On the Sharing Opportunities of Ultra-Dense Networks in the Radar Bands

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Abstract*—In this paper, we propose and evaluate regulatory policies that would improve sharing conditions/opportunities for indoor/outdoor ultra-dense networks to the radar bands where the demand actually is (i.e. hot spots and urban areas). We consider three regulatory policies: area power regulation, area deployment regulation and the combination of both of them. We address the scenario where the ultra-dense network share the spectrum with a rotating radar by means of geo-location databases and spectrum sensing that enables prior knowledge of the radar characteristics. Thus, secondary users can reliably exploit time and space domain sharing opportunities in the S-Band and Ku-Band. We evaluate these opportunities in terms of the required time-averaged separation distance $\bar{r_H}$ between the primary victim and the secondary transmitter in the hot zone (dense urban area) that guarantees a minimum secondary transmission probability, TX_{min}. Our results showed that adjacent channel sharing opportunities in the S-Band can be exploited in urban areas with relative small separation distances, which are further reduced if combined regulation is applied (less than 10 km for very high network density). Instead it is not feasible to exploit indoor and outdoor co-channel sharing opportunities in S-Band for cities close-by the radar even if regulation is applied. In the Ku-Band, the impact of interference aggregation is much less critical so exploitation of indoor sharing opportunities in urban areas close-by the radar is feasible even if no regulation was applied. For the outdoor case, adjacent channel sharing opportunities can be fully exploited without regulation and blind co-channel deployment of the secondary users if any of the proposed regulatory policies is applied. Overall, applying Area Deployment Regulation has the strongest impact on the reduction of the required separation distance, especially for homogeneous environment.

***Index Terms*—radar spectrum, spectrum sharing, sharing opportunities, regulatory policy**

I. INTRODUCTION

The increasing popularity of wireless and mobile Internet access, and the proliferation of high-end handsets (e.g. tablets, smartphones) have originated a "data tsunami" in current wireless network [1]. This enormous growth in the global mobile data traffic is expected to continue in the coming years, reaching even 1000-fold increase by 2020 [2], [3]. Mobile broadband has become not only part of our everyday life, but also a big challenge for the mobile operators who need to improve the capacity of current wireless networks while keeping their business profitable. Traditionally, improving technology has been the main strategy to achieve higher peak rates in a cost-efficient way. However, current capacity demands cannot be satisfied by only improving peak rates, we need to actually improve the average user data rate [1], [4]. This can be achieved by deploying denser networks and finding additional spectrum where the capacity demand is actually high. Approximately 70% of the current data consumption is generated in indoor locations and "hot spots" [5], followed by urban areas with high user density [1]. Having denser networks represents a big investment for the mobile operators, it is thus crucial to have additional spectrum spectrum in these particular locations in order to affordable meet the explosion of traffic demand.

Spectrum sharing has been proposed as a practical solution to quickly open additional, currently underutilized, spectrum for mobile communications [6]. Spectrum sharing is most valuable in frequency bands where spectrum refarming/clearing cannot be done within a reasonable time frame. This paper focuses on vertical spectrum sharing, so called secondary spectrum access. Previous results have shown that the sweetspot for secondary spectrum access lies in short-range and indoor systems with medium to large-capacity demands [7]. TV white space (TVWS) steamed as the prime candidate for providing additional spectrum for short-range communication. However, results in [8], [9] showed that TVWS was not suitable for indoor Wi-Fi like system due to the extended coverage range in this band which increased congestion and self-interference rapidly limiting the system capacity. These previous results raised the need to look for other frequency bands which could provide additional spectrum for short-range communication.

In Europe, the radio spectrum allocated to the radar systems (here denoted as the radar bands) represents a significant portion (approx. 1 GHz) of the allocated spectrum below 6 GHz and exhibits low spectrum utilization [10]. Due to the propagation characteristics of the radar bands, they become ideal candidates for providing additional capacity for indoor and short-range systems. Particularly for indoor systems where the attenuation given by the walls helps to considerably decrease self-interference in the system. Moreover, secondary spectrum access in the radar bands benefits from having prior knowledge of the primary victim location, which allows an accurate estimation of the interference. However, due to the high sensitivity level of the receivers and the extremely low permissible outage probability at the primary system, the control of the aggregate interference over a very large area becomes a challenging task. Secondary spectrum access to the radar bands faces different technical challenges from the ones in the TVWS, leading to different regulatory policies to enable large-scale secondary access which remain still underdeveloped. Technical feasibility of large-scale secondary spectrum access to some portions of the radar bands has been previously demonstrated [11]–[13]. Therefore, it is worthwhile investigating the regulatory policies that would improve sharing conditions/opportunities for large-scale secondary access to the radar bands where the capacity demand actually is (i.e. hot spots and urban areas).

A. Related Work

In the last decade, extensive work has been done on addressing the technical, regulatory and business challenges of secondary spectrum access. Most of the technical work has focused on developing spectrum sensing techniques [14], obtaining theoretical capacity limits [15], [16] and identifying desirable system characteristics for different spectrum sharing scenarios [17]. Diverse aggregate interference models [18], [19] have been proposed to evaluate the scalability of secondary systems [20]. Moreover, the amount of TV white spaces for US and Europe has been quantified with the objective of evaluating the potential real-life benefits of secondary systems [21], [22]. In the regulatory domain, previous work mainly focused on devising new frameworks to support technical requirements of vertical spectrum sharing, such as carrier aggregation [23], fairness between primary and secondary users considering location/time availability of spectrum [24] or the presence of databases [25]. Previous works have mainly considered the TV band as primary system, leaving the evaluation of the potential of other frequency bands (e.g. the radar bands) for spectrum sharing still in early stages.

Spectrum sharing in the radar bands has recently increased its popularity in the international research and regulatory community. In the United States, the National Telecommunications and Information Administration (NTIA) identified a total of 115 MHz of additional spectrum in the radar bands which could open up (by means of spectrum sharing) for wireless broadband service provisioning [26]. Making this a reality will require technical and regulatory changes, which are still not clearly defined. Some previous studies have been devoted to addressing mainly technical challenges of spectrum sharing in the radar bands. Initial feasibility results for LTE usage of the 2.7-2.9 GHz radar spectrum are presented in [27] where the analysis is based on a single secondary interferer. Also, sharing opportunities in the 5.6 GHz radar spectrum were assessed in [28]. Moreover, results in [11], [12] showed that a predictable rotation pattern can further enhance the sharing opportunities for the secondary users. Some of these results were employed to identify initial policy reforms needed to facilitate the implementation of vertical spectrum sharing in the radar bands [29]. These previous investigations mainly targeted technical challenges while the regulatory policies to enable large-scale secondary access in the radar bands remains still underdeveloped.

B. Contribution

In this paper, we analyze regulatory policies that improve the sharing opportunities/conditions for ultra-dense networks in the radar bands. We are taking as reference frequency bands the S-Band and the Ku-Band to analyze the sharing opportunities in frequency bands below and above 10 GHz. We are considering Air Traffic Control (ATC) radars (2.7-2.9 GHz) and Surveillance Radars (16.7-17.3 GHz) as examples of primary systems operating in the S-Band and the Ku-Band, respectively. By ultra-dense network we refer to a massive scale deployment of indoor/outdoor APs and mobiles providing high capacity broadband services for future scenarios in 2020 and beyond [30]. The ultra-dense network share the spectrum with a rotating radar by means of geo-location databases and spectrum sensing that enables the secondary users to have prior knowledge of the radar rotation pattern, location, operating frequency, and transmission power. Thus, secondary users can reliably exploit time and space domain sharing opportunities. In our evaluation, these opportunities are inversely proportional to the required time-averaged separation distance $\bar{r_H}$ between the primary victim and the secondary transmitter in the hot zone that guarantees a minimum secondary transmission probability of TX_{min}.

The sharing opportunities in time and space domain will highly depend on the aggregate interference, which is determined by the secondary system characteristics. For instance, if freewheeling transmission and deployment of a very dense secondary system is allowed, we may end up with an required separation distance of several kilometers. This could eliminate the availability of sharing opportunities in cities (where capacity demand is high) that are nearby the radar. Thus, regulatory policies are needed to better exploit the tradeoff between the density of secondary users and the required separation distance. We consider three alternatives: regulation on the area power density, regulation on the deployment and the combination of both of them. In this paper, we aim at answering the following research questions:

- What are the sharing opportunities for the indoor/outdoor deployment of ultra-dense networks in the radar bands?
- What regulation policy should be preferred? How is the selection impact by the radar operating frequency impact or the spatial distribution of secondary users?

The rest of the paper is organized as follows: the secondary access scenario is described in Section II. The proposed regulatory policies are outlined in Section III. In Section IV, we specify the simulation parameters and discuss our numerical results. Finally, the main conclusions of this work are given in Section V.

II. SECONDARY ACCESS SCENARIO

A clear description about the secondary access scenario is the first step towards the evaluation of the sharing opportunities in the radar spectrum bands. In [31], the authors identified the key elements that constitute a comprehensive assessment scenario: a primary system and spectrum, a secondary system and usage, and the methods and context of spectrum sharing. These elements will be presented in this section.

A. *Primary system description*

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. 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 Ground based Aeronautical Navigation, Marine Navigation, Weather Detection and Radio Altimeters [32]. In this paper, we consider the ground-based rotating radars deployed in the S-Band and Ku-Band. As example, we are considering Air Traffic Control (ATC) radars operating in the S-Band (2.7-2.9 GHz) and Surveillance Radar in the Ku-Band (16.7-17.3 GHz) as candidate primary systems. For the ATC radars, the channel bandwidth can vary from 2 MHz to 6 MHz, depending on the radar type [33]. The different radar operating frequencies impact the radar antenna size and rotating pattern. For instance, radars operating in the S-Band are typically medium range systems (50 to 100 nm) with medium sized antennas rotating at 12 to 15 rpm in contrast to the radar operating in the X or Ku-Band which are short range systems ($<$ 20 nm) with much smaller antennas and faster rotation of 20 to 60 rpm [32].

Protection criteria

In order to guarantee that the detection performance of radar systems is not degraded by harmful interference, a maximum interference-to-noise ratio (INR) threshold is established. The INR value defines the maximum allowable interference level relative to the noise floor at the radar receivers. For radars with safety-related functionality, the INR value is often set to very conservative value (i.e. -10dB) due to the high sensitivity of the radar receivers and very high antenna gain of the typical radar [33].

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,

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

where I_a is the aggregate interference from the ultra-dense network or secondary system, A_{thr} is the maximum tolerable interference at the radar and β_{PU} is the maximum permissible probability of harmful interference at the primary receiver. Due to the safety-related functionality of the radar, we applied very conservative values for A_{thr} and β_{PU} which practically implies 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, $\beta_{PU} = 0.001\%$ [33]. We set A_{thr} based on the INR value, $A_{thr}(dB) = INR{+}N$, which drops to A_{thr}=-119dBm/MHz for co-channel secondary access.

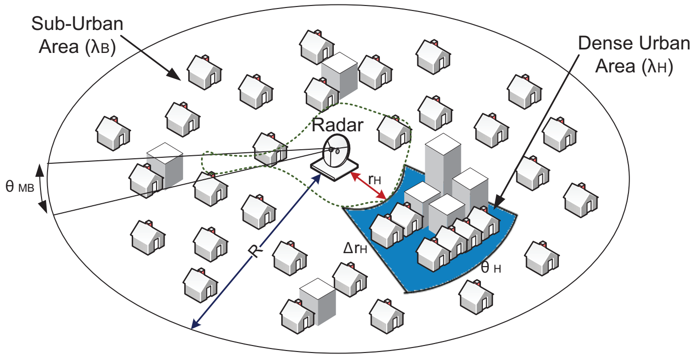


Fig. 1. Secondary Access Scenario. Radar is the primary user rotating with a beamwidth θ_{MB}. Notice that the exclusion region (dotted line) has an irregular shape.

B. *Secondary system description*

We envisage an ultra-dense network as the secondary system in the radar bands. Secondary spectrum access would be the most beneficial and attractive from the commercial point-of-view where we find the highest capacity needs considering the fact that it has emerged as a solution to deal with the exploding mobile traffic demand. We consider the scenario where an already cellular network operating in dedicated/licensed spectrum opportunistically expand its network capacity by employing available spectrum in the radar bands. Due to the tremendous number of secondary users simultaneously transmitting over a large geographical area, controlling the aggregate interference with very high reliability becomes a difficult challenge.

In real environments, several zones with different user densities can be found in a large geographical area. For instance, user density in cities is typically higher than in rural areas. In order to reflect the heterogeneity in the spatial distribution of secondary users, we consider that hot zone model previously proposed in [34]. The hot zone is represented by an annulus sector which is modeled by three parameters: r_H, $\triangle r_H$, and θ_H. As illustrated in Fig. 1, r_H is the distance between the hot zone and the primary user, the length of the hot zone (depth) is $\triangle r_H$, and the central angle (width) is given by θ_H.

For this investigation, we consider circular region with one hot zone representing a highly populated urban area with density λ_H surrounded by a less populated sub-urban/rural area or background area with density λ_B. Within the hot zone and background area, secondary users are assumed to be spatially distributed according to a homogeneous Poisson point process in a two dimensional plane $\Re^2$. The primary receiver is located at the center of the circular region limited by the radius R, which is the maximum distance from the primary receiver. Since we are considering a rotating radar with a predefined rotating pattern as the primary victim, secondary users are able exploit sharing opportunities in the time domain. Thus, sharing opportunities for secondary users in the radar band will depend not only on the distance r_j to the primary victim, but also on the angle θ_j from the radar. Let us consider an arbitrary secondary user j, the interference that the primary user would receive if it were to transmit at a distance r_j and at an angle θ_j from the radar receiver 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 secondary user 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 secondary user and rotation of the antenna. Thus, $G_r(\theta_j)$ value will be changing in time-domain for a secondary user with a fixed location, according to

$$G_r(\theta_j) = \begin{cases} G_r^{max}, & \text{if } 0 \leq \theta_j \leq \theta_{MB} \\ G_r^{min}, & \text{otherwise} \end{cases} \tag{3}$$

where θ_{MB} is the radar main beamwidth, G_r^{max} and G_r^{min} are the maximum and minimum antenna gain of the radar. Each secondary user decides whether it can access a particular channel or not by estimating the interference it will generate to the primary user. Let I_{thr} denote the interference threshold imposed on the individual secondary users. The value of I_{thr} is given to the secondary users by a central spectrum manager. This ensures that each secondary user makes its own decision without interacting with the others. The interference from a secondary user j is given by

$$I_j(r_j, \theta_j) = \begin{cases} \xi_j(r_j, \theta_j), & \text{if } \tilde{\xi}_j(r_j, \theta_j) \leq I_{thr} \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

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

$$I_a = \sum_{j \in N_t} I_j \tag{5}$$

where N_t is the set of transmitting secondary users. The mathematical models employed to compute the aggregate interference can be found in [13].

C. Secondary sharing scheme

In this analysis we consider the sharing mechanism proposed in [13], which is based on three design principles. The first principle states that a central spectrum manager controls the aggregate interference from potentially thousands or millions of secondary users and makes a decision on which user can transmit with what power. Thus, 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. Notice that due to the combined use of spectrum sensing and geo-location databases, spectrum sensing is expected to be reliable enough to ignore missed detection and false alarm. Thus, secondary users can reliably exploit time and space domain sharing spectrum opportunities. 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.

Performance Metric

We analyze the sharing opportunities in terms of the time-averaged minimum required separation distance $\bar{r_H}$ between the radar receiver and the hot zone such that the transmission probability of an arbitrary secondary user j in the hot zone is able to access the radar bands with a minimum transmission probability, TX_{min}. Thus, $\bar{r_H}$ is given by

$$\bar{r}_H = \mathbb{E}_{\theta i}[r_H] \tag{6}$$

where $r_H = f(\theta_i)$ which is determined by the following condition

$$\Pr[\tilde{\xi}_j(r_H, \theta_i) \leq I_{thr}] \geq TX_{min}, \forall \theta_i \in [0, 2\pi] \tag{7}$$

Notice that the transmission probability of the secondary users will vary according to the value of I_{thr} determined by the transmission power and number of active secondary transmitters, which will vary for every proposed regulatory policy. In our evaluation, we consider $TX_{min} = 95\%$.

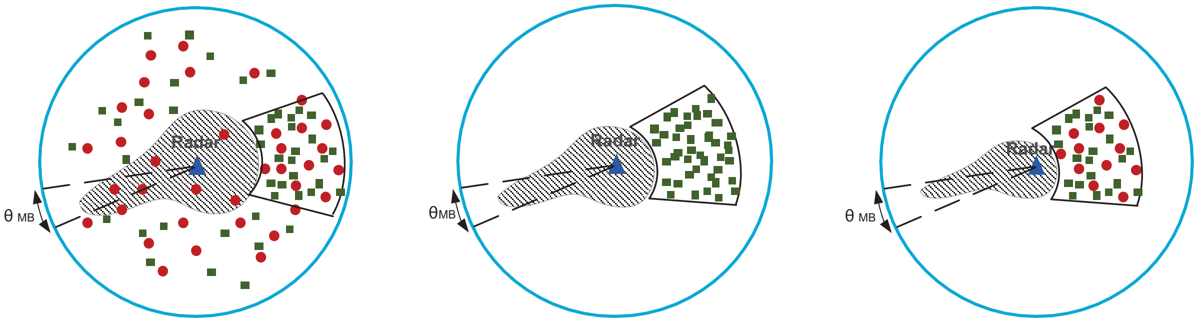
III. REGULATORY POLICY OPTIONS

In this section, we describe different regulatory policies that impact the tradeoff between the density of secondary users and the required separation distance. This consequently also impacts the availability of time and spatial sharing opportunities in the radar bands. These regulatory policies are illustrated in Fig. 2 which shows how the different policies impact the size of the irregular exclusion region.

A. Area Power Regulation (APR)

We consider that the secondary system transmissions are based not only on the protection of the radar system or primary, but also on the number of simultaneous transmissions within a contention area. This means that if secondary users are located very close to each other, then only one of them will be able to transmit at a given time. Thus, the secondary system area power is regulated to effectively reduce the interference between secondary users and the aggregate interference towards the primary victim. Then, the transmission of a secondary user j will be regulated by the following

$$I_j^{APR} = \begin{cases} \xi_j, & \text{if } \tilde{\xi}_j \leq I_{thr}^{CS} \text{ and } I_{SU} \leq I_{CS} \\ 0, & \text{otherwise} \end{cases} \tag{8}$$



(a) (b) (c)

Fig. 2. Regulatory Policy Options: a)Area Power Regulation, b)Area Deployment Regulation and c)Combined Regulation. The radar (blue triangle) is surrounded by transmitting secondary users (green squared), not transmitting secondary users (red circles) and an irregular exclusion region (shadow area).

where I_{thr}^{CS} denote the interference threshold imposed on each secondary user to protect the primary system, ξ_j is the interference that the primary user would receive if the secondary user were to transmit, $\tilde{\xi}_j$ is the estimate of ξ_j by the secondary user j, I_{SU} is the interference to the nearest secondary user and I_{CS} is the maximum tolerable interference at the secondary user. The aggregate interference at the primary victim can be described as

$$I_a^{APR} = \sum_{j \in N_{APR}} I_j^{APR} \tag{9}$$

where N_{APR} is the set of transmitting secondary users which fulfill (8).

B. Area Deployment Regulation (ADR)

We consider that secondary system transmissions are only allowed within a specific geographical area (e.g. a city or a town). This means that secondary access to certain frequency band is not allowed outside this area. In contrast to Area Power Regulation, secondary users are able transmit even if they are very close to each other, meaning that network density is not regulated within the allowed area. Thus, secondary users regulate its interference according to (10)

$$I_j^{ADR} = \begin{cases} \xi_j, & \text{if } \tilde{\xi}_j \leq I_{thr}^{ADR} \text{ and } D_j \in S_A \\ 0, & \text{otherwise} \end{cases} \tag{10}$$

where D_j refers to the location of the secondary user j and S_A represents the area where secondary user transmissions are allowed. Then, the aggregate interference at the primary victim can be described as

$$I_a^{ADR} = \sum_{j \in N_{ADR}} I_j^{ADR} \tag{11}$$

where N_{ADR} is the set of transmitting secondary users. This regulatory policy aims at enabling and improving sharing opportunities in urban or metropolitan areas where the capacity demand is typically extremely high.

C. Combined Regulation (CBR)

We consider that secondary system transmissions are only allowed within a specific geographical area (e.g. a city or a town) and the number of simultaneous transmissions within a contention area is also regulated. Notice that this option is a combination of Area Power Regulation and Area Deployment Regulation, thus secondary users regulate its interference by combining (8) and (10).

IV. NUMERICAL EVALUATION

A. Simulation Environment

The parameters used for our numerical evaluation are described in Table I. For the case of sharing in the S-Band, we model the propagation loss between the primary victim and the secondary user using Modified Hata model for suburban area [35]. Instead for the case of sharing in the Ku-Band, we employ the propagation model proposed in [36] combined with the rain attenuation values given in [37]. In both frequency bands, we investigate the impact of the proposed regulatory policies on the sharing opportunities for an ultra-dense secondary system and we provide results for co-channel usage and as well as adjacent channel usage. This means that the condition (1) is changed to $\Pr[I_a > (A_{thr} + ACR)] \leq \beta_{PU}$ when we evaluate the adjacent channel usage. The values of ACR will vary according to the frequency separation. In this investigation, we assume a conservative ACR value of 40dB which much lower than typical ACR values given in [38].

As mentioned in Section II-B, we consider the hot zone model to account for the impact of the spatial heterogeneity on the benefits that different regulatory policies. In our evaluation, we consider as typical scenario when the network density in the suburban/rural area is half of the one in the urban area ($\lambda_H/\lambda_B = 2$). Moreover, we look into the extreme cases: homogeneous scenario ($\lambda_H/\lambda_B = 1$) and very heterogeneous scenario ($\lambda_H/\lambda_B = 10$). Finally, we also take into consideration the impact of above the clutter indoor users which means that 25% of indoor users are located at height of 30 m.

B. Results

We present our numerical results on the benefits that different regulatory policies could bring in different radar frequency

TABLE I
PARAMETERS USED FOR NUMERICAL EXPERIMENTS

Parameters for S-Band	
path loss model SU - PU	Modified-Hata [35]
Fading standard deviation ($\sigma^{dB}_{X_j}$)	9 dB [35]
path loss model SU - SU	Keenan-Motley
height of the radar	8 m
building penetration loss	10 dB
outdoor secondary user transmission power	10 dBm/MHz
Parameters for Ku-Band	
path loss model SU - PU	Outdoor Model [36]
Fading standard deviation ($\sigma^{dB}_{X_j}$)	9 dB
path loss model SU - SU	Keenan-Motley
height of the radar	8 m
building penetration loss	20 dB [39]
outdoor secondary user transmission power	20 dBm/MHz
Common parameters	
radius of interference aggregation (R)	200 km
radar antenna gain	12 dBi
indoor secondary user antenna gain	0 dBi
indoor secondary user transmission power	0 dBm/MHz
indoor secondary user height	1.5 and 30 m
outdoor secondary user antenna gain	10 dBi
outdoor secondary user height	10 m
area of the Hot Zone	245 km^2
radar main beamwidth	3^o

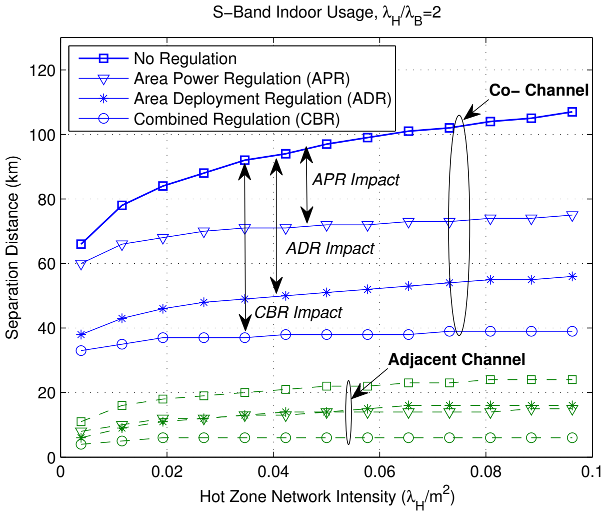


Fig. 3. S-Band Indoor Usage, $\lambda_H/\lambda_B = 2$

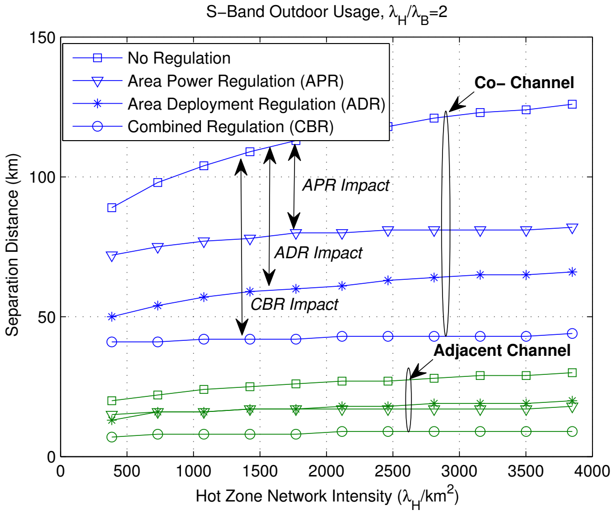


Fig. 4. S-Band Outdoor Usage, $\lambda_H/\lambda_B = 2$

bands. These benefits are evaluated in terms of the required time-averaged separation distance between the primary victim and the hot zone to avoid harmful interference.

1) S-Band: Fig. 3 and Fig. 4 show how the proposed regulatory policies can impact the indoor and outdoor sharing opportunities to the 2.7-2.9 GHz band, respectively. Based on these results, we can observe that exploiting indoor/outdoor co-channel sharing opportunities in this band requires challenging sharing conditions (i.e. very large separation distance) if no regulation is applied. Applying the proposed regulatory policies can considerably reduce the required separation distance (around 60% for the highest network density when applying Combined Regulation), but still the exploitation of co-channel sharing opportunities seem quite difficult since at least 40 km separation distance is required to protect the radar receivers. This could potential melt down any possibility of secondary usage in close-by cities.

On the other hand, adjacent channel sharing opportunities are more promising for the indoor and outdoor scenario even though we considered a very conservative ACR value of 40 dB. By applying either Area Power Regulation or Area Deployment Regulation, the required separation distance can be reduced 50%, reaching values of 16 km (indoor) and 20 km (outdoor) for extremely high network density. Notice that both regulatory policies have an equivalent impact, opposite to the co-channel case where benefits from Area Deployment Regulation were significantly larger. Also, considering Combined Regulation makes more sense for exploiting indoor/outdoor adjacent channel sharing opportunities since the required separation distance could drop to 6 km (indoor) and 9 km (outdoor), enabling blind deployment of a secondary system in cities near the radar.

Previously, we observed that Combined Regulation could actually reduce the required separation, therefore improving the sharing opportunities. But, if we could only applied a single regulation option, which *regulatory option* should we choose? In Fig. 5 and Fig. 6, we look into the impact of the spatial heterogeneity on the benefits that different regulatory policies. Based on the results, applying Area Deployment Regulation has the strongest impact on the reduction of the required separation distance if only co-channel usage is considered. However, looking at the adjacent channel usage, Area Deployment Regulation is still the best regulatory option for the homogeneous scenario ($\lambda_H/\lambda_B = 1$) or when the difference in network density between urban and rural areas is negligible. Instead for very heterogeneous scenario ($\lambda_H/\lambda_B = 10$), Area Power Regulation would be more beneficial.

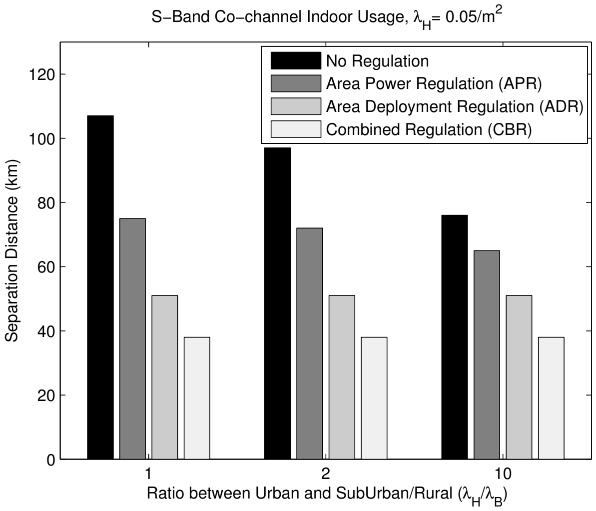


Fig. 5. Impact of spatial heterogeneity: S-Band Indoor Co-channel Usage

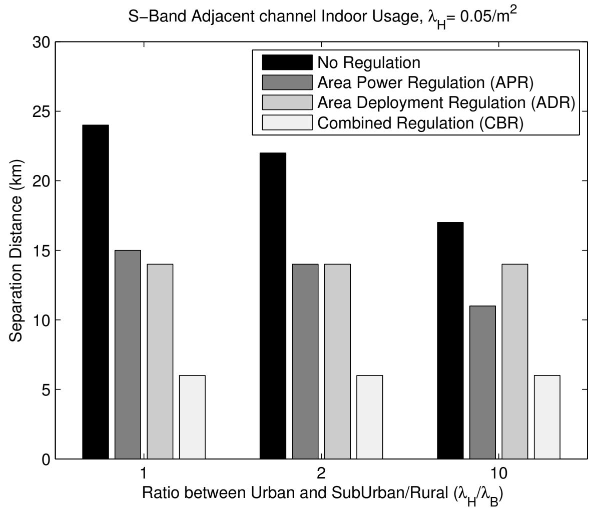


Fig. 6. Impact of spatial heterogeneity: S-Band Indoor Adjacent Channel Usage

2) Ku-Band: We also analyze the sharing opportunities for an ultra-dense secondary system in the 17 GHz band. The first observation is that even though the propagation characteristics of this frequency band, ultra-dense deployment of secondary users can lead to a required separation distance of up to 13 km (indoor) and 30 km (outdoor) for co-channel secondary access with very high network densities. Fig. 7 shows that applying any of the three proposed regulatory policies can almost eliminate the need for a minimum separation distance (around 1 km) in order to exploit indoor co-channel sharing opportunities. For the outdoor case, Fig. 8 shows that aggregate interference can have a larger impact, leading to a required separation distance of up to 30 km. However, applying Area Deployment Regulation can reduce the separation distance to less than 5 km.

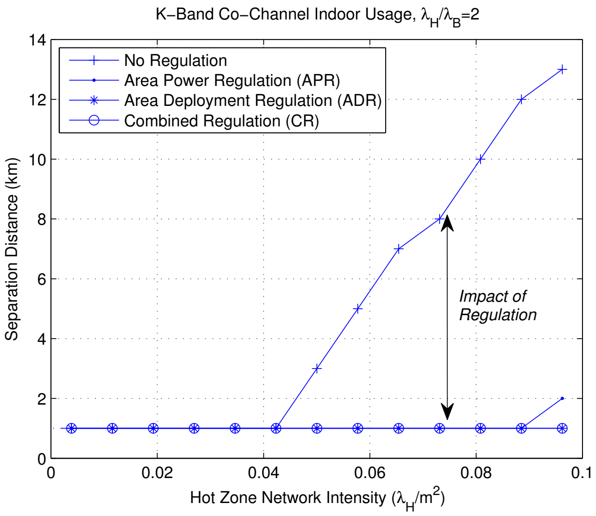


Fig. 7. Ku-Band Co-Channel Indoor Usage, $\lambda_H/\lambda_B = 2$

Based on these results, we can conclude that applying any of the proposed regulatory policies can enable blind co-channel deployment of the secondary users or exploitation of sharing opportunities in the space domain. Improving co-channel sharing opportunities in the 17 GHz can be more beneficial than in the 2.7-2.9GHz due to the existence of 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 spectrum for vertical spectrum sharing in the Ku-band. Our results for the case of adjacent channel secondary access show that the impact of aggregate interference is negligible even with pessimistic assumptions and high secondary user transmission power (20 dBm/MHz). Thus, the benefit of applying any type of regulation is marginal for exploiting adjacent channel indoor/outdoor sharing opportunities since blind deployment of very dense secondary system is feasible without requiring any regulation.

V. CONCLUSIONS

The "data tsunami" and the large expected increase in the total mobile traffic demand has raised new capacity requirements in current wireless networks. One of the key resources to meet these new requirements in a cost-efficient way is finding additional spectrum where the capacity demand is high (hot spots and urban environments). Spectrum sharing is a practical solution to quickly open additional, currently underutilized, spectrum for mobile communications. In this paper, we analyze regulatory policies that could improve sharing conditions/opportunities for indoor and outdoor ultra-dense networks in the radar bands, specifically the S-Band to Ku-Band. These policies have been proposed with the objective of better exploiting the tradeoff between the density of secondary users and the required separation distance. We consider three regulatory policies: area power regulation, area deployment regulation and the combination of both of them.

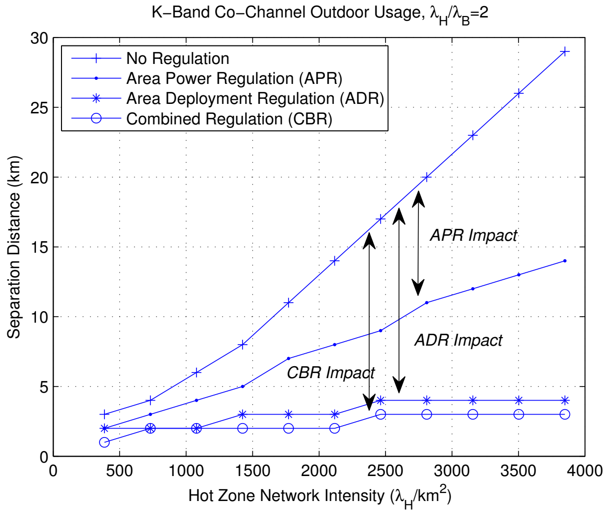


Fig. 8. Ku-Band Co-Channel Outdoor Usage, $\lambda_H/\lambda_B = 2$

Numerical results showed that indoor and outdoor co-channel sharing opportunities in S-Band are limited for cities near the radar since large separation distances (around 40 km) are required even if apply Combined Regulation. Instead indoor and outdoor adjacent channel sharing opportunities seems promising and applying combined regulation could lead very small separation distances (less than 10 km) even for very high network density. In the Ku-Band, the impact of interference aggregation is much less critical so exploitation of indoor sharing opportunities in urban areas close-by the radar is possible even if no regulation was applied (13 km separation distance for the highest density). For the outdoor case, adjacent channel sharing opportunities can be fully exploited without regulation and blind co-channel deployment of the secondary users if any of the proposed regulatory policies is applied.

Overall, applying regulation results more beneficial in the S-Band given that the impact of interference aggregation is higher. Instead in the Ku-Band, the benefit of applying any type of regulation were less significant since (almost) blind deployment of very dense secondary system is feasible without requiring any regulation. The heterogeneity in the spatial distribution of secondary user impacts the selection of a regulatory policy: applying Area Deployment Regulation has the strongest impact on the reduction of the required separation distance, especially when the difference in network density between urban and rural areas is negligible (homogeneous environment).

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