On the Permissible Transmit Power for Secondary User in TV White Spaces

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***Abstract*—Secondary spectrum access to TV white spaces is considered as a promising solution to relieve the spectrum shortage. In Europe, SE43 working group in CEPT is leading the discussion on the technical requirements for exploiting TV white spaces through the recent ECC report 159. Its analytical approach for determining the maximum permissible power for the secondary user, however, overestimates the power level, and leads to significant violation of the interference limit for TV reception. In this letter, we address the problem by proposing a new approach for determining the secondary user transmit power based on the framework established in ECC report 159. Monte Carlo simulation shows that our method keeps the interference close to the target.**

***Index Terms*—TV white space, ECC Report 159, interference protection, transmit power, shadow fading.**

I. Introduction

Radio spectrum has become a scarce resource due to the growing demands for wireless broadband services. On the other hand, the static spectrum allocation scheme has left large amount of spectrum under-utilized. Hence the concept of secondary access is developed, which allows the 'secondary user' (SU) to access the temporally or locally unoccupied spectrum licensed to the 'primary user' (PU), without violating its quality of service (QoS). In particular, the TV white space (TVWS), referring to the locally or temporally unoccupied spectrum in VHF/UHF digital terrestrial TV broadcasting system, is considered as the most promising candidate band for secondary access for its attractive properties, such as: fixed frequency planning, favorable indoor penetration and significant amount of potential spectrum [1].

To regulate the secondary access in TVWS, ECC's working group spectrum engineering project team 43 (SE43) in CEPT, a leading research group in Europe, has recently published a framework addressing the technical requirements of the secondary access in ECC report 159 [2]. In the report, a methodology is proposed for determining the power level permitted for secondary transmission based on SU's location and TV signal strength. The level of permitted secondary transmit power is the key to both the PU protection and the SU spectrum sharing opportunity: overestimating the power level will potentially cause excessive violation to TV reception, while underestimating it will reduce the spectrum opportunity for secondary services.

As stated in [2, p.30], the most reliable way to determine the permissible transmit power is via Monte Carlo simulation, where the transmit power level is adjusted in an iterative manner until the simulated violation probability is within the required limit. However, the computational load for such simulation approach can be rather demanding especially for large area scenarios. For many studies in TVWS, an analytical approach with low computational cost would be preferred, as it can be easily adapted to different environment settings and scales.

One such analytical approach was proposed by SE43 working group in ECC report 159 [2, p.135] (hereafter referred to as "SE43 approach"). This approach is recently gaining popularity in the literature (see e.g., [3], [4]). Another analytical method for finding the lower bound of the permissible power is proposed in [5].

As we will demonstrate in this paper, the SE43 approach overestimates the permissible power due to an approximation error, which could lead to significant violations of the interference limit for TV reception. Further, we propose a new method to be used within the framework provided by SE43. Our method gives a more reliable estimate of the permissible power, which shows a tight match with Monte Carlo simulation results.

In the following of this paper, we will briefly explain the interference problem of secondary access in TVWS in the beginning of Section II, and describe the SE43's approach and our proposal in Section II-A and Section II-B, respectively. Then the performance of these approaches are compared in the numerical results in Section III. Finally conclusions are drawn in Section IV.

II. Transmit Power of Secondary User

Consider a TV receiver with sensitivity level P_{tv}^{min} inside the TV coverage area. Apart from the desired TV signal P_{tv}, it also receives the interference from other TV transmitters, I_{tv}, and the interference from SU (see Fig.1). The TV signal is subjected to shadow fading, with standard deviation σ_S. (Fast fading is not considered in this paper, as the wideband orthogonal frequency division multiplexing (OFDM) signals, used by the TV system and presumably also the secondary system, is less prone to severe short term fading.)

The TV coverage protection is defined by the *location probability*, referring to the chance of successful TV reception at a given location. Unsuccessful TV reception is termed *outage*.

Let q_1 denote the location probability in the absence of

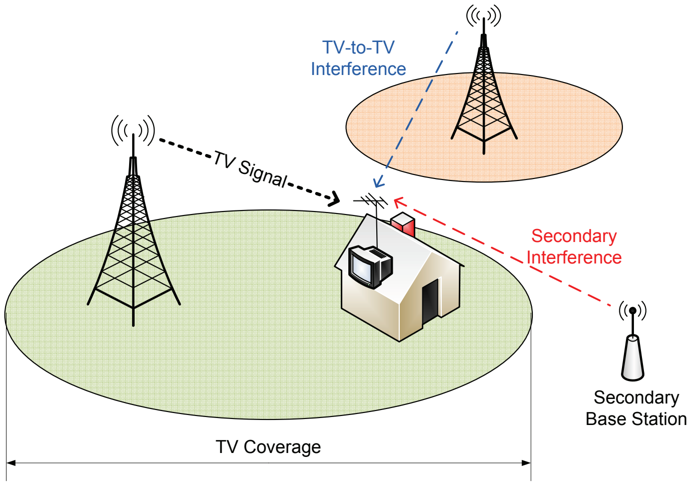

Fig. 1. System Model.

secondary access

$$q_1 = \Pr\left\{P_{tv} \geq P_{tv}^{min} + \sum_{k=1}^{K} \gamma_{tv}^{k} I_{tv}\right\}, \quad (1)$$

where K is the number of interfering TV transmitters, and γ_{tv}^{k} defines the minimum ratio required for successful TV reception between desired TV signal power and the k^{th} interference power.

When additional interference is introduced by an SU transmitting with equivalent isotropically radiated power (EIRP) P_{su} on one locally unoccupied TV channel, the location probability for a TV receiver in the coverage area of that channel will be reduced to q_2. The regulators must limit the maximum amount of interference generated by the SU, such that the deterioration in the location probability is restricted to Δq. Thus, the resulting location probability under the SU interference must be greater than or equal to $q_1 - \Delta q$

$$\begin{aligned} q_2 = &\Pr\{P_{tv} \geq P_{tv}^{min} + \sum_{k=1}^{K} \gamma_{tv}^{k} I_{tv} \\ &+ \gamma_{su}(\Delta f)\, G P_{su}\} \geq q_1 - \Delta q, \end{aligned} \quad (2)$$

where $\gamma_{su}(\Delta f)$ is the minimum required TV signal to SU interference ratio with frequency offset of Δf, and G is the coupling gain between the SU and the TV receiver. G is also assumed to be affected by shadow fading, with standard deviation σ_G.

By limiting the transmit power of the SU, we can restrict the degradation in location probability, $q_1 - q_2 \leq \Delta q$. Letting Z denote $P_{tv} - (P_{tv}^{min} + \sum_{k=1}^{K} \gamma_{tv}^{k} I_{tv})$, and $q_2^* = q_1 - \Delta q$. we can calculate the maximum permissible secondary transmit power P_{su}^* using the expression

$$\begin{aligned} q_2^* &= q_1 - \Delta q = \Pr\{\gamma_{su}(\Delta f) G P_{su}^* \leq Z\} \\ &= \Pr\left\{P_{su}^* \leq \frac{1}{\gamma_{su}(\Delta f) G} Z\right\}. \end{aligned} \quad (3)$$

A. SE43 Approach

Note that, P_{tv}, I_{tv}, and G are usually modeled by log-normal random variables due to shadow fading, therefore Z consists of log-normal random variables and a linear constant. In [2], a simple approximate method is proposed, which converts the variables in (3) into dB domain, with $10\log_{10}(Z)$ approximated by a normal random variable $\widehat{Z}_{\text{dBm}}$.

$$q_2^* \approx \Pr\left\{P_{su(\text{dBm})}^* \leq \widehat{Z}_{(\text{dBm})} - G_{(\text{dB})} - \gamma_{su}(\Delta f)_{(\text{dB})}\right\}, \quad (4)$$

where $G_{(\text{dB})}$ and $\widehat{Z}_{(\text{dBm})}$ are normal random variables with the mean values of $m_{G(\text{dB})}$ and $m_{\widehat{Z}(\text{dBm})}$, and the standard deviation values of $\sigma_{G(\text{dB})}$ and $\sigma_{\widehat{Z}(\text{dB})}$, respectively. The estimation of $m_{\widehat{Z}(\text{dBm})}$ and $\sigma_{\widehat{Z}(\text{dB})}$ requires a numerical technique such as method of moments [6].

Let $P_{su(\text{dBm})}^{SE43*}$ be the maximum allowed SU transmit power obtained by the SE43 approach. It can be derived analytically from (4).

$$\begin{aligned} P_{su(\text{dBm})}^{SE43*} \leq\ & m_{\widehat{Z}(\text{dBm})} - m_{G(\text{dB})} - \gamma_{su}(\Delta f)_{(\text{dB})} \\ & - \sqrt{2}\text{erfc}^{-1}[2(1-q_2^*)]\sqrt{\sigma_{\widehat{Z}(\text{dB})}^2 + \sigma_{G(\text{dB})}^2}, \end{aligned} \quad (5)$$

where $\text{erfc}^{-1}(\cdot)$ is the inverse complementary error function.

The approximation of Z as a log-normal random variable and its conversion into dB domain in (5), however, is not valid, as Z is negative with the probability of $1-q_1$ according to (1). Thus the outage due to shadow fading of TV signal or TV-to-TV self-interference is ignored in this approach. As illustrated in Section III, the interference alone from an SU transmitting with $P_{su(\text{dBm})}^{SE43*}$ would cause violation with probability close to $1 - q_2^*$, instead of Δq.

B. Proposed Approach

To reduce the approximation error incurred by ignoring the negative part of Z, we propose to separate the cases between $Z \geq 0$ and $Z < 0$ with conditional probability applied to (3).

$$\begin{aligned} q_2 =\ & \Pr\left\{P_{su}^* \leq \frac{1}{r(\Delta f)G} Z\right\} \\ =\ & \Pr\{Z < 0\} \cdot \Pr\left\{P_{su}^* \leq \frac{1}{\gamma_{su}(\Delta f)G} Z | Z < 0\right\} \\ &+\ \Pr\{Z \geq 0\} \cdot \Pr\left\{P_{su}^* \leq \frac{1}{\gamma_{su}(\Delta f)G} Z | Z \geq 0\right\}. \end{aligned} \quad (6)$$

Since P_{su}^* must be non-negative, it follows that, $\Pr\{P_{su}^* \leq \frac{1}{r(\Delta f)G} Z | Z < 0\} = 0$.

Recall that $\Pr\{Z \geq 0\} = q_1$. (6) can be written as

$$q_2^* = 0 + q_1 \Pr\left\{P_{su}^* \leq \frac{1}{\gamma_{su}(\Delta f)\, G} Z | Z \geq 0\right\}. \quad (7)$$

Since Z in the remaining term is now conditioned on being non-negative, (7) can be directly converted into logarithmic domain without any approximation error.

$$q_2^* = q_1 \Pr\{P_{su(\text{dBm})}^* \leq Z'_{(\text{dBm})} - G_{(\text{dB})} - \gamma_{su}(\Delta f)_{(\text{dB})}\}, \quad (8)$$

where $Z'_{(\mathrm{dBm})} = 10\log_{10}(Z)|_{Z\geq 0}$. $Z'_{(\mathrm{dBm})}$ can be approximated by a normal random variable, $\widehat{Z'}_{(\mathrm{dBm})}$. Its parameters, $m_{\widehat{Z'}(\mathrm{dBm})}$ and $\sigma_{\widehat{Z'}(\mathrm{dB})}$, can be described by that of $\widehat{Z}_{(\mathrm{dBm})}$ for simplicity, as the mean and standard deviation of $\widehat{Z}_{(\mathrm{dBm})}$ differ only slightly from that of $Z'_{(\mathrm{dBm})}$. Then the maximum permissible transmit power $P^{prop*}_{su(\mathrm{dBm})}$ is calculated as

$$\begin{aligned} P^{prop*}_{su(\mathrm{dBm})} \leq\ & m_{\widehat{Z'}(\mathrm{dBm})} - m_{G(\mathrm{dB})} - r(\Delta f)_{(\mathrm{dB})} \\ & -\sqrt{2}\mathrm{erfc}^{-1}[2(1-\tfrac{q_2}{q_1})]\sqrt{\sigma^2_{\widehat{Z'}(\mathrm{dB})} + \sigma^2_{G(\mathrm{dB})}}. \end{aligned} \tag{9}$$

Comparing the expressions for the permissible power, (9) and (5), we notice the major differences is the argument of the inverse complementary error function, which has changed from $2(1-q_2)$ to $2(1-\frac{q_2}{q_1})$. Thus, it is now explicitly required that $q_2 \leq q_1$, while in (5), q_2 can be theoretically set to a value even higher than q_1 despite its logical contradiction.

III. Numerical Results

The performances of these two approaches are evaluated against Monte-Carlo simulation with the following settings: the minimum signal to interference and noise ratio required for successful TV reception is 17.4 dB; the TV receiver noise is assumed to be -98 dBm; the TV-to-TV self-interference is modeled as 6 dB increase in the receiver noise for simplicity; Hata model for urban environment is used for the median coupling gain calculation; the maximum allowed degradation in location probability is 1%.

In Fig.2, the permissible transmit power estimated by different approaches are compared with Monte Carlo simulation, for an SU transmitting at different distance from the victim receiver, when $q_1 = 95\%$. And the resulting outage probabilities are shown in Fig.3.

From Fig.2, we can observe the general trends of increasing permissible transmit power as the separation distance grows larger. But the SE43 approach overestimates the permissible transmit power by almost 10 dB, whereas the proposed approach matches closely with the Monte Carlo simulation. As a result, the interference generated by an SU following SE43 approach would cause significant violation to the TV reception, with outage probability around $(1-q_1+\Delta q)+(1-q_1) = 11\%$.

Fig.4 depicts the permissible secondary transmit power for an SU transmitting at 50 kilometers away from the victim TV receiver, when the TV coverage quality (q_1) varies from 90% to 100%. The SE43 approach significantly overestimates the permissible transmit power at lower q_1, but converges to the simulation result as $q_1 \to 1$. And the resulting outage probability is twice as much as the intended target, as seen in Fig.5. This again confirms our belief that the approximation error of SE43 method is caused by neglecting the negative part of Z. However, in real TV networks, q_1 at TV coverage boundary is less than 1 as the digital TV system is usually interference-limited. And since it is those TVs in poorer coverage that are more vulnerable to the secondary interference, the estimation accuracy for the permissible transmit power at lower q_1 is of particular importance.

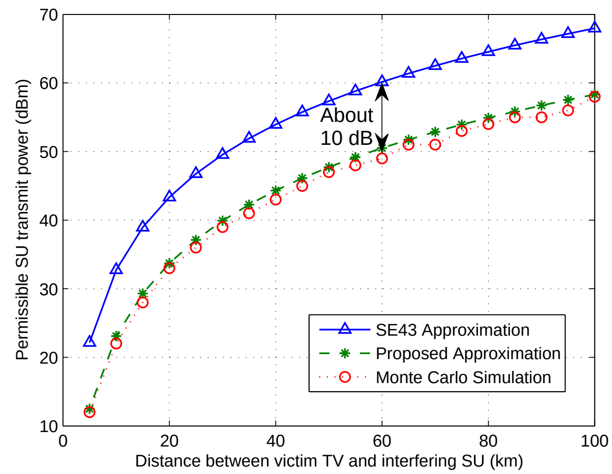

Fig. 2. Permissible transmit power for SU located at different distances from victim TV receiver ($q_1 = 95\%$, $\sigma_S = 8$dB, $\sigma_G = 10$dB).

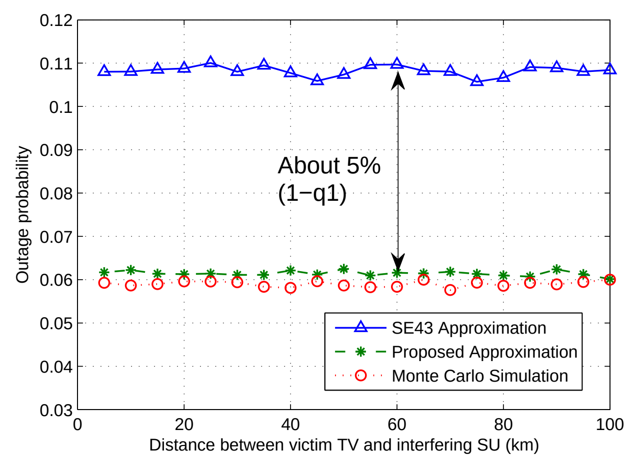

Fig. 3. Total TV outage probability when SU is transmitting at different distances from victim TV receiver ($q_1 = 95\%$, $\sigma_S = 8$dB, $\sigma_G = 10$dB).

On the other hand, $P^{prop*}_{su(\mathrm{dBm})}$ closely matches with the Monte Carlo simulation result, and the resulting interference violation is limited to the permissible level. Our proposal also performs better than the lower bound estimates introduced in [5].

The sensitivity analysis of the proposed approach is shown in Fig.6 and Fig.7, where the permissible transmit power is depicted over different standard deviation values of the shadow fading in TV signal and secondary interference. Again, the good match between the proposed approach and the simulation is observed within wide range of the standard deviation values. The SE43 approach overestimate the permissible transmit power by a rather constant margin, while the lower bound approach is becoming more conservative with higher shadow fading variance.

It worth noting that, greater shadow fading variance in the TV signal actually leads to higher permissible transmit power. The reason behind this counter-intuitive phenomenon

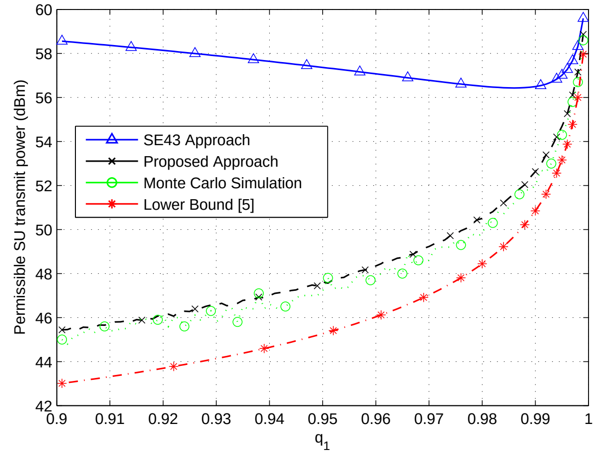

Fig. 4. Permissible transmit power for SU located at 50 km away from victim TV receiver with different q_1 ($\sigma_S = 8$dB, $\sigma_G = 10$dB).

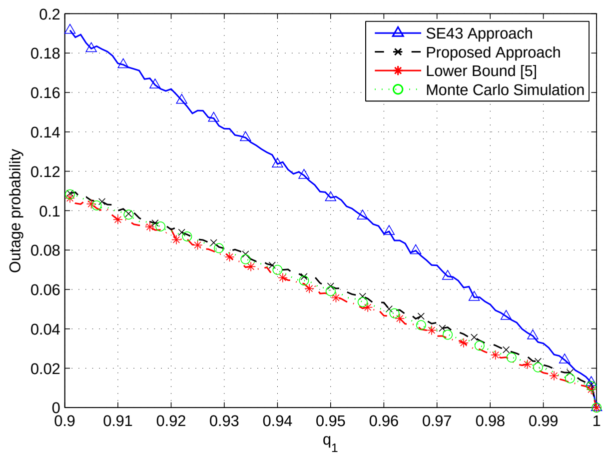

Fig. 5. Total outage probability caused by interference from SU at 50 km away from victim TV receiver with different q_1s ($\sigma_S = 8$dB, $\sigma_G = 10$dB).

is because we have fixed the TV coverage quality in this particular example: the median received TV signal must be increased to cope with the higher shadow fading variance and to keep q_1 constant. Consequently, there are more room for the secondary interference. In contrast, the permissible transmit power decreases when the shadow fading variance of the secondary interference increases, due to the larger interference margin needed to protect the TV reception in a more unpredictable environment.

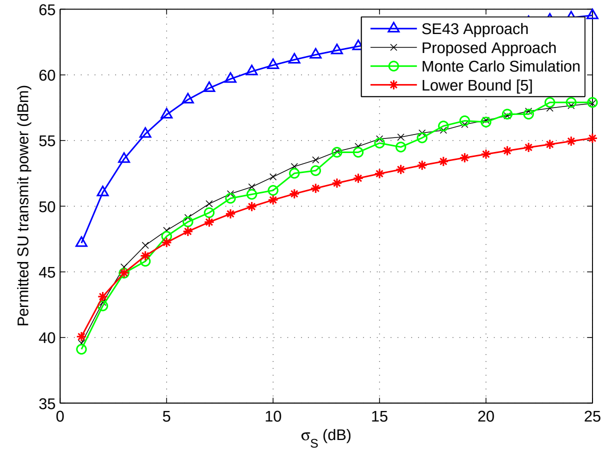

Fig. 6. Permissible transmit power for an SU at 50 km away from victim TV receiver with varying TV signal shadow fading variance ($\sigma_G = 10$dB, $q_1 = 95\%$).

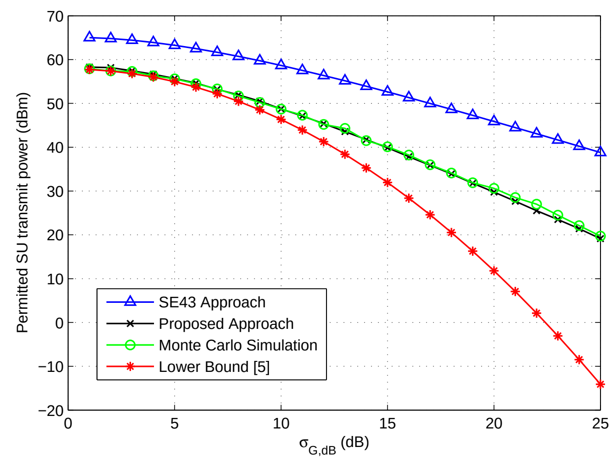

Fig. 7. Permissible transmit power for an SU at 50 km away from victim TV receiver with varying secondary interference shadow fading variance ($\sigma_S = 8$dB, $q_1 = 95\%$).

IV. Conclusion

In this paper, we briefly explained the methodology for determining permissible secondary transmit power in TV white space proposed by SE43 working group in CEPT. Then we analyzed and evaluated its analytical approach, which turns out to be overestimating the permissible power and consequently causing significant violation to TV reception. To ensure the TV protection, we proposed a new approach by applying conditional probability, whose performance is in good agreement with Monte Carlo simulations.

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