

Area Spectrum Efficiency of TV White Space Wireless System with Transmit Power Control

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Abstract— As a technical approach to solve spectrum scarcity problem, cognitive radio (CR), which enables more flexible use of spectrum through spectrum sharing technology, draws huge attention recently. TV White Space which means geographically unused spectrum in TV broadcasting band is considered as a good frequency band candidate for CR based spectrum sharing technology due to some reasons. However, primary user such as TV receivers, wireless microphone should be protected from interference because White Space device operates as secondary user and its spectrum sensing technology is at an early stage yet. Nonetheless, if properly used, transmit power control (TPC) is believed to be able to improve spectrum efficiency significantly by some regulation authorities such as FCC (Federal Communications Commission) and Ofcom. In this paper, we investigate the effect of TPC in the respect of area spectrum efficiency (ASE) in white space wireless system and analysis results show significant improvement of ASE by incorporating TPC scheme.

Keywords— white space, spectrum efficiency, power control

I. INTRODUCTION

Recently, spectrum is widely recognized as scarce and valuable resource as shown in some spectrum auctions where the price is up to multi billion dollars. In 15 years, the FCC has raised about \$50 billion from auctioning spectrum, including \$19 billion in the 700 MHz auction [1]. However, some measurement campaign results shows that spectrum bands are underused for considerable time [2] and this implicate that the spectrum shortage problem is due to not a shortage of spectrum but the spectrum management scheme based on exclusive spectrum access. Thus, while the amount of spectrum may not be unlimited, the spectrum shortage problem can be considerably alleviated by spectrum sharing technologies such as cognitive radio [3], [4].

Geographically unused spectrum in TV broadcasting band, called 'TV White Space', is authorized by FCC in 2008 to be accessed on a unlicensed basis. TV white space is considered as good candidate for CR based spectrum sharing technology for some reasons [5]. First, spectrum usage behaviour is relatively static in that location of radio station, transmit power, and frequency since these bands are mainly used for TV broadcasting service. With the fact that the channel

bandwidth is wide of 6 or 8MHz, this facilitates spectrum sensing. Relatively low UHF band enables economical system deployment because of good propagation characteristics. Furthermore, the fact that 80% of TV subscribers receive DTV signal through CATV lower the possibility of suffering harmful interference from white space devices (WSD).

Since protecting primary users from harmful interference is most important issue in unlicensed spectrum access on a secondary basis, regulatory authorities mandate the use of geo-location and database access capability as a supplemental measure of spectrum sensing [6], [7]. In this scenario, first, WSD notifies its location information getting from geo-location capability, e.g. GPS, to white space database (WSDB), then WSDB informs WSD of available channels (and maximum transmit power level) in order to protect incumbent users from harmful interference induced by WSD. When WSDB notifying available channel, maximum transmit power of WSD can also be controlled by informing possible maximum power level while keeping interference at an acceptable level for the purpose of making spectrum efficiency increased rather limiting maximum transmit power to a fixed level.

In this paper, area spectrum efficiency (ASE) of TV white space wireless system with transmit power control (TPC) capability is considered. The remainder of this paper organized as follows. The next section ASE, performance measure is described. Section III presents channel and system model. ASE is analysed in section IV and numerical results is shown in section V. Finally, conclusion will be drawn in section VI.

II. AREA SPECTRUM EFFICIENCY(ASE)

In this section, we introduce the concept of area spectral efficiency and consider the meaning of ASE in white space wireless system.

A. Definition of ASE

Since spectrum is scarce, spectrum efficiency is primary concern in the design of wireless system. In cellular system, spectrum efficiency, measured in $[b/s]/[Hz \cdot m^2]$, can be increased by re-using the same frequency channel at spatially separated locations. This means, assuming that the data rate is constant and equal for all users, system channel efficiency can be increased by reducing cell radius [8]. However, reducing cell radius inevitably introduces co-channel interference, which

results in link quality degradation, i.e, there is trade off between system spectrum efficiency and the communication link quality.

ASE is defined as the sum of maximum average data rates per unit bandwidth per unit area for a specified BER [9]. The ASE definition captures the tradeoffs between system capacity, link spectral efficiency, and communication link quality provided to these users. Practically, the maximum average data rate, which is calculated from Shannon capacity, can be achieved by adaptive transmission techniques which continuously adapt data rate relative their fading and interference condition.

Define the reuse distance D_u [m] to be the distance between two BS's using the same set of frequencies. Since the area covered by one of these partition is roughly $\pi(D_u/2)^2$ [m²]. The ASE, A_e [b/s/Hz/m²], is therefore approximated by

$$A_e = \frac{\sum_{k=1}^N C_k}{2\pi D_u^2 W} \quad (1)$$

where N is the number of user per cell, C_k [b/s] is the maximum data rate of k th user, and W is total allocated bandwidth per cell. We define the maximum rate C_k to be the Shannon capacity of the k th user, which depends on γ_k , the received CIR of that user, and W_k , the bandwidth allocated to that user. The ASE quantifies the tradeoff between the increased system efficiency induced by a small frequency reuse and the decreased capacity of each user resulting from the corresponding increase of co-channel interference.

B. ASE of White Space Wireless System

In [10], system spectrum efficiency of IEEE802.22 WRAN network was analysed. However, since constant data rate is assumed, it concluded that spectrum efficiency can be increased by dense frequency reuse pattern as in [8].

Thus, in analysing system spectrum efficiency of white space system, the use of ASE concept, which reflects the effect of co-channel interference, may give more meaningful implication. Moreover, in white space system, transmit power of WSD is constrained in order to keep primary users, e.g. DTV receiver or wireless microphone, from harmful interference. Therefore, the capacity is determined by not only co-channel interference but also maximum allowed transmit power.

Regulatory authorities specify maximum transmit power. Maximum transmit power of mobile/portable white space devices is specified as 40mW and 2.5mW for US and UK, respectively [6], [7]. However, regulatory authority such as Ofcom of UK also allows higher power levels than those suggested for the sensing only device if transmit power control is applied [7]. As referred in section I, an intelligent WSDB can be used for transmit power control in such a way

that WSDB returns to WSD not only the channel it could use but also the transmit power that could be used in each channel. These powers could be calculated depending how far away the spectrum was in licensed use and how far away adjacent channels were also used.

The aim of this paper is to investigate the theoretical limits of spectral efficiency, i.e. ASE, for white space wireless system where transmit power control is applied. For our analysis, we consider only the uplink (mobile to BS) of the systems using frequency-division multiple access (FDMA) or time-division multiple access (TDMA).

III. CHANNEL AND SYSTEM MODELS

In this section, we first outline propagation model, then present our white space system configuration including transmit power control algorithm.

A. Channel Model

Though signal propagation in radio mobile environment is affected by deterministic path-loss variation with distance, random slow shadowing, and random fast multipath fading, we consider only path-loss for the simplicity of analysis. The effect of the other channel impairments may also be analysed straightforwardly. Path loss in TV broadcasting band is modelled by F-curves, which are statistical propagation models derived from actual measurements, and are fully specified by operating band, effective radiated power (ERP), antenna height above average terrain (HAAT), location (l), and time (t) percentage reliability requirements in the format of $F(l, t)$ [11]. The FCC has long defined the protected service contour level in terms of minimum TV signal E-field strength based on F-curve propagation model. Table 1 shows protected service contour levels

Table 1. Protected Service Contour Level

Type of TV Station	Band/Channel	Protected E-field Level (dBu)
Full power Analog TV	Low VHF (2-6)	47
	High VHF (7-13)	56
	UHF (14-69)	64
Low power Analog TV	Low VHF (2-6)	62
	High VHF (7-13)	68
	UHF (14-69)	74
Full power Digital TV	Low VHF (2-6)	28
	High VHF (7-13)	36
	UHF (14-51)	41
Low power Digital TV	Low VHF (2-6)	43
	High VHF (7-13)	48
	UHF (14-51)	51

The FCC has proposed utilizing F(50,10) propagation curves for modelling WSD co-channel interference levels, and F(50,50) curves for modelling adjacent channel interference model. However, F(50,10) curves are generally ill-defined for propagation distances of less than 15km, and both F(50,10) and F(50,10) curves are undefined for transmit antenna height below 30m, which corresponds many WSD use cases.

respectively where $d_{B,T}$ and $d_{B,W}$ is break-point corresponding to propagation channel of TV transmitter and MS, respectively. Thus, maximum transmit power is given by

$$P_{TX,max} = \alpha P_t (s/D)^4 \quad (4)$$

where $s = \sqrt{r^2 + (R + D + D_0)^2 - 2r(R + D_0 + D)\cos\theta} - D$ and $\alpha = (1/\beta)(d_{B,T}/d_{B,W})^2$.

In practice, it may be difficult for WSDB to control transmit power precisely because CIR estimated from propagation model may be imperfect. Thus, additional margin ($\Delta\beta$) should be added to protection ratio, i.e., $D_p/U_p > \beta + \Delta\beta$. Using this additional margin, the effect of other co-channel interferences can also be evaluated indirectly. ASE with additional margin is shown numerically in section V.

IV. ASE ANALYSIS

In this section ASE of uplink will be analysed. Since we assumes that the same channel is used in both white space cell and TV broadcasting, reuse distance D_u corresponds to R . Thus, ASE can be rewritten as

$$A_e = \frac{\sum_{k=1}^N C_k}{2\pi R^2 W} \quad (5)$$

Maximum rate C_k of the k th user is given by Shannon capacity: $C_k = W_k \log_2(1 + \gamma_k)$. Since both the interference and signal power of the k th user will vary with mobiles locations and propagation conditions, the average channel capacity of the k th user is given by

$$\bar{C}_k = W_k \int_0^\infty \log_2(1 + \gamma_k) p_{\gamma_k}(\gamma_k) d\gamma_k \quad (6)$$

where $p_{\gamma_k}(\gamma_k)$ is the PDF of the k th user's CIR. In (6) γ_k and its PDF is identical for all users, so if we assume that all users are assigned the same bandwidth, i.e., $W_k = W_0$ for all user, $\bar{C}_k$ also becomes the same for all users as

$$\bar{C} = W_0 \int_0^\infty \log_2(1 + \gamma) p_\gamma(\gamma) d\gamma. \quad (7)$$

Thus, the average ASE is given by

$$\bar{A}_e = \frac{N\bar{C}}{2\pi R^2 W}. \quad (8)$$

Consider first FDMA system where all users are allocated the same bandwidth $W_k = W_0 = W/N$. Substituting this in (8) yields

$$\bar{A}_e^{FDMA} = \frac{1}{2\pi R^2} \int_0^\infty \log_2(1 + \gamma) p_\gamma(\gamma) d\gamma. \quad (9)$$

In TDMA system, the total bandwidth is allocated only one active user per time slot ($W_k = W$, $N = 1$). Substituting this in (8), we see that TDMA systems have the same ASE, so

$$\bar{A}_e^{FDMA} = \bar{A}_e^{TDMA} = \bar{A}_e. \quad (10)$$

Uplink CIR, γ , can be calculated as follows. First, interference signal power obtained from Figure 1 as

$$P_i = K \left(\frac{\sqrt{d_{B,T}}}{D + D_0 + R} \right)^4 P_t. \quad (11)$$

Note that interference signal only from TV transmitter is assumed. Received signal power from MS with distance r also can be obtained in a similar manner. However, since transmit power is controlled as in (4), received signal power from MS can be written as

$$P_{RX} = \alpha K \left(\frac{s\sqrt{d_{B,W}}}{rD} \right)^4 P_t. \quad (12)$$

From (11) and (12), uplink, CIR is given by

$$\gamma(r, \theta) = \frac{P_{RX}}{P_i} = \frac{1}{\beta} \left(\frac{(D + D_0 + R)s}{rD} \right)^4. \quad (13)$$

Therefore, using (7), (8), and (13), the average ASE can be obtained as

$$\bar{A}_e = \frac{1}{2\pi R^2} \int_0^{2\pi} \int_{R_0}^R \log_2(1 + \gamma(r, \theta)) p_r(r) p_\theta(\theta) dr d\theta \quad (14)$$

where $p_r(r)$ and $p_\theta(\theta)$ are PDF of mobile location in polar coordinates (r, θ) relative to their BS's. MS's are assumed to be uniformly distributed in the cell, i.e, PDF of mobile location is given by

$$p_r(r) = \frac{2(r - R_0)}{(R - R_0)^2}, \quad R_0 \leq r \leq R \quad (15)$$

$$p_\theta(\theta) = \frac{1}{2\pi}, \quad 0 \leq \theta \leq 2\pi \quad (16)$$

where R_0 corresponds to the closest distance the mobile can be from the BS antenna, and is approximately equal to 20 m for microcellular systems and 80 m for macrocellular systems.

V. NUMERICAL RESULTS

Since it is hard to express (14) in a closed form, numerical results are obtained by Monte-Carlo simulation as in [9]. Table 3 shows simulation parameters.

Table 3. Simulation Parameters

Parameter	Number
Carrier frequency	600 MHz (CH 35)
Keep-out distance (D_0)	15 km
Antenna height (h_{TX}, h_{RX})	MS : 9 m, BS : 30 m, TV transmitter : 450m, TV receiver : 10m
TV transmit power (P_t)	5 kW
TV service area (E-field strength over 41dBu)	168 km
Interference protection ratio (β)	Co-channel :23 dB Adj-channel : -28dB

Figure 2 shows the plot of average ASE versus cell radius. Figure 2 quantifies how spectral efficiency increases as cell size decrease. The solid lines in Figure 2 correspond to co-channel system, whereas the dotted lines correspond to adjacent channel system where adjacent channel is used in white space cell. It is shown that the ASE of the adjacent channel is higher than that of co-channel system. As shown in (4), lower interference protection ratio allows higher maximum transmit power through transmit power control. Therefore, adjacent channel system is able to achieve higher ASE. Average ASE of white space system without transmit power control is also depicted in Figure 2. In white space system without transmit power control, we assume that the transmit power is constant which is determined as the value of maximum transmit power when MS is located at the position closest to TV service contour. By using this possible lowest transmit power, wherever MS is located, incumbent users within TV service contour can be protected from harmful interference when transmit power control is not applied. Finally, ‘worst case’ shows ASE (not average) when all MS is located at the position closest to TV service contour.

Figure 3 depicts the effect of average ASE decrease as a result of additional interference protection ratio margin ($\Delta\beta$), which should be take into account when implementing practical system due to the incorrectness of propagation estimation in real cases. As shown in (3), increased interference protection ratio decreases power of undesired signal which corresponds to MS’ power. Thus, average ASE may be decreased due to additional interference protection ratio margin. As expected, Figure 3 shows average ASE decreases monotonically as a result of additional interference protection ratio margin. Note that cell radius is fixed at 50 km.

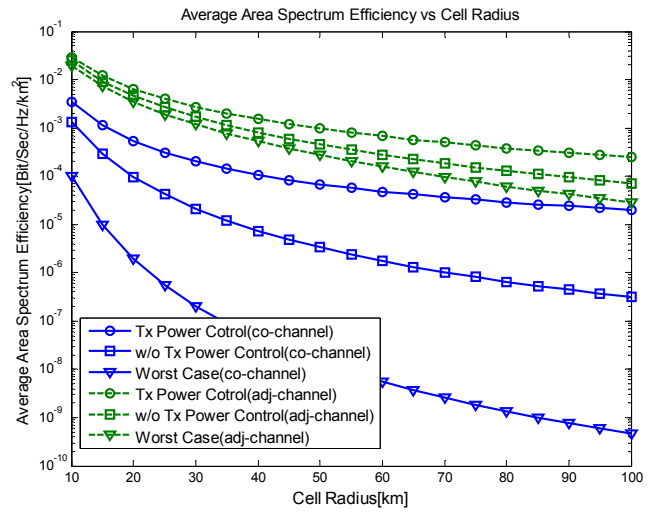


Figure 2. Average Area Spectrum Efficiency vs Cell Radius

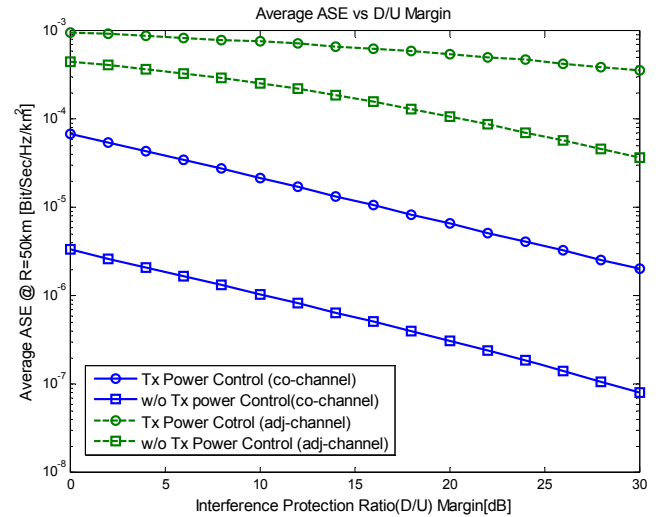


Figure 3. Average ASE vs Interference Protection Margin

VI. CONCLUSION

We have evaluated system spectral efficiency of white space wireless system with transmit power control in terms of area spectrum efficiency. Transmit power control is considered in some regulation authorities as a scheme to enhance spectrum efficiency of white space wireless system if interference to incumbent users are controlled adequately. Currently, this transmit power control scheme is believed to be implemented by geo-location and WSDB access capability.

As a performance measure, we adopt ASE which presents system spectrum efficiency, measured in [b/s]/[Hz·m³], including the effect of link spectral efficiency, and the communication link quality [9]. By using this ASE concept, we quantified theoretical maximum capacity and system spectral efficiency. Through some analysis and simulation, we found that spectral efficiency is significantly improved by adapting

transmit power control in white space wireless system as expected in [7].

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