance capability. For radars with safety-related functionality, the INR value is often set to -10dB [12]. Due to the high sensitivity and low selectivity of the radar receivers and very high gain of the typical radar antenna, the maximum tolerable co-channel interference level could drop to -119dBm/MHz. Therefore, devising policies and sharing mechanisms for an efficient control of the co-channel and adjacent channel aggregate interference over a large geographical area becomes critical for allowing secondary access to the radar bands.

### 2.2. Current regulatory trends

Some portions of the radar bands have been recently allocated to communication services. For instance, the ITU decided to allocate the spectrum between 5150 and 5350 MHz and between 5470 and 5725 MHz on a co-primary basis to “Wireless Access Systems including RLANs” under the condition that RLANs would implement a sharing mechanism called Dynamic Frequency Selection

(DFS) according to ITU-R Recommendation M.1652 [13]. Such a mechanism has the objective of detecting and avoiding causing co-channel interference into radars [14].

In the United States, the National Telecommunications and Information Administration (NTIA) has recently devoted efforts on identifying frequency bands that could be made available for wireless broadband service provisioning. Based on the results of the Fast Track evaluation, a total of 115 MHz of additional spectrum (1695-1710 MHz and 3550-3650 MHz bands) has been identified for wireless broadband implementation [15]. Making this a reality will require changes on the equipment of current systems (e.g. radar systems) and the regulatory rules given by the Federal Communications Commission (FCC). President's Council of Advisors on Science and Technology (PCAST) investigations in [16] suggest that a feasible way to enable broadband deployment on the 3550-3650 MHz (radar) band would be implementing an extension of the White Space system already developed and deployed by the FCC and various third party vendors in the TV Bands. Meanwhile, the Commission just recently proposed sharing with the radar system by means of “licensed-light” basis [17]. To date, the identification of the needed technical and regulatory changes is an open issue.

Secondary spectrum access to the TVWS has been extensively studied during the last decade. From the regulatory viewpoint, the main condition was to avoid harmful interference to the TV receivers and PSME with unknown location. To fulfill this constraint, different methods were proposed and evaluated by a several regulators: geolocation databases, spectrum sensing and beacons. The latter one was discarded due to its costly infrastructure requirements and its lack of guaranteed protection against harmful interference. Instead the use of geolocation databases has been adopted worldwide, i.e. US, UK, Europe, due to its proven technical capability to protect the primary system. Approaches based on spectrum sensing only has been mostly discarded, unless very low transmission power is employed (50mW), since it does not guarantee the protection of passive TV receivers [18]. However, the combination of geolocation databases and spectrum sensing could be beneficial when dealing with aggregate interference or fairness in secondary sharing. This combination could be particularly beneficial in the radar bands since the potential of spectrum sensing could be better exploited given that the hidden node problem[1] is not present in these bands. Moreover, the control of the aggregate interference can be done more accurately so extremely conservative values can be avoided. In the radar bands, the conservative values could be much lower than in the TV bands due to the high sensitivity of the receivers, eliminating the opportunities for secondary access.

The regulatory bodies OFCOM and FCC have considered the licensed-exempt approach for secondary spectrum with the objective of promoting innovation in the use of the TVWS [18]. However, the commercial take-off of mobile networks using the TVWS is retarded mainly due to the lack of incentives for long-term investments on the network deployment and equipment development. Recent studies in [16] suggest that other types of licensing, even though they may not be totally free or may

---

[1] The hidden node problem occurs in the wireless networks when a node is not visible to other nodes communicating during the sensing phase. This leads to harmful interference or corrupted data since the transmitter is not aware of the other node's presence.

not allow universal access in space or time domain, could be an incentive for a better economy of scale in the white spaces.

## 3. Secondary Access Availability in the "radar bands"

In this analysis, we explore the fact that having a denser secondary system leads to a larger *exclusion region* due to the higher aggregate interference. By exclusion region, we typically mean a circular area where no secondary user is allowed to guarantee the acceptable level of interference at the primary receiver which is located at the center of this area [19]. Then, if freewheeling transmission and deployment of a very dense secondary is allowed, we may end up with an exclusion region radius of several kilometers. Regulatory policies are needed to better exploit the tradeoff between the density of secondary users and the size of the exclusion region. This work considers three alternatives: regulation on the density of transmitting secondary users (e.g. by means of CSMA), regulation on the deployment of secondary users (e.g. allowed secondary usage in the big cities only) and the combination of both of them. The benefits of these alternatives for the secondary access availability are evaluated in terms of the time-averaged exclusion region radius.

Our analysis mainly focused on the primary-secondary sharing between a radar system and indoor system providing broadband services. The ground-based radar radiolocation systems deployed in the S and Ku band are the candidate primary systems. Particularly, we are considering Air Traffic Control (ATC) radars operating in the 2.7-2.9 GHz band and Surveillance Radar in the 16.7-17.3 GHz. The latter frequency band is also allocated to other services such as earth exploration satellites, space research and defense systems. Considering these two frequency bands with different propagation characteristics will give us insights on how the frequency band can impact the technical and regulatory approach for enabling secondary access in the radar bands. Due to the random nature of the radio propagation, the protection of the radar is expressed as a 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,

$$\mathrm{Pr}(\mathrm{I_a} \geq \mathrm{A_{thr}}) \leq \beta_{\mathrm{PU}}$$

where $\mathrm{I_a}$ is the aggregate interference from the secondary system, $\mathrm{A_{thr}}$ is the maximum tolerable interference at the radar and $\beta_{\mathrm{PU}}$ is maximum probability of harmful interference. Since the two primary systems provide safety related services, we adopt the INR value of -10dB and $\beta_{\mathrm{PU}}$ is set to an extremely small value which practically implies almost no interference violation, $\beta_{\mathrm{PU}} = 0.001\%$[12].

In the numerical analysis conducted in Section 3.1 and 3.2, we consider multiple secondary users sharing with single rotating radar. We envisage a large-scale deployment of indoor access points and mobiles providing high capacity broadband services as secondary system, which exploits the space and time domain sharing opportunities in the radar band. We consider indoor secondary usage due to the high capacity needs in indoor environments, i.e. 70% of today's total mobile traffic demand [20]. Moreover, the indoor secondary usage would be helpful for mitigating the interference towards the primary victim because each secondary device would emit very low transmission power with a short coverage requirement. The reliable control of the aggregate interference in the radar band is a critical requirement due to the high sensitivity of the receivers. Therefore, a reliable sharing mechanism is needed to control the interference from a huge amount of secondary user simultaneously transmitting over a large area.

In this analysis we consider the sharing mechanism proposed in [21], which was tailored to the distance measuring equipment (DME) system but can be also adapted to the radar bands in consideration. That mechanism is based on three design principles. The first principle stipulates that *a central spectrum manager* controls the aggregate interference from potentially millions of secondary users and makes a decision on who can transmit with what power. Therefore, simple interference control functionality at the device level can be implemented for the real-time execution of the transmission decision. The second principle requires that secondary users employ the combined use of *spectrum sensing and geolocation database* for the interference estimation. Even though the hidden node problem is not present in the radar bands, spectrum sensing alone cannot provide the required accuracy because it could be affected by detection errors. The third principle demands fast feedback loop between the primary user and the spectrum manager, so any violation of the maximum tolerable interference can be rapidly detected.  These design principles has been set mainly considering the primary receiver protection. Therefore, the current analysis aims at devising new principles that could improve the secondary access availability from the secondary system perspective. The parameters employed in our investigation are summarized in Table 1.

**Table 1 Simulation Parameters [11]**

| | S - Band | Ku - Band |
|---|---|---|
| Antenna main beam gain (dBi) | 35 | 38 |
| Antenna side-lobe attenuation (dB) | 21 | 26 |
| Antenna height (m) | 8 | 8 |
| Out Of Band Attenuation (dB) | 40 | 40 |
| Frequency Accuracy (MHz) | 0.05-10 | 3-40 |
| Propagation Model | Modified Hata | EPM73 |

## 3.1. S-Band

Secondary access availability in the 2.7 – 2.9 GHz band is evaluated for co-channel secondary access (secondary users access the same frequency channel as the primary user) and adjacent channel secondary access (secondary users access a different frequency channel as the primary system). In Figure 1 and Figure 2, we examine how the exclusion region radius for different secondary system densities varies according to the applied type of regulation. Due to the high antenna gain and high sensitivity of the radar receivers, exploiting sharing opportunities with co-channel secondary access seems extremely difficult since it requires very large exclusion region radius as shown in Figure 1. Applying regulation on the density does not improve co-channel sharing opportunities in the S-Band. On the contrary, allowing secondary access only in a specific area (a mid-sized city is considered in this evaluation) significantly reduces the size of the exclusion regions. However, exclusion region radiuses of around 27Km are needed even if combined regulation is considered. Regulating the density or the deployment of transmitting secondary users significantly improves secondary access to adjacent channels since practically no exclusion region is required as shown in Figure 2.

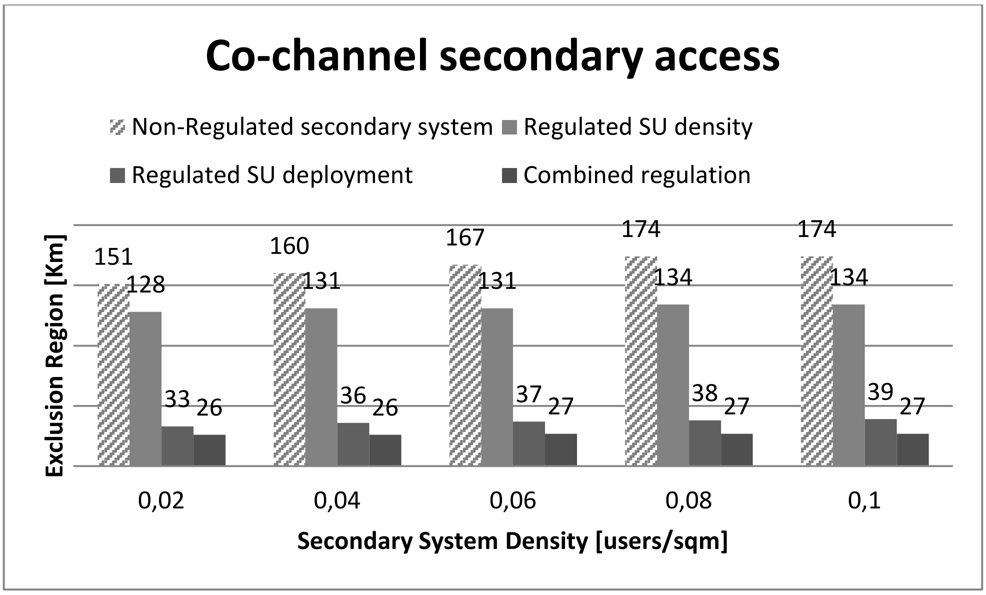


**Figure 1 Exclusion Region Radius for co-channel secondary access to the 2.7-2.9GHz band**

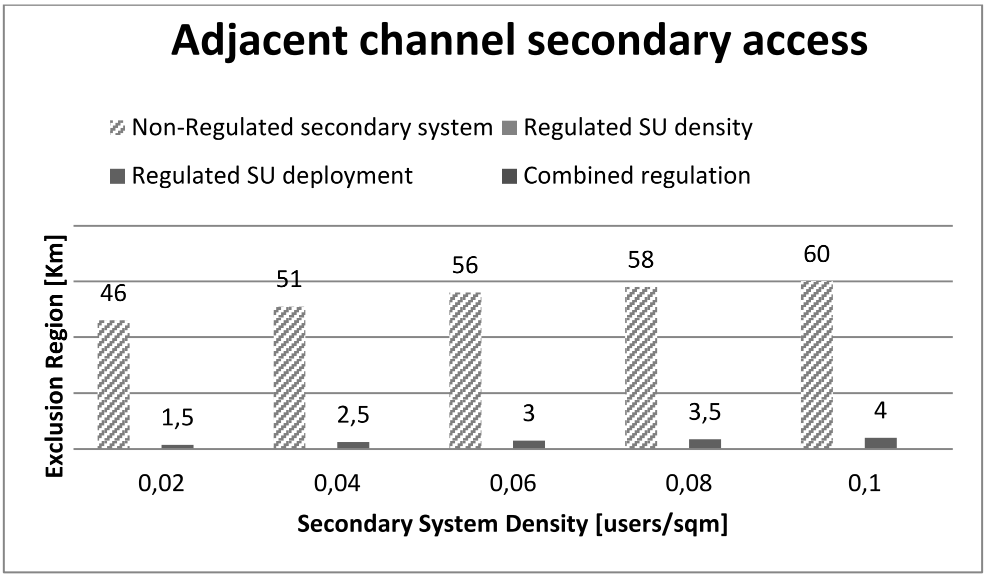


**Figure 2 Exclusion Region Radius for adjacent channel secondary access to the 2.7-2.9 GHz band**

## 3.2. Ku-band

In this section, we evaluate the secondary access availability in the 17 GHz band. The first observation is that even though the high propagation loss in this frequency band, massive co-channel secondary access can be harmful to the radar operation. Figure 3 shows that if no regulation on the density or the deployment of secondary user is applied, exclusion regions radius of up to 59Km are needed to protect the radar receiver. On the contrary, regulating the deployment of secondary user can considerably decrease the exclusion region radius for co-channel secondary access, reaching to less than 30Km even for very dense secondary system. In contrast, the benefit of regulating the density of secondary user is marginal for adjacent channel secondary access, where almost blind deployment of very dense secondary network is feasible without requiring an exclusion region radius larger than 4Km.

Improving co-channel sharing opportunities in the 17GHz can be more critical than in the 2.7-2.9GHz because of the existence of 40-year-old transmitter technologies with poor filtering characteristics and the more challenging requirements for the exploitation of the time domain sharing opportunities. Therefore, infeasible co-channel secondary access can significantly decrease total available secondary spectrum in the Ku-band.

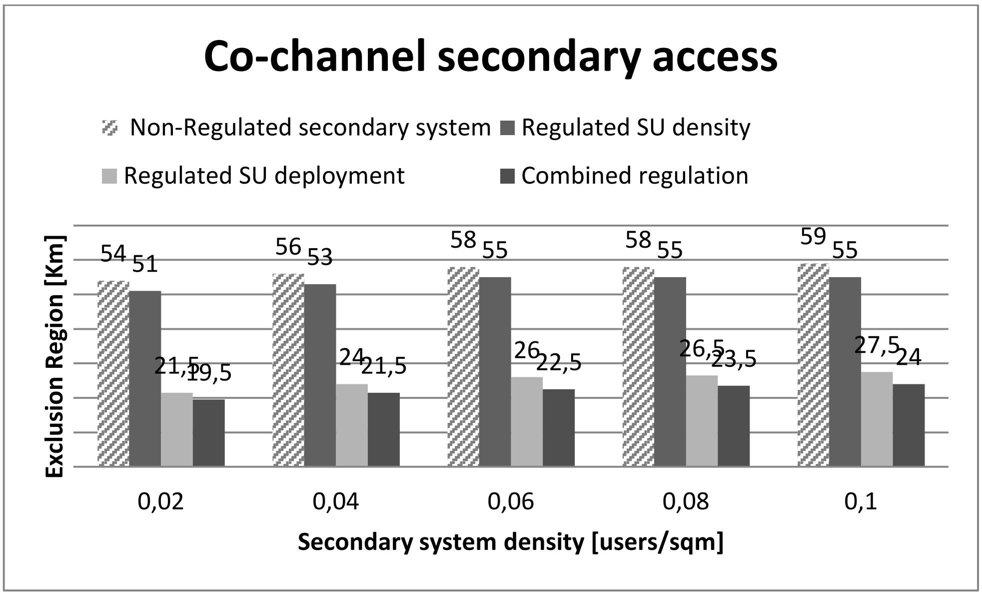


**Figure 3 Exclusion Region Radius for co-channel secondary access to the 17GHz band**

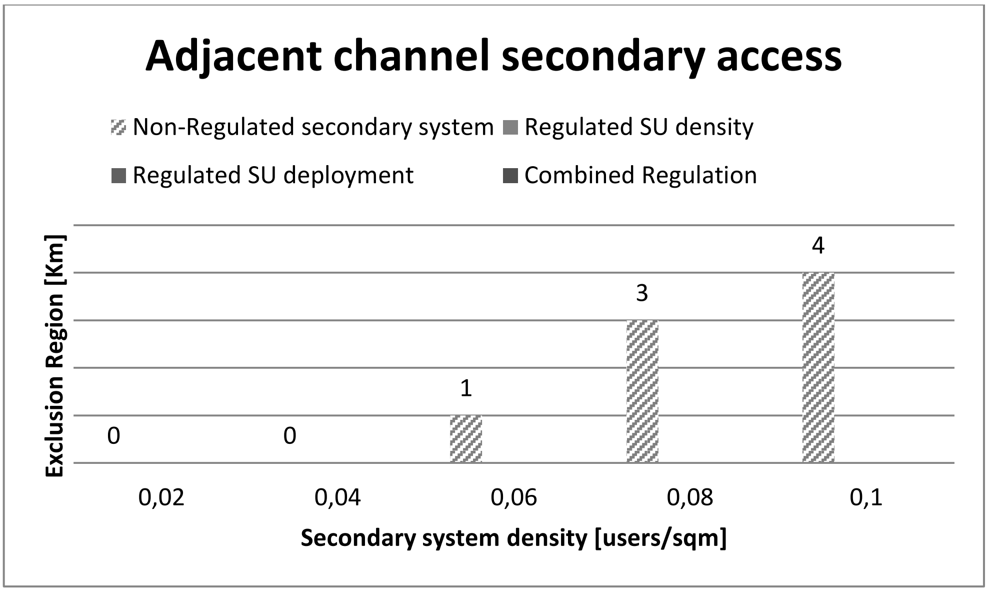


**Figure 4 Exclusion Region Radius for adjacent channel secondary access to the 17GHz band**

## 4. Regulatory and business implications

The regulatory regime for enabling secondary spectrum access to radar bands is still undefined. A key question is: *should we allow universal secondary spectrum access to the radar bands in space or time domain?* This question has been already answered in the TVWS where the licensed-exempt approach was adopted, meaning that any device can access the TVWS anywhere as long as it complies with the sharing rules. However, adopting the same approach in the radar bands may result counterproductive because the radar system characteristics which could require exclusion region radius of up to several hundreds of kilometers to protect the primary system. This could eliminate the possibility of secondary usage in cities close-by the radar, melting down any business opportunity and social benefit since additional spectrum will not be available where the highest demand is.

This paper proposes regulatory policies to better exploit the tradeoff between the density of secondary users and the exclusion region size for co-channel and adjacent channel usage. Our analysis look at three alternatives: regulation on the density of transmitting secondary users (e.g. by means of CSMA), regulation on the deployment of secondary users (e.g. allowed secondary usage in the big cities only) and the combination of both of them. Results showed that applying regulation on the deployment of secondary users can dramatically improve co-channel and adjacent channel sharing opportunities, leading to practically blind or unrestricted deployment of secondary systems *within* the regulated area in adjacent channels and much smaller exclusion region size for dense co-channel secondary access. These improvements are more visible in lower frequency bands, i.e. S-band, where the impact of interference aggregation is higher. Notice that improving co-channel sharing opportunities can significantly increase the amount of available spectrum, especially in frequency bands where the transmitter technology employs 40-year-old magnetron designs that has a increment of 10 times in the occupied -40 dB bandwidth compared with a newer technologies. An upgrade of the transmitter technology can increase the cost up to 100%, which directly impact the cost-effectiveness and business attractiveness of secondary access. The benefits of the other two regulatory policies were found marginal. This means if the deployment of an extremely dense secondary system is allowed only *within a specific area*, secondary users could access the entire band with a relatively small exclusion region size by exploiting the time domain sharing opportunities. Thus, large secondary access availability in dense cities with high capacity demand would be possible. But, *is it attractive from the business perspective?* The answer will depend on the selected authorization model and the operator type.

The selection of a suitable authorization model that not only considers the protection of the primary system but also the exploitation of sharing opportunities by secondary systems is crucial. Regulators promoted the licensed-exempt approach in the TVWS with the objective of promoting innovation, boosting competition and eliminating barriers for potential new players in the mobiles communication industry. However, the commercial take-off of secondary access to the TVWS is still not happening mainly due to the licensed-exempt approach that does not attract long-term investments from operators. In the radar bands, a key requirement for selecting an authorization model is the establishment of a sharing mechanism that provides reliable protection against the harmful interference due to the safety related systems operating in this band. To achieve the required level of reliability, it is needed an authorization model that guarantees the enforcement of the sharing rules and liability in case these rules are violated. Moreover, the sharing mechanism requires accurate information exchange between primary and secondary systems which involves negotiations with multiple primary systems under different administrative control (e.g. military and civil radar), arising the need of a spectrum manager or regulatory entity and a small number of licensees to ease the complexity of sharing process. Based on those requirements, applying license-exempt authorization model would not be recommendable because of two reasons: the lack of registration and the unlimited number of licensees that would make extremely difficult for providing the required level of enforcement and liability. An interesting alternative is Licensed Shared Access (LSA since it requires *registration* and allows *access for only few* of licensees. Based on the LSA concept given in [22], applying LSA would imply a common agreement between primary system and licensees on the sharing rules. This would lead to almost negligible probability of non-compliant devices, effective correction in case of rules violations and accurate estimation of an economic compensation or a fee for the licensees accessing the radar spectrum. Contrary to the license-exempt approach, LSA would involve *a fee* which could be an incentive for the primary system to enable sharing in its licensed spectrum. However, it can also be a stopper for the potential licensees if it is not carefully established to promote long-term investments.

We consider that the candidate licensee is an incumbent MNO willing to significantly improve its indoor capacity to satisfy customer demands. The MNO is also interested in a cost-effective solution that will help to keep its revenues. Indoor secondary access under LSA model in the radar bands is a potential solution, but there could be other solutions such as indoor Wi-Fi deployment in licensed-exempt spectrum and heterogeneous networks (Het-Nets) operating in licensed spectrum. In

Table 2, we identified different attributes related to spectrum, performance and complexity that could impact the selection of one of these solutions. Based on Table 2, we can identify the advantages and disadvantages that the MNO will face if choose indoor secondary access under LSA model. One of the main disadvantages is the location-based availability of secondary access. However, applying regulation on the deployment of secondary users leads us to talk about area-based or city-based availability make this solution competitive with the other alternatives in the areas with high capacity demand. This solution 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 of 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 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 secondary access availability such as: the amount and the granularity of the available spectrum over space and time domain, the complexity of sharing mechanism and the devices implementation issues. Clearly, a large amount of available spectrum anytime and anywhere with a low complexity is desirable but not always feasible in secondary spectrum.

**Table 2 Comparison between three solutions for indoor offloading**

| | Wi-Fi deployment | Het-Net deployment | Secondary system deployment |
|---|---|---|---|
| Spectrum availability | Anywhere | Anywhere | Location -based |
| Spectrum management | Distributed | Centralized | Centralized |
| Service performance | Low /Medium | Medium/High | Medium/High |
| Spectrum access cost | Free | Marginal | *Undefined* |
| Service reliability | Best-effort | Guaranteed | Guaranteed |
| System Complexity | Low | High | Medium |
| Spectrum access | Open | Exclusive | Few licensees |

## 5. Conclusions

The large expected increase in the total traffic demand has raised new capacity requirements to current wireless networks. One of the key resources to meet these new requirements is radio spectrum which is inefficiently utilized due to current static spectrum allocation regime. Secondary spectrum access was proposed as a technical solution to improve spectrum utilization. However, making secondary spectrum access a cost efficient solution that attracts long-term investments requires innovation in the technical and regulatory domain. This paper has analyzed how the techno-regulatory conditions of secondary access to the "radar bands" could impact its business attractiveness for incumbent MNOs.

We conducted a coexistence analysis to identify key regulatory policies to better exploit the sharing opportunities in the radar bands. For that, we focused on the tradeoff between the density of secondary users and the exclusion region size. Numerical results showed that applying regulation on the density of secondary users gives marginal improvements in terms of sharing opportunities. Instead, applying regulation on the deployment of secondary users can dramatically improve these opportunities, leading to practically blind deployment of secondary systems *within* the regulated area in adjacent channels and much smaller exclusion region size for dense co-channel secondary access. Therefore, secondary access to the radar bands can be made available in cities or areas with very high data demand.

For assessing the business attractiveness of secondary access to the radar bands from the MNO's perspective, we first selected Licensed Shared Access (LSA) as suitable authorization model since it provides the level of reliability on the protection against harmful interference. This level is achieve mainly because LSA model allows access to a small number of licensees and requires registration. Towards the assessment of business attractiveness, we identified two alternative competitor solutions for indoor deployments (Wi-Fi and Het-Net) and qualitatively compared them against indoor secondary access to the radar bands. Based on this comparison, we confirmed that applying regulation on the deployment of secondary users under LSA model can give competitive edge of secondary access in terms of spectrum availability and spectrum access. We also spotted the importance of establishing the right spectrum access cost or license fee (currently still undefined) for motivating the MNOs to make long-term investments on this solution. Further work can be done on establishing a license fee under LSA model, leading to a quantitative evaluation of business feasibility of large scale secondary access.

## Acknowledgement

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. The authors would like to acknowledge the contributions of their colleagues in METIS, although the views expressed are those of the authors and do not necessarily represent the project.

## Bibliography


[1] Ericsson, Traffic and Market data report: *On the Pulse of the Networked society*, White Paper, June 2012.

[2] Q. Zhao and B. Sadler, *A survey of dynamic spectrum access*, IEEE Signal Processing Magazine, vol. 24, no. 3, pp. 79 - 89, May 2007.

[3] 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.

[4] J. Markendahl and T. Casey, *Business opportunities using white space spectrum and cognitive radio for mobile broadband services*, in 2012 7th International ICST Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM), pp. 129-134, 2012.

[5] European Frequency Allocation Table, "*Inventory and review of spectrum use: Assessment of the EU potential for improving spectrum efficiency",* (WIK,2012).

[6] M. Tercero, K. Sung, and J. Zander, *Exploiting temporal secondary access opportunities in radar spectrum*, Wireless Personal Communications, pp. 1-12, 2013.

[7] J. M. Peha, *Spectrum sharing in the gray space*, Telecommunications Policy, vol. 37, no. 23, pp.167 - 177, 2013.

[8] Markendahl, J.; Gonzalez-Sanchez, P.; Molleryd, B., "*Impact of deployment costs and spectrum prices on the business viability of mobile broadband using TV white space*," 2012 7th International ICST Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM), pp.124,128, 18-20 June 2012.

[9] Frias, Zoraida; Moral, Antolín; Vidal, Josep; Pérez, Jorge; "*Spectrum pricing assessment in the 2.6 GHZ frequency band for long term lease*," 23rd European Regional Conference of the International Telecommunication Society, Vienna, Austria, 1-4 July 2012.

[10] G. Baldini, O. Holland, V. Stavroulaki, K. Tsagkaris, P. Demestichas, A. Polydoros, S. Karanasios, and D. Allen, *The evolution of cognitive radio technology in Europe: Regulatory and standardization aspects*, Telecommunications Policy, vol. 37, no. 23, pp. 96-107, 2013.

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

[12] ITU-R Recommendation M.1464-1, "*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*,", 2003.

[13] ITU-R Resolution 229, "*Use of the bands 5 150-5 250 MHz, 5 250-5 350 MHz and 5 470-5 725 MHz by the mobile service for the implementation of wireless access systems including radio local area networks*", 2012.

[14] ITU-R RECOMMENDATION M.1652, *"Dynamic frequency selection (DFS) in wireless access systems including radio local area networks for the purpose of protecting the radiodetermination service in the 5 GHz band",* 2003.

[15] U.S. Department of Commerce, "*An Assessment of the Near-Term Viability of Accommodating Wireless Broadband Systems in the 1675-1710 MHz, 1755-1780 MHz, 3500-3650 MHz, and 4200-4220 MHz, 4380-4400 MHz Bands*," 2010.

[16] President's Council of Advisors on Science and Technology (PCAST), "*Realizing the Full Potential of Government-Held Spectrum to Spur Economic Growth*", 2012.

[17] Wireless Telecommunications Bureau Office of Engineering & Technology, "The *Mobile Broadband Spectrum Challenge: International Comparisons*", FCC International Spectrum White Paper, 2013.

[18] Nekovee, M.; Irnich, T.; Karlsson, J., "*Worldwide trends in regulation of secondary access to white spaces using cognitive radio,*" IEEE Wireless Communications, vol.19, no.4, pp.32,40, August 2012.

[19] M. Vu, N. Devroye and V. Tarokh "The primary *exclusive region in cognitive networks*", 5th IEEE Consumer Communications and Networking Conference (CCNC) 2008, pp.1014-1019, 10-12 Jan 2008.

[20] Ericsson, "*Heterogeneous Networks – meeting mobile broadband expectations with maximum efficiency*", White Paper, February 2012

[21] Obregon, E., Sung, K. W., & Zander, J. "*On the Feasibility of Indoor Broadband Secondary Access to the 960-1215 MHz Aeronautical Spectrum*" to appear in European Transactions on Telecommunications, [Online]. Available: http://arxiv.org/abs/1205.3932.pdf.

[22] Radio Spectrum Policy Group, "*Report on Collective Use of Spectrum and Other Sharing Approaches*", RSPG11-392, 2011.