Stochastic-Geometric Model of Expected Service Area for Cognitive TV White Space Wireless Networks

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***Abstract*—We address the problem of interference between cognitive wireless networks coexisting in the TV White Space (TVWS). We perform stochastic geometry analysis in order to evaluate the service area secondary cognitive devices can expect under mild to severe interference of neighboring networks. From our analysis, we foresee severe service area reduction, especially in densely populated areas, indicating a future need for coexistence techniques tailored to enable communication in TVWS while preventing harmful interference between cognitive wireless networks. Furthermore, we give a concise overview of the current activities undergoing in international standardization bodies towards the realization of communications in the TVWS.**

***Index Terms*—TV White Space, Cognitive Networks, Coexistence Mechanisms.**

I. Introduction

Different wireless technologies operating in the same space, time and frequency has been a known research topic in the unlicensed industrial, scientific and medical (ISM) frequency band for many years. Systems, such as IEEE 802.11 WLANs, IEEE 802.15 WPANs can share the same frequency band, causing severe mutual interference and, therefore, disrupt the service or significantly affect the performance of each other [1], [2] (and references therein).

The relative efficiency of coexistence mechanisms in the unlicensed ISM band and recent measurements [3], [4] revealing the inefficiency inherent to fixed spectrum allocation characteristic of licensed regimen urged authorities to reconsider traditional spectrum management policies. The Federal Communications Commission (FCC), in the United States, and the Office of Communications (Ofcom), in UK, responded by investigating the feasibility of having cognitive radios (CR) as opportunistic secondary users (SU) of the TV licensed spectrum, hereafter referred to TV band devices (TVBD). A bold, however, crucial step towards efficient spectrum utilization.

In November 2008, the FCC has issued a report and order (R&O) [5] regulating the unlicensed access to unused broadcast TV spectrum between 54-698 MHz, hereafter referred to as TV White Space, therefore creating bandwidth expansion necessary to provide users with an alternative to the current 2.4GHz and 5GHz wireless access. The Ofcom, has followed the initiative and issued its consultation document [6], in February 2009, outlining several key points for cognitive devices to access the TVWS. Other regulatory bodies, such as the European Conference of Postal and Telecommunications Administrations (CEPT) and the Japanese Ministry of Internal Affairs and Communications (MIC) are following the same path and also considering TVWS utilization [7].

The commercial importance and benefits brought by TVWS communications are, however, as big as the challenge and controversy underlying this promising application of CR technology. On the one hand, efficient VHF-UHF spectrum utilization introducing new wireless services without setting aside new frequency bands. This attractive characteristic of TVWS communications has motivated an overwhelming activity towards its standardization, which was manifested by the creation of IEEE 802.22 Working Group (WG) and IEEE 802.11af Task Group (TG), respectively, in 2004 and 2009. Activities in ECMA Technical Committee 48 Task Group 1 (TC48-TG1) towards the creation of PHY and MAC standards for operation in TVWS, also followed in 2009. On the other hand, the opposition from TV broadcasters in sharing with TVBDs the spectrum dedicated to primary users (PUs), also referred to as incumbents, is, as expected, strong. Furthermore, the FCC requirements to allow TVBDs opportunistic spectrum access are quite stringent, therefore, contributing to make the realization of TVWS communications even more challenging. Although FCC has removed the spectrum sensing requirement, in September 2010, the implementation of TVWS database [8], out-of-band emission limitations as well as specification on accessible channels are mandatory in order to offer high degree of incumbent protection.

A more recent challenge, however, is the prevention of harmful interference between multiple secondary networks formed by TVBDs upon the availability of TVWS. This problem has drawn so much attention that IEEE 802.19 Wireless Coexistence WG has created the IEEE 802.19.1 TG whose aim is to create radio technology independent standard methods for coexistence among dissimilar TVBD networks in the TVWS. The IEEE 802.19.1 TG has taken a high level approach, that is to say, new PHY and/or MAC design is not considered.

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Expected outcomes from this TG are coexistence mechanisms providing efficient spectrum sharing, otherwise impossible if TVBD networks are left to *fight* for spectrum.

In this paper we utilize stochastic-geometric analysis to infer on the influence that mutual interference between cognitive radio networks has on the service areas expected by cognitive users. The analysis allow us to gain insight on how environmental factors, $i.e.$, propagation characteristics, number of available TV channels, together with device-system parameters, $i.e.$, transmit power, desired signal-to-noise ratio, interact so as to reduce the service area to a fraction of the one inherent to cases where mutual interference is inexistent.

II. Existing and Under-Development TVWS PHY-MAC Standards

Insight on how popular will wireless access through unoccupied TV channels be, is easily derived from a quick look on the current enormous mobilization from industry stakeholders in international standardization activities. Massive industry participation in standardization is a pointer which indicates future success of a technology and it should not be different with wireless access in TVWS. As a result of such intense activities, four projects on the creation of MAC and PHY standards for operation in TVWS have been created. The outcomes of these projects are listed bellow in order of completeness:

- ECMA 392 Standard [9] - specifies PHY layer and MAC sub-layer for personal/portable cognitive wireless networks operating in TV bands. It also specifies a MUX sub-layer for higher layer protocols. This standard was approved in December 2009.
- IEEE 802.22 Draft Standard [10]- specifies PHY layer and MAC sub-layer of fixed point-to-multipoint wireless regional area networks (WRAN) communication in the TV bands. It targets operating range up to 100km with maximum data rate of 31Mbps. The IEEE 802.22 WG is still resolving internal comments on the draft standard, a process known as Letter Ballot.
- IEEE 802.11 af Draft Standard - defines modications to the PHY layer and MAC sub-layer design with reference to the WLAN legacy standard IEEE 802.11 revision 2007 [11]. It will likely reuse portions from IEEE 802.11y [12] (long range operation up to 5km) and from IEEE 802.11n [13] (high data rate up to 600Mbps) as well. IEEE 802.11 WG will probably start Letter Ballot by January 2011.
- IEEE SCC41 Committee on WS Radio - created in March 2010, this project is in its early stages and, currently, investigates the interest in, feasibility of, and necessity to develop a new PHY layer and MAC sub-layer standard for white space communication system.

With the completion of the above standards, one can expect a high demand from the market, which will exploit the TVWS in the form of various services including low data rate smart grids [14], rural wireless access [15] and broadband home wireless [16]. Therefore, one can expect mild to severe mutual interference between networks depending on population density.

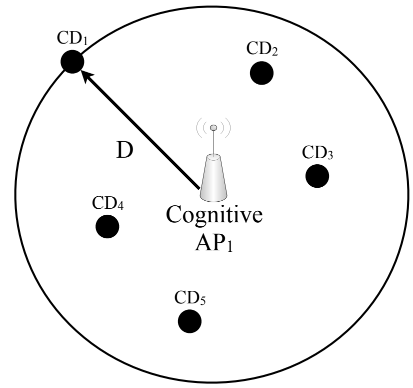


Fig. 1. Cognitive network composed of an AP and various CD with service area delimited by distance D, under the ideal interference free scenario.

III. Problem Statement

Consider a cognitive network composed of a cognitive access point (AP_1) and multiple cognitive devices (CD) in the absence of interference, as shown in Fig.1. Let the minimum required signal-to-noise ratio be SNR in order to guarantee wireless services, $i.e.$, real-time video streaming, video conferencing, to users. That is to say, the ratio between the received power and noise power at the output of the cognitive receivers is given by

$$\mathrm{SNR} = \frac{\mathrm{P}_r}{\mathrm{P}_n}. \quad (1)$$

If both AP and CDs transmit with power P and the radio propagation environment is governed by a path loss exponent α, (1) can be written as

$$\mathrm{SNR} = \frac{\mathrm{PD}^{-\alpha}}{\mathrm{P}_n}, \quad (2)$$

where D is the maximum distance a CD can be apart from the AP in order to experience a desirable quality-of-service (QoS). The distance D determines the service area of $\pi \mathrm{D}^2$ and is given by

$$\mathrm{D} = \sqrt[\alpha]{\frac{\mathrm{P}}{\mathrm{P}_n \mathrm{SNR}}}. \quad (3)$$

Now, consider the more realistic case, depicted by Fig.2, where several other stations ($\mathrm{AP}_2, \cdots, \mathrm{AP}_{n+1}$) operate in the vicinity of AP_1.

Under the interference-avoiding principle of cognitive radios, assuming that there are n orthogonal channels available, the first $n-1$ neighboring access points ($\mathrm{AP}_2, \cdots, \mathrm{AP}_n$) are able to autonomously select distinct channels so as to avoid interference amongst themselves. Still under the same interference-averse principle, however, and in the absence of any "free" channel, the n-th neighboring station AP_{n+1} selects the channel with minimum interference, $i.e.$, the one utilized by the furthest station AP_1.

Due to the inevitable interference between these stations, the coverage within which the original quality-of-service can

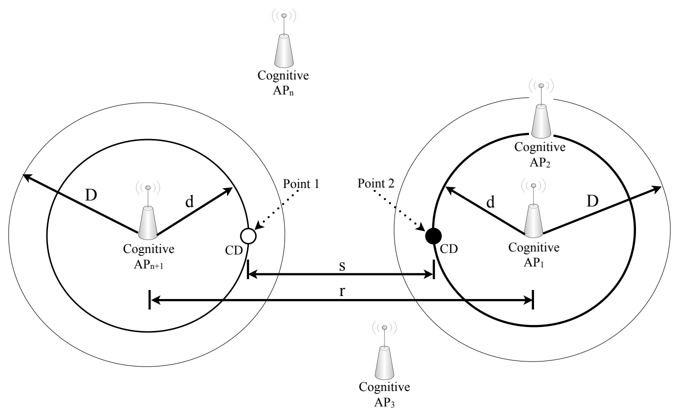


Fig. 2. Cognitive networks under mutual interference. CDs are no longer able to keep the same QoS when at a distance D, referent to service area under interference free scenario, apart from AP. A new, reduced, distance d limits the service area of desired QoS.

be maintained reduces to *d*, for both stations, due to the reciprocity of the wireless channel. With basis on these conditions, one can define a *Fractional Service Area* (FSA) under dynamic frequency selection coexistence as

$$\text{FSA} = 1 - \left(\frac{\pi\text{D}^2 - \pi\text{d}^2}{\pi\text{D}^2}\right). \tag{4}$$

The FSA measures the fraction of service area attained under mutual network interference conditions, compared to that attained under no interference, and is a parameter that captures the "penalty" incurred by network frequency reuse. A FSA close to unity indicates that a small reduction in the interference-free coverage area is suffered by users. As a rule-of-thumb, an FSA of about 80% is effectively unnoticeable by users; between 80% and 60% is perceived in the form of a reduction in download speeds and limitation of coverage, and below 60% significanlty compromises user experience [17].

Notice that under the assumption of Gaussian channels with typical path loss exponents [18] ranging from $\alpha = 2$ to $\alpha = 6$, the interference over AP_1 of another (further) station utilizing the same channel is negligible. Furthermore, since the stations are indexed according to their distance to an arbitrary reference (namely AP_1), the interference scenario described above is sufficient to model an arbitrarily large setting of randomly and uniformly distributed access points.

IV. Network Stochastic Geometry Model

The ensemble of randomly and uniformly distributed access points AP_i can be modeled as a 2-dimentional Poisson point process [19],

$$\mathbb{P}[\text{k access points in S}] = e^{-\lambda|(S)|}\frac{(\lambda|(S)|)^k}{k!}, \tag{5}$$

where $|S|$ is the area of region *S*.

Let r be the distance between AP_1 and AP_{n+1}, hereafter referred to as *access point separation*, as depicted in Fig.2. Without loss of generality, r is the distance between an AP and its n-th neighbor, which has been found to be a random variate with distribution [20]

$$p(r) = e^{-\lambda\phi r^2}\frac{2(\lambda\phi r^2)^n}{r\Gamma(n)}, \tag{6}$$

for a 2-dimetional process and where λ is the density of access points (see Table I).

Now, defining s = r - 2d, as can be easily verified from Fig.2, the signal-to-interference-plus-noise ratio (SINR) at Point 2, which is equal to the SNR that yields the desirable QoS, is given by

$$\text{SINR} = \frac{\text{P d}^{-\alpha}}{\text{P s}^{-\alpha} + \text{P}_n}. \tag{7}$$

It should be noted that Point 1 and Point 2 are critical to the analysis since they define the smallest Euclidian distance between mutually interfering networks. Therefore, if the SNR requirement is satisfied at these points, it will also be at any other location within the fractional service area defined by the distance d. It should also be noted that the interference caused by other CD devices can be considered negligible since networks have internal mechanisms of coexistence among CDs. Therefore, even in the independently operated neighboring AP_{n+1} network, most likely only a single CD will be transmitting at a given time.

After manipulating (7), we find the intrinsic relationship between the reduced coverage radius d to SNR, α, P_n and r, with the later relating to n, λ, as seen from (6),

$$\text{d}^\alpha(\text{r - 2d})^\alpha \text{ SNR P}_n + \text{d}^\alpha\text{SNR P - P (r - 2d)}^\alpha = 0. \tag{8}$$

Unfortunately (8) has no closed form solution[1] for general α. On the other hand, due to the monotonic behavior of d as a function of r and the fact that $0 < d < r$, (8) can be easily solved numerically.

Let d be the solution of (8) for a given access point separation r under parameters n, ϕ, λ. Then, the average FSA is given by

$$\text{E[FSA]} = 1 - \left(\frac{\int_0^\infty (\pi\text{D}^2 - \pi\text{d}^2)e^{-\lambda\phi r^2}\frac{2(\lambda\phi r^2)^n}{r\Gamma(n)}\,dr}{\pi\text{D}^2}\right). \tag{9}$$

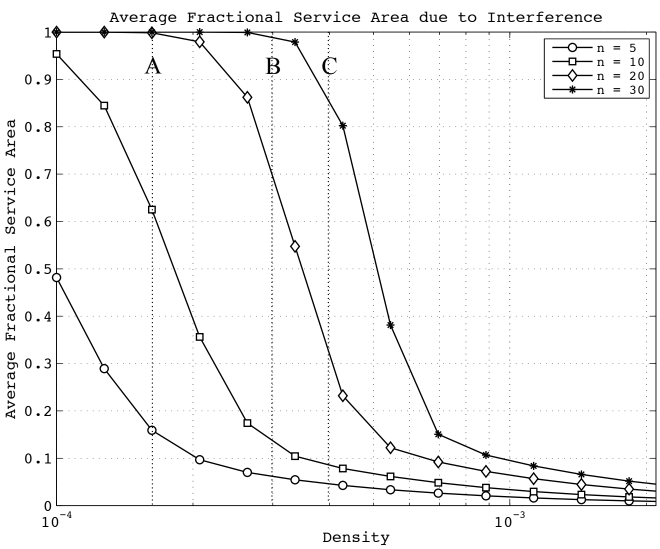
V. Results and Discussion

In this section we discuss some preliminary results that can be earned through equation (9) as a function of the density λ, parameterized by the number of channels n and the path loss exponent α, as given in figures 3(a) and 3(b), respectively. Moreover, the desired SNR is set to 45 dBs and the considered P_n is the one experienced by a device with noise figure of 13 dBs operating in a TV channel of 6 MHz bandwidth.

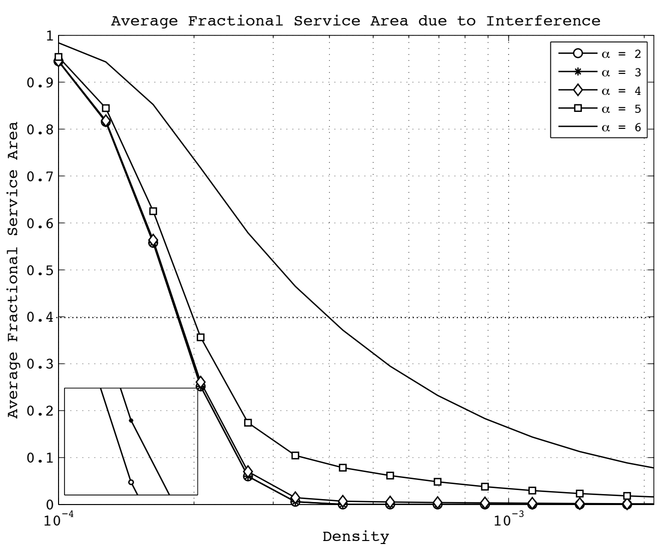
[1]Even for the simplest case of $\alpha = 2$, (8) leads to a quartic relationship between d and r.

TABLE I
RELATIONSHIP BETWEEN DENSITY λ IN APS/m^2 AND WHITE SPACE AP PENETRATION (AP$_p$) IN %, UNDER INTERNET PENETRATION (I$_p$) OF 90%. TOTAL NUMBER OF HOUSE-HOLDS IS HH = ($\lambda 10^6$)/(AP$_p$I$_p$), IN HH/km^2.

λ \ AP penetration	20%	50%	90%
1.7E-4 (A)	945 $\frac{hh}{km^2}$	370 $\frac{hh}{km^2}$	210 $\frac{hh}{km^2}$
3.0E-4 (B)	1666 $\frac{hh}{km^2}$	667 $\frac{hh}{km^2}$	370 $\frac{hh}{km^2}$
4.0E-4 (C)	2220 $\frac{hh}{km^2}$	890 $\frac{hh}{km^2}$	493 $\frac{hh}{km^2}$



(a) Effect of TVWS set on the fractional service area ($\alpha = 5$).



(b) Effect of Path Loss Exponent on the fractional service area ($N = 10$)

Fig. 3. Fractional Service Area as a function of the density of Access Points.

First, refer to Fig.3(a). It can be observed that, as expected, the quality-of-service (as indicated by the FSA) is larger for lower densities and larger n, since naturally this combination of parameters leads to less interferences.

Further conclusions can also be drawn from figure 3(a). First, it is found that unless the number of channels is sufficiently large, no reasonable provision of service can be achieved. For instance, with $N = 5$, the FSA is below 50% even for a density as small as λ = 1.7E-4, region A, which models relatively unpopulated areas (see Table I). It is important to notice the relationship of ($\lambda 10^6$)/(AP$_p$I$_p$) that λ holds with house-hold density, measured in hh/km^2. The later one is readily available to the public by the government of each country in the form of national population census. User and/or TVWS service providers can extract from the house-hold density parameter the expected fractional service area in a given region and, therefore, voluntarily taking measures to reduce mutual network interference, $i.e.$, reducing the transmit power.

Also from Fig.3(a) we can infer that as N grows, the behavior of the FSA figure of merit becomes increasingly sensitive on λ. Specifically, for $n = 20$ or $n = 30$, it is found that essentially a critical density exists, $\lambda \approx 3 \times 10^{-4}$ and $\lambda \approx 4 \times 10^{-4}$ (regions B and C, respectively), below which a good QoS is available, but above which coexistence based on dynamic frequency selection alone results in catastrophically failure.

Now, referring to Fig.3(b), one can derive that if the number of TV channels is held constant, rural and urban regions will obtain equivalent effective service coverage areas. Due to the low population density inherent to rural areas, intuitively, one would imagine that networks located significantly apart from each other would be a condition strong enough to ensure interference-less networks operating with the desirable QoS. However, the favorable propagation characteristics of the wireless medium in rural areas (governed by smaller α), desirable from the communications point of view, becomes the culprit for service area reduction. From the coexistence perspective, good propagation characteristics is undesirable since it allows interfering signals to travel large distances with small magnitude attenuation. From the same figure, we can see similar performances of around 40% between regions A (rural area with $\alpha = 3$ or $\alpha = 4$) and B (urban area with $\alpha = 6$), despite the significant density difference.

VI. CONCLUSIONS

We have performed stochastic geometry analysis to model the problem of coexistence of multiple neighboring networks operating in the TV White Space. We define a new metric named fractional service area (FSA). It allow us to understand how the city densities will affect the coverage area expected by users utilizing the TVWS enabled wi-fi owing to mutual interference. Through our analysis, we figured out the intrinsic relationship between environmental and system parameters. This allows us to gain insight on the problem so as to develop, in the future, effective coexistence mechanisms tailored to allow multiple secondary networks operate in the TVWS while preventing QoS-nocive interference. Furthermore, we have presented a concise overview on current international standardization activities as well as regulations related to cognitive operation in unused TV bands.

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