Hindawi Publishing Corporation
Journal of Electrical and Computer Engineering
Volume 2012, Article ID 245895, 12 pages
doi:10.1155/2012/245895

Research Article

Power Allocation in the TV White Space under Constraint on Secondary System Self-Interference

Byungjin Cho, Konstantinos Koufos, Kalle Ruttik, and Riku Jäntti

Department of Communications and Networking, School of Electrical Engineering, Aalto University, 02150 Espoo, Finland

Correspondence should be addressed to Byungjin Cho, byungjin.cho@aalto.fi

Received 10 February 2012; Revised 30 April 2012; Accepted 26 June 2012

Academic Editor: Paul Dan Cristea

The Electronic Communication Committee (ECC) in Europe proposed a location-based transmission power allocation rule for secondary devices operating in the TV white space (TVWS). The further the secondary device is located from the TV cell border the higher transmission power level it can utilize. The Federal Communication Committee (FCC) in the US proposed a fixed transmission power allocation rule for all secondary transmitters. Both rules do not consider the secondary system's self-interference while setting the transmission power levels. In this paper, we propose a power allocation scheme for a cellular secondary system. Unlike the ECC and the FCC proposals we do the power allocation by considering the self-interference. We define the power allocation scheme as an optimization problem. The sum cell border data rate of the secondary network is selected to be the optimization objective. We observe that the optimal transmission power levels become approximately constant over the secondary deployment area. The FCC rule captures the general trend for cellular deployment in the TVWS, since it suggests the use of constant power. However, the transmission power should not be set equal to 4 W but according to the allowable generated interference at the borders of the TV and secondary cells.

1. Introduction

Recently, cellular networks have transitioned from providing mobile telephony with limited data to supporting diverse types of applications with high capacity requirements. The increasing capacity demands for the next-generation cellular systems cannot be accommodated within the currently allocated spectrum resources. To some extent, the cellular spectrum deficit can be overcome by enabling cellular access to the unused portions of spectrum in the TV bands, also known as TV white spaces (TVWSs). The operation of cellular networks in the TVWS has been already recognized as a scenario with clear business and economic impact [1].

The main requirement for secondary operation in the TVWS is to maintain the QoS at the TV receivers. The QoS can be maintained if the interference level at the TV receivers is controlled. In the absence of secondary transmissions the TV receivers experience only the TV system's self-interference. The difference between the TV self-interference level and the maximum interference level not violating their QoS is called interference margin [2]. The interference margin can be treated as an available resource and the problem of allocating the transmission power to the cellular network can be viewed as a resource-sharing problem. Each secondary user is allowed to take a bite out of the available resource; that is, it is allowed to generate some amount of interference at the TV receivers provided that the aggregate interference of secondary transmissions does not exceed the interference margin.

The standardization bodies in the USA and Europe have so far proposed different approaches for transmission power allocation to secondary spectrum users. The Electronic Communication Committee (ECC) in Europe [3] proposes a location-based transmission power allocation rule: the further the secondary user is located from the TV cell border the higher transmission power it can utilize. For a small number (up to four) of simultaneous secondary transmissions, the ECC suggests to reduce the transmission power of each user by a fraction equal to the number of active users. This means that each user generates the same amount of interference at the TV cell border. Essentially, the available interference margin is shared equally among the active users. For a higher number of simultaneous secondary transmissions the ECC rule controls the aggregate interference by means of an additional safety margin. The Federal Communications Committee (FCC) in the USA [4] proposes a fixed transmission power level allocation equal to 4 W. The interference generated at the TV cell border can be controlled by setting protection distance. Given the same transmission power level and the different distances to the TV cell border, the secondary users take unequal shares of the available interference margin. One can deduce that the current proposals by ECC and FCC have a fundamental difference in splitting the available resource under multiuser transmission scenario.

The existing aggregate interference control methods adopted by the two standards can lead to unacceptable interference increase at the TV receivers as demonstrated in [5]. Aggregate interference control algorithms that guarantee the protection of TV receivers in the presence of secondary operation have been proposed in the academic research community. Most of the proposed algorithms make one of the following assumptions: (i) the generated interference is modelled only through its mean value and channel uncertainties due to the fading are not considered [6, 7]; (ii) the generated interference is controlled only at a single point and not along the TV coverage cell border [7–9]; (iii) the transmission power allocation in the secondary devices is uniform [8–10]. In [11] the aggregate interference control algorithm does not suffer from the above simplifications. The algorithm proposes to divide the secondary deployment area into multiple regions. The emitted spatial power density is allocated per region such that the sum power density is maximized and the aggregate interference along the TV cell border is controlled. Unfortunately, the capacity requirements of the cellular systems are overlooked in [11]. The proposed algorithm will associate regions that are deployed far from the TV coverage areas with a high power density at the cost of regions located close to the TV cell borders which will remain practically silent.

In this paper, we propose a scheme for setting the transmission power level in a cellular secondary network without violating the protection criteria of the TV receivers. While planning the coverage of a cellular network the system designer must guarantee a minimum signal to interference and noise ratio (SINR) at the cell edge. Unlike the ECC and the FCC proposals we take into consideration the secondary system self-interference constraints while setting the transmission power levels. Our scheme is formulated as an optimization problem. The sum cell border data rate is selected to be the optimization objective. Our scheme can be viewed as a method to divide the available interference margin among the cellular base stations.

We observe that the optimal transmission power becomes approximately constant over the secondary deployment area. The FCC rule appears to capture the general trend for cellular secondary deployment in the TVWS, since it suggests the use of constant power. However, the transmission power level should not be arbitrarily set equal to 4 W but according to the interference margin available at the borders of the TV and secondary cells. Note that the current FCC proposal may violate the interference margin as demonstrated in [5]. The constant power allocation rule has low complexity and it can be useful for determining countrywide power allocation for cellular networks in the TVWS. Thanks to the low complexity, this rule can be used for determining the minimum possible protection distance that allows the TV and the cellular network to coexist without generating harmful interference to each other.

The outline is as follows. Section 2 presents the system model and introduces the interference margin for the TV and the cellular systems. Section 3 formulates the problem of downlink transmission power allocation as an optimization problem. Section 4 illustrates that a constant power allocation rule is approximately optimal for secondary cells of the same size. The rule is also utilized to plan a secondary cellular network in a country-wide level. Section 5 concludes this paper.

2. System Model

Figure 1 depicts the coverage area of a TV transmitter and a part of the cellular network deployed outside of the TV protection contour. The cellular network operates in the same frequency spectrum as the TV transmitter.

In TV network planning the location probability describes the percentage of locations within a square area of $100 \times 100\,\text{m}^2$, also known as pixel, where the TV reception is satisfactory [3]. For evaluating the location probability in the presence of secondary transmissions we allocate a set of pixels at the border of the TV coverage area. If the location probability at these pixels, hereafter referred to as the TV test points, is maintained above a target threshold the operation of any TV receiver inside the TV coverage area is deemed satisfactory. Similarly, we assume that a minimum target data rate is available at the cellular end users if it can be achieved at the cellular cell border. For that purpose, another set of test points is allocated at the borders of secondary cells (see Figure 1).

For successful TV operation a target SINR, Γ_t, must be maintained with specific outage probability O_{TV} due to the slow fading. The outage probability O_{TV} is complementary to the location probability, $q = 1 - O_{\text{TV}}$, widely used in the definition of TV coverage contour [3]. The SINR, Γ_j, at the jth TV test point is

$$\Gamma_j = \frac{S_j}{I_{\text{TV},j} + I_{\text{SU},j} + P_N}, \tag{1}$$

where S_j is the wanted TV signal level, $I_{\text{TV},j}$, $I_{\text{SU},j}$ denote the aggregate interference due to the interfering TV and secondary transmissions, respectively, and P_N denotes the noise power level at the TV receivers. The condition for acceptable TV operation can be read as

$$O_{\text{TV}} \geq \Pr\left(\Gamma_j \leq \Gamma_t\right), \quad \forall j. \tag{2}$$

Similarly, while planning the coverage of a cellular network, a minimum data rate should be guaranteed at the cell edge. The impact of fast fading to the achievable

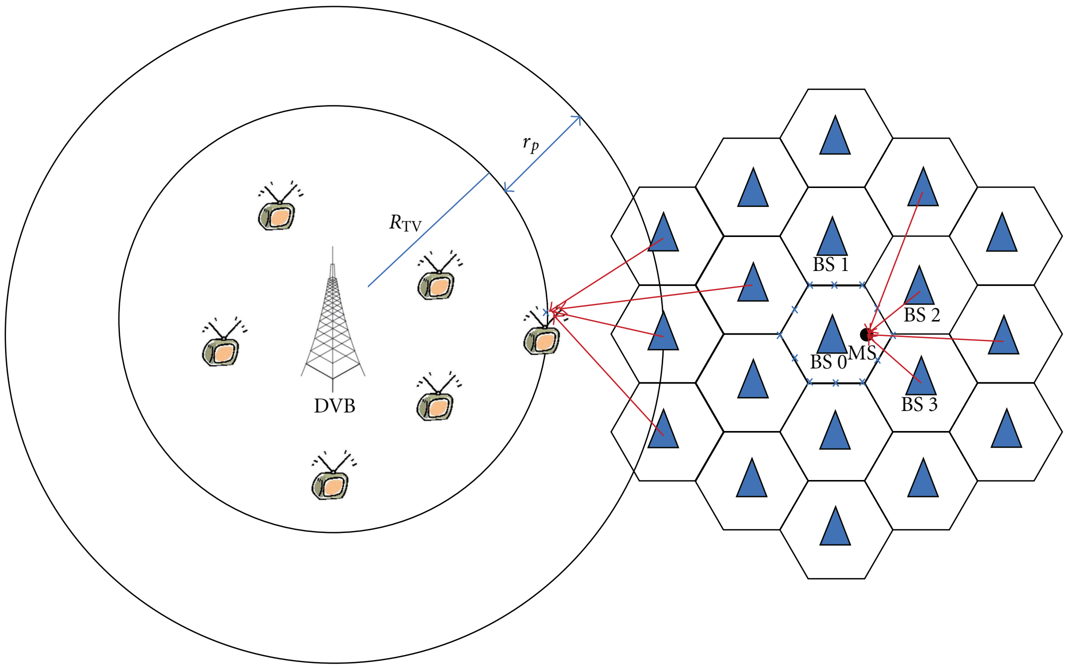


FIGURE 1: System illustration for single TV transmitter case. The cellular network operates co-channel to the TV transmitter and it is deployed outside of the TV protection area. The aggregate interference has to be controlled at the TV test points and the cellular cell borders.

data rate is ignored which is a valid assumption for a low mobility scenario. In the presence of slow fading the minimum data rate is achieved if a target SINR γ_t with given outage probability O_{SU} is satisfied. The condition for successful operation of a cellular end user can be read as

$$O_{SU} \geq \Pr(\gamma_i \leq \gamma_t), \quad \forall i. \tag{3}$$

The SINR, γ_i, at the ith secondary test point is

$$\gamma_i = \frac{s_i}{I_{TV,i} + I_{SU,i} + p_N}, \tag{4}$$

where s_i is the wanted signal level and p_N denotes the noise power at the secondary receivers.

Data traffic in cellular systems has an asymmetric behaviour with more traffic generated in the downlink than in the uplink [12]. Due to the unbalanced traffic behaviour, the downlink transmissions will affect the TV services more critically [13]. In this context, only the downlink interference is modelled. It is assumed that the cellular base stations are located at the centre of secondary cells. The aggregate cellular interference at the jth TV test point is

$$I_{SU,j} = \sum_k p_k \cdot g\left(r_{k,j}\right), \tag{5}$$

where p_k is the transmission power of the kth cellular base station, g stands for the channel model used to describe the secondary transmissions, and $r_{k,j}$ is the distance between the kth base station and the jth TV test point. Similarly, the generated TV self-interference is

$$I_{TV,j} = \sum_{m \neq m'} P_m \cdot G\left(r_{m,j}\right), \tag{6}$$

where P_m is the transmission power level for the mth interfering TV broadcaster, m' is the TV broadcaster where the jth TV test point belongs, and G is the channel model used to design the TV system.

The generated interference at the ith cellular test point consists also of two parts: cellular self-interference, $I_{SU,i}$, and TV interference $I_{TV,i}$:

$$\begin{aligned} I_{SU,i} &= \sum_{k \neq k'} p_k \cdot g(r_{k,i}), \\ I_{TV,i} &= \sum_m P_m \cdot G(r_{m,i}), \end{aligned} \tag{7}$$

where k' is the cell where the ith test point belongs. For modelling the TV and cellular transmissions

$$\begin{aligned} G(r) &= A_{TV}(r) \cdot 10^{X_{TV}/10}, \\ g(r) &= A_{SU}(r) \cdot 10^{X_{SU}/10}, \end{aligned} \tag{8}$$

where the X_{TV} and X_{SU} are zero mean Gaussian random variables modelling the slow fading with standard deviations σ_{SU} and σ_{TV}, respectively, and $A_{TV}(r)$ and $A_{SU}(r)$ describe the distance-based pathloss due to the TV and cellular transmissions, respectively, and as a function of the propagation distance r and other parameters such as operational frequency, antenna height, and environment.

Since the locations of the secondary transmitters and the TV receivers are known, the parameters $A_{TV}(r)$ and $A_{SU}(r)$ are deterministic. The only randomness in the propagation pathloss is introduced through the parameters X_{TV} and X_{SU}.

2.1. Interference Margin. In the absence of secondary transmissions condition (2) is satisfied while planning the TV network. The difference between the TV system's self-interference and the maximum generated interference not violating (2) is the interference margin [2]. The interference margin is in general different for different TV test points because different locations in the TV coverage area experience different SINR.

The interference margin at the TV coverage cell border has been calculated in [2] by using the Wilkinson method to approximate the distribution of the aggregate secondary interference. The accuracy of the Wilkinson approximation for log-normal fading [14] has been already investigated in [2, 15]. The approximation is good particularly in the upper tail of the interference distribution which necessitates a good match at the lower tail of the SINR distribution. In our system model this is of particular importance because it determines whether the protection of TV receivers is satisfactory or not.

In general, the interference margin depends on the locations of secondary transmitters. However, one has to notice that the secondary generated interference is usually an order of magnitude less than the TV signal level. This fact provides the approximation tightness for the lower bound of the interference margin illustrated in [11]. The lower bound of interference margin at the jth TV test point, $I_{\Delta,j}^{(\mathrm{TV})}$, is independent of the secondary users' locations and because of that it makes the interference control process easier:

$$I_{\Delta,j}^{(\mathrm{TV})}(\Gamma_t) = \exp\left(\frac{M_{I,j}(\Gamma_t)}{\xi}\right) - \exp\left(\frac{\sigma_{\mathrm{TV}}^2}{2\xi^2}\right) \times \sum_{m \neq m'} P_m \cdot A_{\mathrm{TV}}\left(r_{m,j}\right) - P_N, \tag{9}$$

where $M_{I,j}(\Gamma_t) = Q^{-1}(1 - O_{\mathrm{TV}})\sigma_{\mathrm{TV}} - \xi \ln(\Gamma_t) + M_{\mathrm{TV},j}$. The $M_{\mathrm{TV},j}$ is the mean useful TV signal level in dB at the jth TV test point, m are the indices of the TV broadcasters generating interfering signals at the jth TV test point, $\xi = 10/\ln(10)$ is a scaling constant, and Q^{-1} is the inverse of the Gaussian Q function.

By using a similar approach as in [2] the interference margin at the ith test point of the cellular system is

$$I_{\Delta,i}^{(\mathrm{SU})}(\gamma_t, \mathbf{p}) = \exp\left(\frac{M_{I,i}(\gamma_t, \mathbf{p})}{\xi} + \frac{\sigma_{I,i}^2}{2\xi^2}\right) - \exp\left(\frac{\sigma_{\mathrm{TV}}^2}{2\xi^2}\right) \sum_m P_m \cdot A_{\mathrm{TV}}(r_{m,i}) - p_N, \tag{10}$$

where $M_{I,i}(\gamma_t, \mathbf{p}) = Q^{-1}(1 - O_{\mathrm{SU}})\sqrt{\sigma_{\mathrm{SU}}^2 + \sigma_{I,i}^2} - \xi \ln(\gamma_t) + m_{\mathrm{SU},i}(p_k)$. The $\mathbf{p}$ stands for the vector of transmission power levels for the cellular base stations. The kth element of $\mathbf{p}$ has been denoted by p_k. The $\sigma_{I,i}$ in dB is the standard deviation of the aggregate TV and secondary self-interference and the $m_{\mathrm{SU},i}(p_k)$ is the mean useful signal level in dB at the ith test point of the kth cellular base station. The $M_{I,i}$ depends on the transmission power levels of the interfering cellular base stations through the parameter $\sigma_{I,i}$ and on the transmission power level of the base station generating the useful signal through the function $m_{\mathrm{SU},i}(\cdot)$.

Unlike the TV test points, the generated interference at the cellular cell borders is in the same order with the useful signal level. Nevertheless, Figure 2(b) shows that the approximation by setting $\sigma_{I,i} = 0$ in (10) is valid unless the standard deviation σ_{SU} takes a high value or the reuse distance becomes small. After setting $\sigma_{I,i} = 0$ in (10) the interference margin $I_{\Delta,i}^{(\mathrm{SU})}$ depends only on the transmission power p_k. In fact, it is a linear function of p_k. Hereafter,

$$I_{\Delta,i}^{(\mathrm{SU})}(\gamma_t, p_k) = \exp\left(\frac{M_{I,i}(\gamma_t, p_k)}{\xi}\right) - \exp\left(\frac{\sigma_{TV}^2}{2\xi^2}\right) \sum_m P_m \cdot A_{\mathrm{TV}}(r_{m,i}) - p_N, \tag{11}$$

where $M_{I,i}(\gamma_t, p_k) = Q^{-1}(1 - O_{\mathrm{SU}})\sigma_{\mathrm{SU}} - \xi \ln(\gamma_t) + m_{\mathrm{SU},i}(p_k)$.

3. Problem Formulation

We are looking for the power allocation maximizing the sum cell border data rate of the cellular system while not violating the protection criteria of TV and cellular systems. We assume one-by-one scheduling in each cell. In order to evaluate the sum rate optimization function we compute for each cell the average cell border data rate over the test points of that cell. Then, we sum the calculated values over all the cells. Our optimization function has the form of (12a). Note that it is straightforward to extend the optimization function to include also test points inside the cells. For reducing the amount of computations in the country-wide case study, we have considered only points located at the cellular cell borders.

The interference margins $I_{\Delta,j}^{(\mathrm{TV})}$, $I_{\Delta,i}^{(\mathrm{SU})}$ are equal to the maximum mean secondary interference level that does not violate the TV and cellular protection criteria, respectively. In order to maintain the mean generated interference under the margins (9) and (11) the cellular base stations must set appropriately their transmission power levels. In the presence of slow fading the mean interference level is equal to the distance-based path loss calculated in (5) scaled with the mean of the slow fading $\exp(\sigma_{\mathrm{SU}}^2/2\xi^2)$. Solving $I_{\Delta,j}^{\mathrm{TV}}(\Gamma_t) \geq \exp(\sigma_{\mathrm{SU}}^2/2\xi^2) \cdot \sum_k p_k A_{\mathrm{SU}}(r_{k,j})$ for the unknown power levels p_k allows to express the TV system constraint (2) in the form of (12b). By following the same approach for the cellular test points constraint (12c) is obtained. Finally, the power allocation scheme can be formulated as the following constrained optimization problem:

$$\underset{\mathbf{p}}{\text{Maximize}} : \frac{W}{N_p} \cdot \sum_k \sum_i \log_2 \left(1 + \gamma_{k,i}(\mathbf{p})\right), \tag{12a}$$

$$\text{Subject to} : \sum_k p_k \cdot A_{\text{SU}}\left(r_{k,j}\right) \leq \exp\left(-\frac{\sigma_{\text{SU}}^2}{2\xi^2}\right) \cdot I_{\Delta,j}^{(\text{TV})}(\Gamma_t), \quad \forall j, \tag{12b}$$

$$\sum_{k' \neq k} p_{k'} \cdot A_{\text{SU}}(r_{k',i}) \leq \exp\left(-\frac{\sigma_{\text{SU}}^2}{2\xi^2}\right) \cdot I_{\Delta,i}^{(\text{SU})}(\gamma_t, p_k), \quad \forall i, \ \forall k, \tag{12c}$$

where W is the transmission bandwidth of the secondary system, N_p is the number of test points per secondary cell, and $\gamma_{k,i}$ is the SINR at the ith test point of the kth secondary cell,

$$\gamma_{k,i}(\mathbf{p}) = \frac{p_k \cdot A_{\text{SU}}(r_{k,i})}{\sum_{k' \neq k} p_{k'} \cdot A_{\text{SU}}(r_{k',i}) + \sum_m P_m \cdot A_{\text{TV}}(r_{m,i}) + p_N}. \tag{13}$$

Note that the optimization problem (12a)–(12c) may not have a feasible solution. If the SINR target γ_t is high, it may not be satisfied no matter how high transmission power the cellular base station utilizes. Also, the SINR target at the TV test points Γ_t imposes an upper limit on how much power the cellular base station can utilize.

3.1. Comments on Optimal Algorithm. The data rates of secondary cells are coupled due to mutual interference. Optimal power allocation is known to be difficult to achieve due to this complicated coupling among the SINR of different links [16]. A single term in (12a) is a quasiconcave function of the transmission power levels $\mathbf{p}$. In contrast to the property of concave functions, quasi-concave functions are not closed under addition, and the optimization problem (12a)–(12c) is not convex.

Possible methods for solving this nonconvex optimization problem are approximation, relaxation, and transformation. For instance, in the high SINR regime the individual rate can be approximated by $W \log_2(\gamma_{k,i})$ [17]. Under this approximation, the optimization problem (12a)–(12c) can be transformed into a convex problem in the form of geometric programming by proper change of variables. However, the high SINR assumption is not valid in general where fading environment is considered or nearby links heavily interfere with each other. The authors in [18] solved the problem by using a generalized linear fractional program. However, this algorithm is limited to only small-scale problems. In this paper we consider the cell border data rate in our optimization function, and thus, we cannot use the high SINR approximation. By using the quotient property of the logarithm, the optimization function (12a) can be written as a difference of two terms:

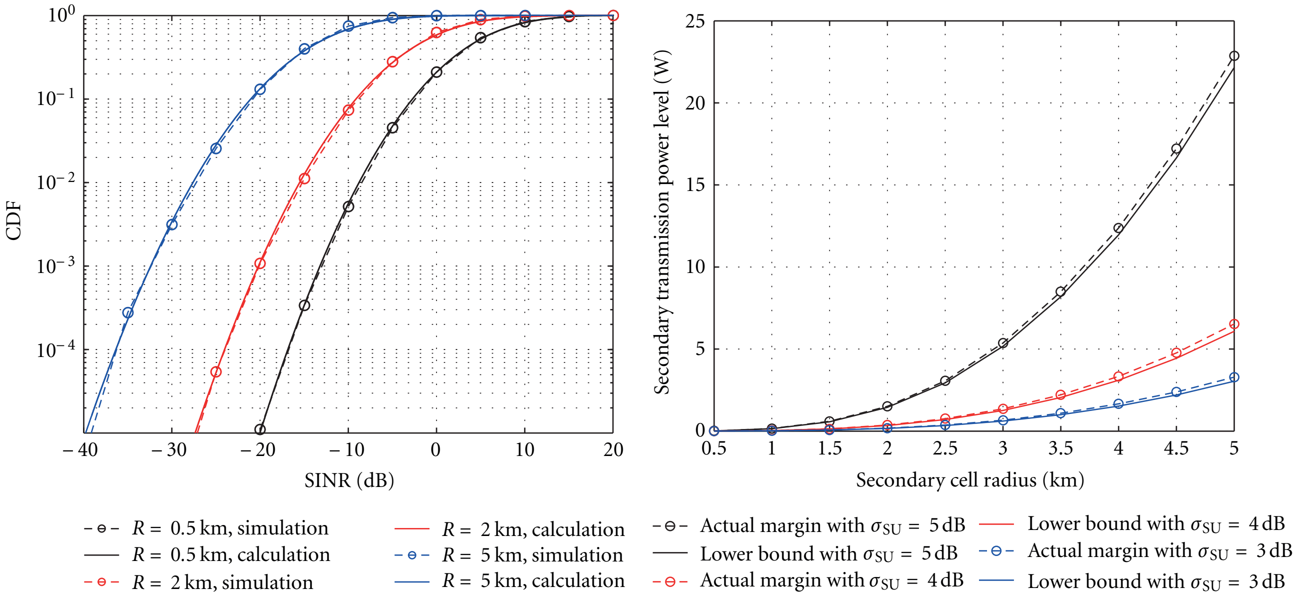
$$\begin{aligned} &\frac{W}{N_p} \sum_k \sum_i \log_2 \left(C_{k,i} + \sum_k p_k \cdot A_{\text{SU}}(r_{k,i}) \right) \\ &\quad - \frac{W}{N_p} \sum_k \sum_i \log_2 \left(C_{k,i} + \sum_{k' \neq k} p_{k'} \cdot A_{\text{SU}}(r_{k',i}) \right), \end{aligned} \tag{14}$$

where $C_{k,i} = p_N + \sum_m P_m \cdot A_{\text{TV}}(r_{m,i})$ are constants.

Both terms are increasing concave functions in $\mathbf{p}$. Therefore the optimization problem (12a)–(12c) can be formulated as a difference convex (DC) programming problem under linear constraints. One can use, for instance, the branch and bound method [19] to obtain the global optimal solution. However, the monotonic optimization techniques are practical only for small-scale optimization problems. In this paper, we will consider a countrywide power allocation scenario with a large number of secondary cells. Due to these reasons we resort to the constrained nonlinear minimization solver with interior point algorithm in the optimization toolbox of Matlab [20].

3.2. Feasibility Check. Feasibility means there exists a set of positive transmit power levels $\mathbf{p}$ such that the cellular coverage constraints (12c) are met while the interference caused to the TV test points does not violate the TV protection constraint (12b). Checking for feasibility in optimization problem (12a)–(12c) is degenerated to identifying whether the system of linear inequalities (12b)–(12c) is consistent. This is straightforward to check by using, for instance, the simplex method. In Figure 3 we plot the minimum protection distance for different secondary SINR target levels. By increasing the distance separation between the two systems the spatial spectrum reuse decreases but the data rate of the cellular system increases.

3.3. Constant Power Allocation. It is computationally difficult to solve (12a)–(12c) for a large number of cellular base stations. In Section 4 it will be illustrated that the optimal solution to the optimization problem (12a)–(12c) results in approximately uniform power allocation over the secondary deployment area. This can be justified as follows: the transmission power level of base stations located close to the



(a) (b)

Figure 2: (a) Distribution of the SINR at the cellular cell borders. The simulations are compared to the calculations. In our calculations the aggregate interference is modelled by the log-normal distribution. Different secondary cell radiuses are tested. The standard deviation is taken equal to $\sigma_{SU} = 5$ dB. (b) Transmission power level required to achieve SINR target $\gamma_t = -3.5$ dB at the cellular cell border with outage probability $O_{SU} = 10\%$ for different cell radiuses and reuse distance $K = 3$. The results obtained by using the actual interference margin (10) are compared to the results obtained by using the lower bound of the interference margin (11). The rest of the parameter setting can be found in Section 4.1.

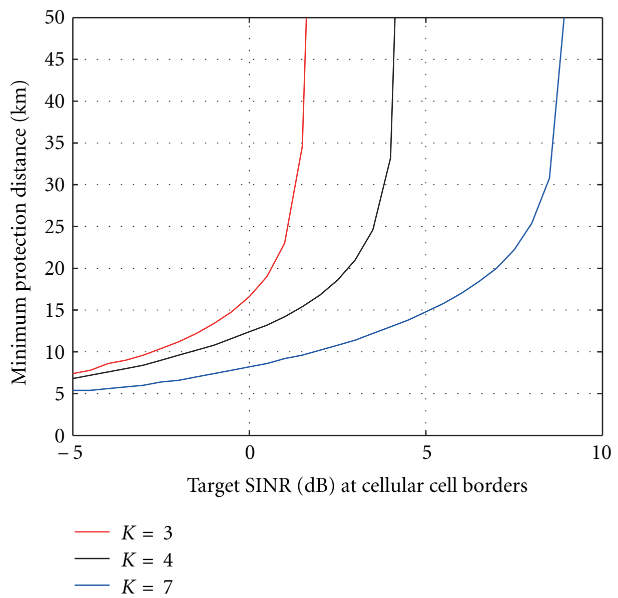


Figure 3: Minimum protection distance satisfying TV and secondary system cell coverage constraints with respect to different cellular SINR target γ_t. Different reuse distances K are tested. The cell radius is taken equal to 1 km. The rest of the parameter settings are the same used in Section 4.

TV cell border is limited due to the generated interference at the TV test points. The base stations located close to the TV coverage areas should use just enough power to satisfy their own coverage constraints (3). On the other hand, the transmission power level of base stations located far from the TV test points is limited due to the interference they generate at nearby located secondary cells. Even though secondary base stations located far from the TV coverage border can utilize high transmission power the gains in data rate will be marginal due to the secondary self-interference.

The optimal common power level that maximizes the cellular cell border data rate under the TV protection and cellular coverage constraints can be obtained by solving the following concave problem:

$$\underset{p_{\mathrm{SU}}}{\text{Maximize}}: \frac{W}{N_p} \cdot \sum_k \sum_i \log_2\left(1 + \gamma_{k,i}\left(p_{\mathrm{SU}}\right)\right), \tag{15a}$$

$$\text{Subject to}: p_{\mathrm{SU}} \leq \exp\left(-\frac{\sigma_{\mathrm{SU}}^2}{2\xi^2}\right) \cdot \frac{I_{\Delta,j}^{(\mathrm{TV})}\left(\Gamma_t\right)}{\sum_k A_{\mathrm{SU}}\left(r_{k,j}\right)}, \quad \forall j, \tag{15b}$$

$$p_{\mathrm{SU}} \leq \exp\left(-\frac{\sigma_{\mathrm{SU}}^2}{2\xi^2}\right) \cdot \frac{I_{\Delta,i}^{(\mathrm{SU})}\left(\gamma_t, p_{\mathrm{SU}}\right)}{\sum_{k' \neq k} A_{\mathrm{SU}}\left(r_{k',i}\right)}, \quad \forall i,\ \forall k. \tag{15c}$$

Thanks to its low complexity, the uniform power allocation rule gives an opportunity to get quickly insight on the impact of various parameters on the cellular data rate and the TV protection criteria. For instance, the system designer can identify the minimum possible protection distance that allows the TV and the cellular network to coexist without violating their own protection constraints. Also, the low complexity makes the uniform power allocation rule attractive for cellular network planning in the TVWS over a country-wide level.

4. Numerical Illustrations

In this section we study the problem of allocating the transmission power level in a cellular network deployed outside the protection area of a TV transmitter. When the cell size is fixed, it is illustrated that all the cellular base stations transmit approximately at the same transmission power level. When the cell size can vary based on the population density it is illustrated that cells of the same size tend to use approximately equal transmission power levels. We use this approximation to study a country-wide cellular deployment in the TVWS.

4.1. Parameter Settings. Different models are used to estimate the field attenuation in the propagation path for the TV transmitters and the cellular base stations. The propagation prediction for DVB-T signal over land path is obtained by using the Recommendation ITU-R P.1546 [21]. The modified HATA model [22] for suburban areas is used to describe the path loss in cellular system. The receiver heights for TV and secondary reception are equal to 10 m and 1.5 m, respectively. The antenna height for cellular base stations is taken equal to 10 m. The standard deviations for the log-normal fading distributions are $\sigma_{\mathrm{TV}} = \sigma_{\mathrm{SU}} = 5$ dB. The outage probability is set $O_{\mathrm{TV}} = O_{\mathrm{SU}} = 10\%$ equal to the complementary of the target location probability motivated from [3]. The thermal noise power is $P_N = p_N = -106$ dBm for signal bandwidth $W = 8$ MHz. The SINR targets for the TV and the secondary receivers are taken equal to $\Gamma_t = 17.1$ dB and $\gamma_t = -3.5$ dB, respectively. The selected SINR target Γ_t for satisfactory TV operation is the minimum required value for quasi-error-free reception with 64 QAM modulation level and 2/3 code rate in the Rician channel [23, page 279]. The selected target SINR value γ_t for the cellular network with reuse distance $K = 3$ gives minimum distance separation between the two systems approximately equal to 9 km which is at the same order with the protection distance proposed by FCC for cochannel primary/secondary operation [4].

First, we carry out the simulation in a single TV cell scenario and ignore the self-interference in the TV network, $I_{\mathrm{TV},j} = 0$ in (1). The TV cell radius is taken equal to 140 km as an illustrative case study. For 350 kW TV transmission power level, the SNR at the TV cell border in the absence of secondary transmissions becomes lower than 21.1 dB with 10% outage probability. Since the target SINR at the same outage level is equal to 17.1 dB, there is a 4 dB margin that creates opportunity for secondary transmissions. The operating frequency is set to 482 MHz same as the TV channel 22 in Finland.

The optimization constraint (12b) has to be satisfied at hundred test points uniformly allocated along the TV cell border. Outside of the TV protection area the secondary system is deployed. The coverage area of the secondary system is limited at 40 km far from the TV protection area border. This value has been motivated from [24] where it is shown that secondary interferers located further than 30 km from the protection area border do not contribute much to the aggregate interference level. Also, constraint (12c) should be satisfied at twelve points located at the border of each secondary cell.

4.2. Uniform Cell Size. In Figure 4 the transmission power levels for secondary base stations have been calculated by solving the optimization problem (12a)–(12c). The protection distance must be larger than 9 km to give feasibility. It is selected equal to 11 km. For better illustration the spatial power density emitted from the secondary deployment area is depicted. The spatial power density is computed by dividing the transmission power level p_k with the secondary cell size scaled by the reuse distance. One can observe that satisfying only the TV constraints results in high difference in transmission power levels between the base stations located close and far from the TV cell border (Figure 4(a)). If the cellular coverage constraint is also taken into account

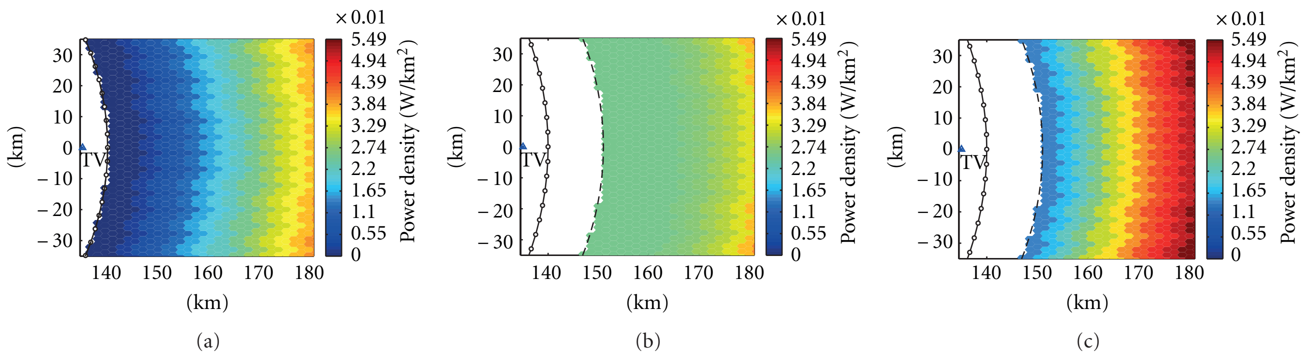


Figure 4: Spatial power density emitted from the secondary deployment area obtained by solving the optimization problem (12a)–(12c) when taking into account (a) only TV protection constraints (12b) with protection distance 0 km, (b) both TV and secondary constraints (12b), (12c) with protection distance 11 km, and (c) only TV protection constraints (12b) with protection distance 11 km.

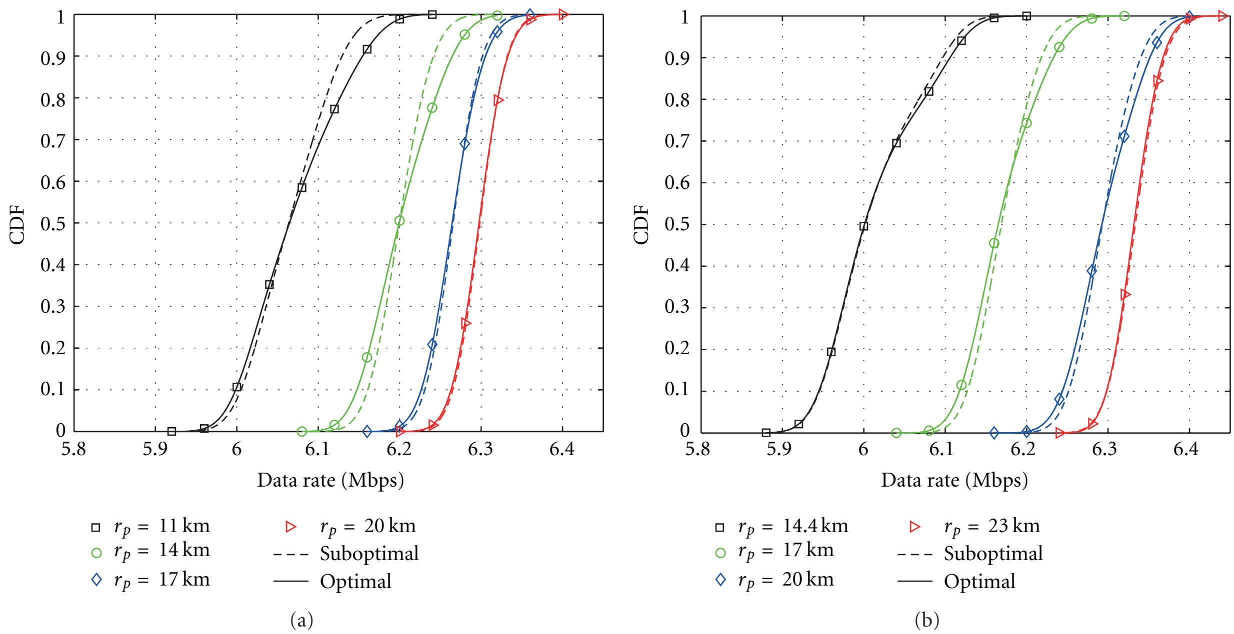


Figure 5: Distribution of average cell data rate for different protection distances. The cellular transmission power levels are obtained by solving the optimization problem (12a)–(12c) and also by solving the optimization problem (15a)–(15c). The cell radius is taken equal to (a) 1 km (b) 2 km.

(Figure 4(b)), two observations can be made. Firstly, a protection distance between the TV and the cellular system is required to guarantee that the two systems do not generate harmful interference to each other. Secondly, the transmission power levels allocated to secondary cells close and far from the TV cell border are about the same. One may argue that the uniform transmission power levels can be attributed solely to the protection distance. However, it is the cellular constraint that prohibits the cells located far from the TV cell border to utilize a high transmission power level; compare Figures 4(b) and 4(c). Note that the higher transmission power levels at the outer region of the secondary deployment area are attributed to the border condition, that is, the limited self-interference these cells experience.

In Figure 5, the distribution of the average cell data rate is depicted for fixed cell radius, equal to 1 km in Figure 5(a) and 2 km in Figure 5(b). For computing the average data rate in a cell, we generate a dense grid of points inside a cell and calculate the average data rate over all the grid points. We compare the distribution resulting from optimizing the transmission power per base station (12a)–(12c) to the distribution resulting from using constant transmission power allocation (15a)–(15c). The data rate distribution curves almost overlap. The cellular base stations far from the TV cell border are able to utilize high transmission power levels without violating the protection limits of TV receivers. However, the gains in data rate are marginal due to the secondary self-interference. Because of that, the constant

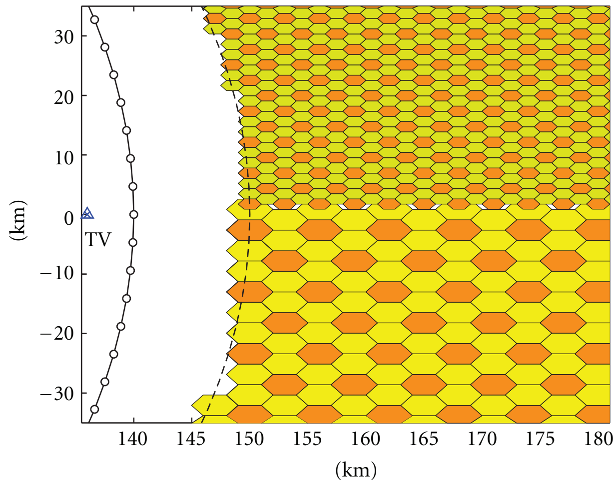


Figure 6: System illustration for different cell size coexistence case.

power allocation rule results in near-optimal data rate values.

One can also notice that the uniform power allocation rule becomes more accurate for larger protection distance. When the secondary network is deployed far from the TV cell border, it can reach the interference-limited mode. In interference-limited mode and provided that all cells have the same radius, the data rate is maximized when all cells utilize the same maximum transmission power level. In our computations the maximum allowable transmission power is set equal to 100 W.

Note also that for 2 km cell radius the optimization problems (12a)–(12c) and (15a)–(15c) do not give any feasible solution for protection distance equal to 11 km. The cellular base stations deployed close to the TV cell border cannot utilize high enough transmission power for meeting their own target SINR without violating the TV constraints. Nevertheless, when constant power allocation is employed, it is computationally easy to find the minimum protection distance resulting in feasible solutions.

4.3. Nonuniform Cell Size. Next, we consider a cellular layout with non-uniform cell size (Figure 6). The secondary deployment area is divided into two parts. The upper part is covered with hexagonal cells of radius 1 km, while the lower part is covered with cells of radius equal to 2 km. The rest of the parameter settings remains the same as in the previous case study. Firstly, the transmission power level is optimized per cell. The distribution of data rate values for the cells of 1 km and 2 km cell radius is depicted in Figures 7(a) and 7(b), respectively, with solid curves. Secondly, it is assumed that cells of the same size utilize the same transmission power level. Therefore, only two transmission power levels are identified while solving the optimization problem (12a)–(12c). For instance, for 14 km protection distance the small cells utilize transmission power equal to 0.275 W while the large cells utilize transmission power level equal to 1.340 W. The distribution of data rate using same power for cells of the same type is depicted in Figure 7 with dashed curves. One can notice that the data rate distribution curves almost overlap. Assuming that cells of the same size utilize same transmission power level results in near-optimal solutions. Next, we use this approximation to study power allocation in the TVWS at a country-wide level.

4.4. Finland Case Study. For the Finland case study the TV transmission power levels are not arbitrarily set as for the single TV cell study. The actual transmission power levels have been taken from Finnish Communications Regulatory Authority (FICORA). The DVB-T coverage is calculated according to [25] by using the Recommendation ITU-R P.1546 [21] for land paths. The mean useful TV signal field strength for 500 MHz is equal to 52.5 dBuV/m [25] which corresponds to −78.6 dBm useful signal power. Also, the TV self-interference terms are taken into consideration while solving the optimization problems.

In order to simplify the cellular deployment we cover the country with square cells. We consider three different cell types, urban, suburban, and rural. The distance R from the centre of the square to its vertices for the different cell types is taken equal to 0.5 km, 2 km, and 5 km, respectively. The cell type is selected such that the population inside a cell does not exceed the 10 000. In Figure 4 the cellular layout in Finland is depicted. Densely populated cities in the south are covered with small urban cells while sparsely populated areas in the north are covered with large rural cells. The cellular base stations inside the protection contour of TV transmitters using channel 22 do not transmit. Our scheme does not consider so far adjacent channel TV protection. Similar to the FCC rules, it is assumed that the cellular transmitters inside the protection area of the first adjacent channels do not transmit. The protection distances used in our simulation are taken from the FCC rules [4], 14.4 km for the co-channel and 0.74 km for the adjacent channel. For frequency reuse distance $K = 3$ it is not possible to satisfy simultaneously the TV and the cellular constraints. Because of that, reuse distance $K = 4$ is utilized.

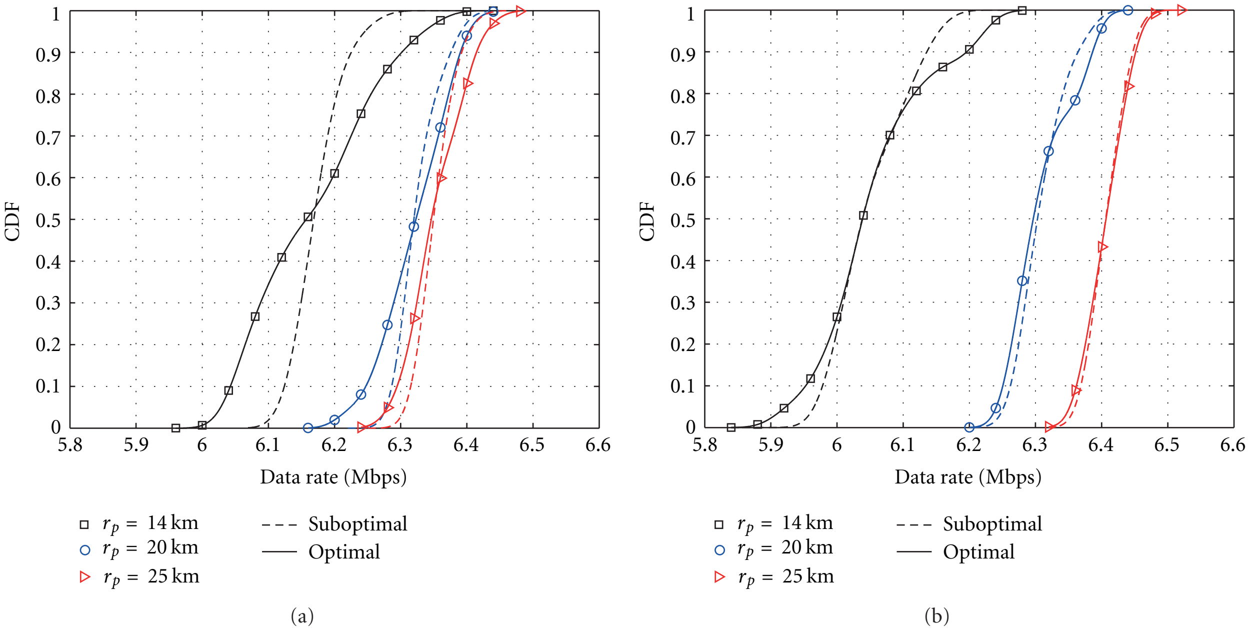


FIGURE 7: Distribution of average cell data rate by optimizing the transmission power for each base station and also by assuming equal transmission power for cells of the same size. (a) Upper part of secondary deployment area with cell radius 1 km. (b) Lower part of secondary deployment area with cell radius 2 km.

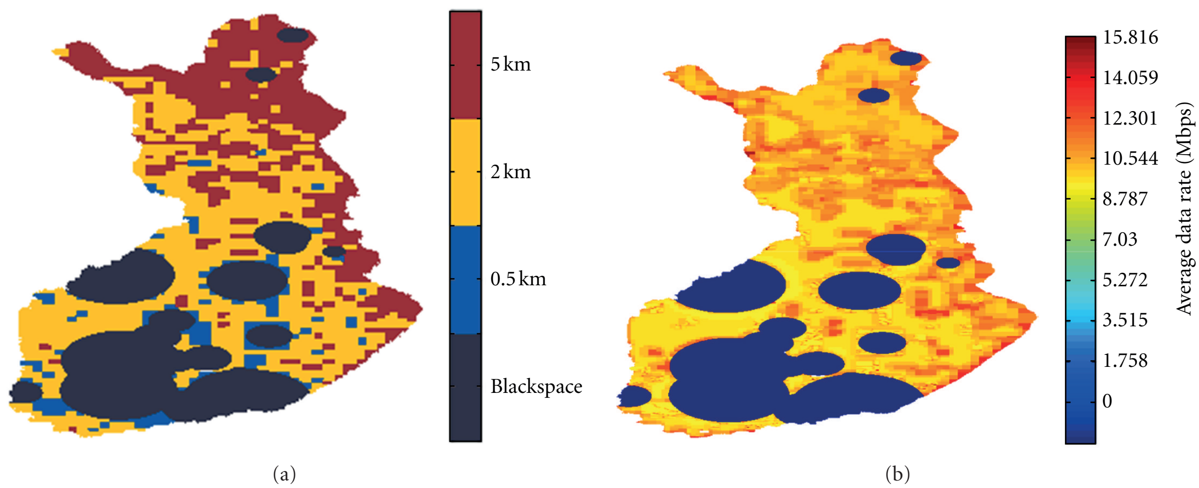
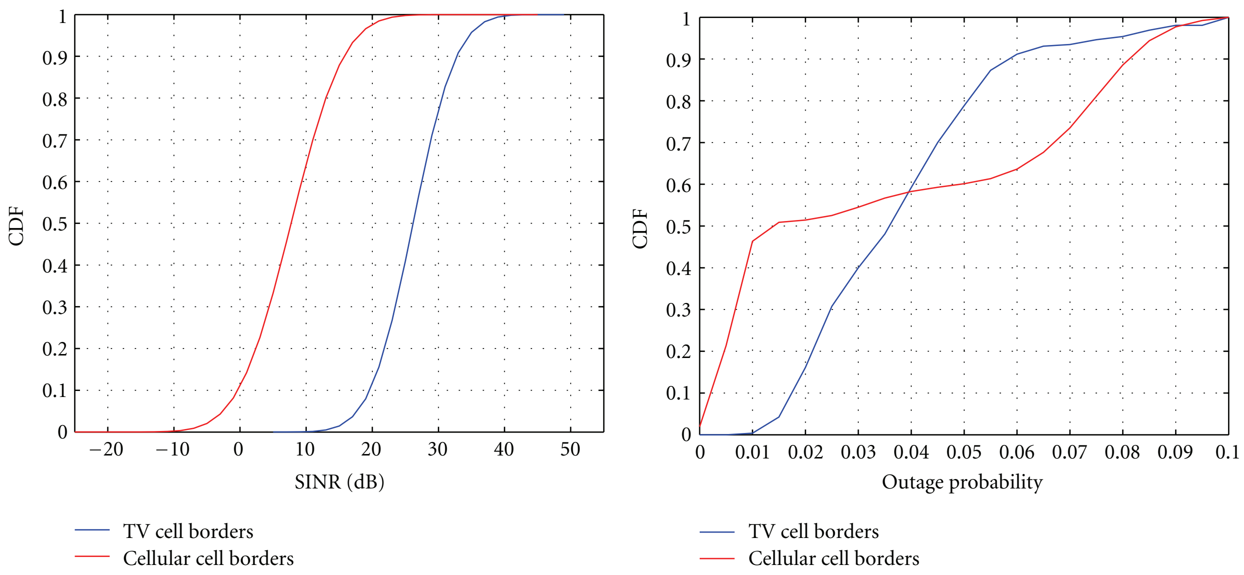


FIGURE 8: (a) Cellular layout in Finland based on the population density. The black space corresponds to the area where the secondary transmissions are not allowed. (b) Color-coded map of average data rate for a cellular network operating in TV channel 22 in Finland.

We assume that the transmission power level is common for cells of the same type. In that case, the solution of the optimization problem (12a)–(12c) results in transmission power levels equal to 88 mW for urban cells, 1.54 W and 10.2 W for suburban and rural cells, respectively. Figure 8(b) depicts the color-coded map of cell average data rate in Finland by using the above-mentioned transmission power values. The cell average data rate is described by the average of the data rate values at 36 points uniformly located along the cell border and inside the cell. One can see that the average data rate for an urban cell in the TVWS for the calculated transmission power levels is on average 10 Mbps.

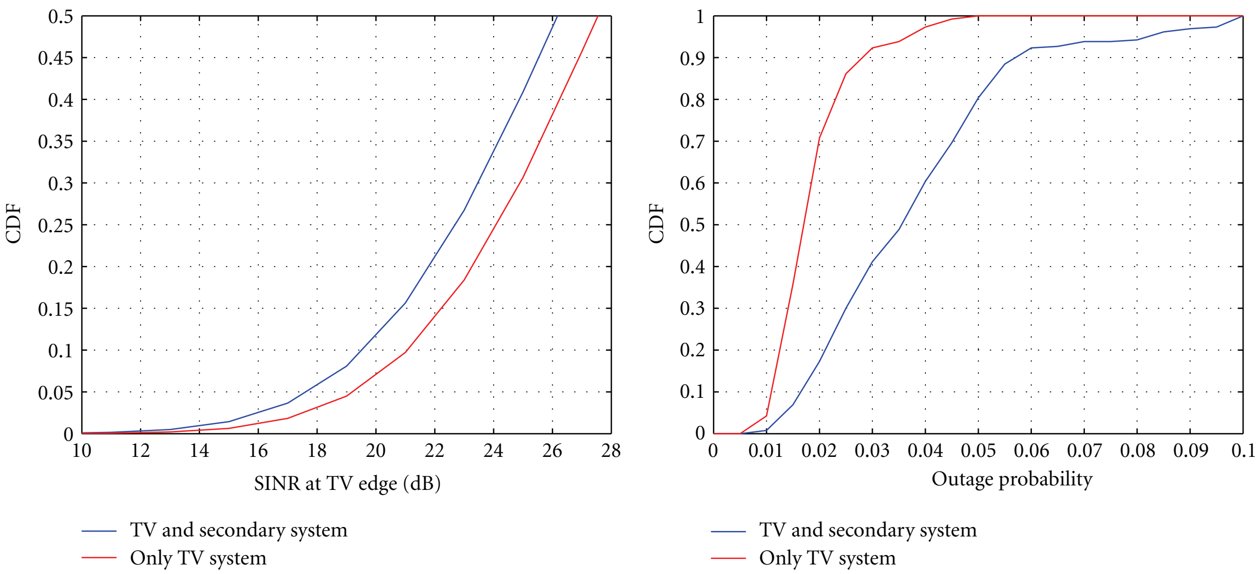
The power density can be calculated as the ratio of allocated transmission power divided by the cellular cell size scaled by the reuse distance. The power density values allocated to urban, suburban, and rural cells are equal to $\{44, 48, 51\}$ mW/km^2, respectively. One can deduce that the power density emitted from the deployment area of the cellular system is almost uniform over all the country. This remark agrees with the recently proposed uniform power density allocation rule [26].

Figure 9 validates that the protection criteria for the TV and the cellular system are satisfied while solving the optimization problem (12a)–(12c). The distribution



(a) (b)

Figure 9: (a) SINR distribution at the TV test points and the cellular cell borders. (b) Distribution of the outage probability at the TV test points and the cellular cell borders.



(a) (b)

Figure 10: (a) SINR distribution at the TV test points. (b) Distribution of the outage probability at the TV test points.

of the SINR at the TV test points and the cellular cell borders is simulated and depicted in Figure 9(a). The outage probability is approximately equal to 4% at the TV and the cellular cell borders which is lower compared with their outage probability target, 10%. Obviously, only few of the constraints (12b)-(12c) are tight. This observation is confirmed in Figure 9(b) depicting the distribution of the outage probability at the test points. One can observe that 80% of the TV test points experience an outage probability of less than 5%.

Figure 10(a) shows the SINR degradation for the country-wide scenario due to the secondary transmissions. In Figure 10(b) one can see that the mean location probability is reduced from 98.2% to 96.3%. Overall, by using the power allocation algorithm proposed in the paper, the secondary transmissions would reduce the location probability of the TV system but will not bring it under its target limit. In this sense, the coverage area of the TV system is not compromised because the target location probability at the target SINR is not violated.

5. Conclusions

In this paper we proposed a method to set the transmission power level in a cellular network operating in the TVWS without violating the protection criteria of TV receivers. Unlike the existing ECC and FCC rules we consider the cellular self-interference constraint while setting the transmission power levels. The paper shows that allocating same power to cells of the same size results in approximately maximum sum cell border data rate. However, the common transmission power level should not be set equal to 4 W as proposed by FCC rules but according to the interference margin available at the borders of the TV and secondary cells. In this paper we did not consider the impact of secondary interference to the adjacent channel TV receivers. We assumed that the FCC rule not allowing secondary transmissions inside the protection area of the first adjacent channels is sufficient. In our future work we plan to extend the power allocation rule including also adjacent channel protection from aggregate secondary interference.

Acknowledgments

This work was partially supported by the TEKES-funded Project IMANET+ and by the EU FP7 Project INFSO-ICT-248303 QUASAR.

References

[1] J. Zander, J. Kronander, A. Achtzehn, M. Nekovee, K. W. Sung, and S.-L. Kim, "QUASAR scenarios for white space assessments and exploitation," in *URSI EMC Conference*, Worclaw, Poland, September 2010.

[2] K. Ruttik, K. Koufos, and R. Jäntti, "Modeling of the secondary system's generated interference and studying of its impact on the secondary system design," *Radioengineering*, vol. 19, no. 4, pp. 488–493, 2010.

[3] Technical and operational requirements for the possible operation of cognitive radio systems in the white spaces of the frequency band 470-790 MHz, ECC Report 159 (under public consultation), 2010, http://www.ero.dk/.

[4] In the Matter of Unlicensed Operation in the TV Broadcast Bands: second Memorandum Opinion and Order, Federal Communications Commission, FCC 10-174, 2010, http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-10-174A1.pdf.

[5] R. Jäntti, J. Kerttula, K. Koufos, and K. Ruttik, "Aggregate interference with FCC and ECC white space usage rules: case study in Finland," in *Proceedings of the IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN '11)*, pp. 599–602, May 2011.

[6] M. Vu, N. Devroye, and V. Tarokh, "On the primary exclusive region of cognitive networks," *IEEE Transactions on Wireless Communications*, vol. 8, no. 7, pp. 3380–3385, 2009.

[7] N. Hoven and A. Sahai, "Power scaling for cognitive radio," in *WirelessCom Symposium on Emerging Networks, Technologies and Standards*, June 2005.

[8] S. A. R. Zaidi, D. C. Mclernon, M. Ghogho, and B. Zafar, "On outage and interference in 802. 22 cognitive radio networks under deterministic network geometry," in *Proceedings of the ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiCom '09)*, Beijing, China, September 2009.

[9] N. S. Shankar and C. Cordeiro, "Analysis of aggregated interference at DTV receivers in TV bands," in *Proceedings of the 3rd International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CrownCom '08)*, May 2008.

[10] E. Larsson and M. Skoglund, "Cognitive radio in a frequency-planned environment: some basic limits," *IEEE Transactions on Wireless Communications*, vol. 7, no. 12, pp. 4800–4806, 2008.

[11] K. Koufos, K. Ruttik, and R. J. Jäntti, "Controlling the interference from multiple secondary systems at the TV cell border," in *Proceedings of the Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC '11)*, Toronto, Canada, September 2011.

[12] W. Lu, *Broadband Wireless Mobile: 3G and Beyond*, Wiley, Hoboken, NJ, USA, 2002.

[13] A. Sadek and S. Shellhammer, "Aggregate interference at a DTV receiver for a hexagonal cell structure," IEEE 802. 22-07/0411r1, 2007.

[14] G. L. Stüber, *Principles of Mobile Communications, Publishers*, Kluwer Academic, 1996.

[15] P. Cardieri and T. S. Rappaport, "Statistical analysis of co-channel interference in wireless communications systems," *Wireless Communications and Mobile Computing*, vol. 1, no. 1, pp. 111–121, 2001.

[16] Z. Q. Luo and S. Zhang, "Dynamic spectrum management: complexity and duality," *IEEE Journal on Selected Topics in Signal Processing*, vol. 2, no. 1, pp. 57–73, 2008.

[17] C. W. Sung, "Log-convexity property of the feasible SIR region in power-controlled cellular systems," *IEEE Communications Letters*, vol. 6, no. 6, pp. 248–249, 2002.

[18] L. P. Qian, Y. J. Zhang, and J. Huang, "MAPEL: achieving global optimality for a non-convex wireless power control problem," *IEEE Transactions on Wireless Communications*, vol. 8, no. 3, pp. 1553–1563, 2009.

[19] R. Horst and N. V. Thoai, "Dc programming: overview," *Journal of Optimization Theory and Applications*, vol. 103, no. 1, pp. 1–43, 1999.

[20] P. Venkataraman, *Applied Optimization with MATLAB Programming*, John Wiley & Sons, 2009.

[21] "Method for point-to-area predictions for terrestrial services in the frequency range 30 MHz to 3000 MHz," ITU-R P. 1546-4, 2009.

[22] ERC Report 68, "Monte Carlo Radio Simulation Methodology," Naples, Italy, 2000.

[23] U. Reimers, *DVB-the Family of International Standards for Digital Video Broadcasting*, Springer, Berlin, Germany, 2nd edition, 2005.

[24] K. Ruttik, K. Koufos, and R. Jantti, "Computation of aggregate interference from multiple secondary transmitters," *IEEE Communications Letters*, vol. 15, no. 4, pp. 437–439, 2011.

[25] "Final Acts of the Regional Radiocommunication Conference for planning of the digital terrestrial broadcasting service in parts of Regions 1 and 3, in the frequency bands 174-230 MHz and 470-862 MHz (RRC-06)," ITU-R, 2006.

[26] K. Harrison and A. Sahai, "Potential collapse of whitespaces and the prospect for a universal power rule," in *Proceedings of the IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN '11)*, pp. 316–327, May 2011.