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Research Article

Proportional Fair Power Allocation for Secondary Transmitters in the TV White Space

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The key bottleneck for secondary spectrum usage is the aggregate interference to the primary system receivers due to simultaneous secondary transmissions. Existing power allocation algorithms for multiple secondary transmitters in the TV white space either fail to protect the TV service in all cases or they allocate extremely low power levels to some of the transmitters. In this paper, we propose a power allocation algorithm that favors equally the secondary transmitters and it is able to protect the TV service in all cases. When the number of secondary transmitters is high, the computational complexity of the proposed algorithm becomes high too. We show how the algorithm could be modified to reduce its computational complexity at the cost of negligible performance loss. The modified algorithm could permit a spectrum allocation database to allocate near optimal transmit power levels to tens of thousands of secondary transmitters in real time. In addition, we describe how the modified algorithm could be applied to allow decentralized power allocation for mobile secondary transmitters. In that case, the proposed algorithm outperforms the existing algorithms because it allows reducing the communication signalling overhead between mobile secondary transmitters and the spectrum allocation database.

1. Introduction

The main requirement for secondary spectrum usage is interference control. For single secondary transmitter, the power level maximizing the secondary transmission rate under primary system protection constraints has been derived in [1]. However, the bottleneck for secondary spectrum usage is the aggregate interference to the primary receivers due to simultaneous secondary transmissions. Allocating the power levels to multiple secondary transmitters has already drawn considerable interest for standardization bodies all over the world [2–4] and also for the academic research community.

The SE43 working group in the Electronic Communications Committee (ECC) in Europe announced a power allocation rule for secondary operation in the TV white space (TVWS), hereafter referred to as the SE43 rule [2]. Initially, the SE43 rule allocates the maximum permitted transmit power level to each secondary transmitter. For 2–4 simultaneous transmissions the maximum transmit power is divided with the number of active transmitters. In that case, each transmitter generates an equal amount of interference at the TV system. For a larger number of simultaneous transmissions a safety protection margin should be utilized. It has been shown that the existing SE43 rule fails to protect the TV service in all cases [5].

Power allocation algorithms that satisfy the TV protection constraints have been proposed by the academic research community [6–17]. In [6–10] all secondary transmitters allocated equal transmit power levels. In that case, there is a single parameter value to determine and the computational complexity is low. The drawback is that the power level for secondary transmitters located far from the TV coverage area would be limited due to secondary transmissions that are originated close to the TV coverage area. The assumption for common allocated power level is dropped in [11] where the sumpower is maximized. In that case, the algorithm associates transmitters located far from the TV coverage area with a high power level at the cost of transmitters in the proximity of the TV coverage area which remain practically silent.

A proportional fair (PF) power allocation rule would favor equally the secondary transmitters by equalizing their resource consumption. The available resource is the maximum permitted generated interference at the TV system. Note that the SE43 rule resembles a PF power allocation scheme in the limiting scenario with 2–4 transmitters. Unlike the SE43 rule, the scheme proposed in this paper is able to protect the TV service in all cases. When the number of secondary transmitters is high, the complexity of the proposed scheme may prohibit a real-time implementation in a spectrum allocation database. Because of that, a suboptimal method with low complexity is also introduced. The suboptimal method not only allows protecting the TV service but also enables power allocation to mobile users in a decentralized manner.

The ECC report [2] is not the first work targeting fairness in secondary type of networks. Fairness in secondary spectrum allocation and scheduling has been studied in [12–14, 18–21] respectively. Also, in [15] the minimum secondary SINR is maximized while in [16] the sum rate utility is maximized. In [17] PF power allocation is proposed but the complexity in large problem instances is not addressed. Unfortunately, the power allocation algorithms in [15–17] assume secondary transmitters with fixed and known locations. The interference that is originated from mobile users is not considered.

The remainder of this paper is organized as follows. In Section 2 we present the TV system model. In Section 3 we formulate the PF power allocation scheme under TV protection constraints. In Section 4 we propose a suboptimal alternative to the PF scheme that is extended to allow decentralized power allocation for mobile devices in Section 5. In Section 6 we demonstrate the flexibility of the proposed scheme in comparison with the current SE43 power allocation rule. In Section 7 we conclude the paper.

2. TV System Model

In TV network planning the location probability describes the percentage of locations within a square area of $100 \times 100\,\mathrm{m}^2$, also known as pixel, where the TV reception is satisfactory [2]. For satisfactory TV operation a target SINR γ_t must be maintained with specific outage probability O_t due to the slow fading. The outage probability O_t is complementary to the location probability widely used in the definition of TV coverage contour [2]. For evaluating the outage probability the TV coverage area is discretized into pixels. Each pixel is considered to be a test point where the following condition should be satisfied:

$$O_t \geq \Pr\left(\gamma_i \leq \gamma_t\right), \tag{1}$$

where γ_i is the SINR at the ith TV test point.

The probability constraint (1) must be satisfied in the presence of secondary transmissions too. A closed-form expression for (1) has been derived in [22] assuming that the TV signal level and the interference level due to each secondary transmitter follow the log-normal distribution within a TV test pixel. The aggregate secondary interference becomes a sum of log-normal random variables whose distribution is not available and approximating methods are commonly employed. In [22] the distribution of the aggregate secondary interference incorporating also the noise level is approximated by the log-normal distribution. The Fenton-Wilkinson method is used to compute the parameters of the approximating distribution.

Expressing (1) in closedform allows computing the maximum permitted mean secondary interference level which has been defined in [22] as the interference margin. The interference margin is a function of the TV system parameters, that is, the protection criteria of TV receivers (γ_t, O_t) and the useful TV signal level at the test point. Also, it depends on the locations of secondary transmitters and their transmission power levels. In order to simplify the interference control process a lower bound for the interference margin has been derived in [22] that is independent of the secondary network parameters:

$$I_{\Delta,i} = 10^{(S_i^{(db)} - \gamma_t^{(db)} + Q^{-1}(1-O_t)\cdot\sigma_{\mathrm{TV},i})/10} - P_N, \tag{2}$$

where $I_{\Delta,i}$ is the available interference margin at the ith TV test point, $S_i^{(db)}$ is the TV signal level by using distance-based pathloss, $\sigma_{\mathrm{TV},i}$ in dB is the standard deviation of TV signal due to slow fading, Q^{-1} is the inverse of the Gaussian Q function, and P_N stands for the noise power level at the TV receiver.

By using the concept of interference margin one essentially turns the chance type of constraint (1) into a constraint of the form $\sum_{j=1}^{N} y_{ij} \leq I_{\Delta,i}$ where N is the number of secondary transmitters and y_{ij} is the mean interference level from the jth transmitter to the ith TV test point. The mean generated interference y_{ij} is a function of the secondary transmission power level P_j, the distance-based propagation pathloss $L_{ij}^{(db)}$, and the mean of the slow fading. For log-normal fading the mean interference level y_{ij} is

$$y_{ij} = P_j \cdot e^{\sigma_{ij}^2/2\xi^2} \cdot 10^{L_{ij}^{(db)}/10}, \tag{3}$$

where σ_{ij} in dB is the slow fading standard deviation due to the secondary transmission and $\xi = 10/\log(10)$ is a scaling constant. The standard deviation σ_{ij} is in general different for different secondary transmitters and TV test points due to the irregular terrain morphology.

3. Proportional Fair Power Allocation Scheme

By using the concept of interference margin the probability constraint (1) is turned into a linear constraint $\sum_j g_{ij} \cdot P_j \leq I_{\Delta,i}$ where $g_{ij} = e^{\sigma_{ij}^2/2\xi^2} \cdot 10^{L_{ij}^{(db)}/10}$ is the link gain. Therefore the interference margin can be treated as an available resource. Each transmitter 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 test point provided that the mean interference of secondary transmissions does not exceed the interference margin.

Allocating the transmit power levels can be viewed as a resource sharing problem. In order to equalize the resource consumption we propose a PF power allocation scheme. For PF power allocation the sum of secondary transmission power levels in the log-domain should be maximized [23]. As a result, the power allocation algorithm can be formulated as a constrained optimization problem:

$$\begin{aligned} &\underset{P_j \geq 0}{\text{Maximize}}: \quad \sum_j \log\left(P_j\right). \\ &\text{Subject to}: \quad \sum_j g_{ij} \cdot P_j \leq I_{\Delta,i} \quad \forall i. \end{aligned} \tag{4}$$

The optimization function and the constraints are continuously differentiable functions of P_j. The Lagrangian function is $L = \sum_j \log(P_j) - \sum_i \lambda_i(\sum_j g_{ij}P_j - I_{\Delta,i})$ where $\lambda_i \geq 0$ is the Lagrangian multiplier. The Karush-Kuhn-Tucker conditions are

$$\begin{aligned} &\frac{\partial L}{\partial P_j} = 0 \quad \forall j, \\ &\lambda_i \geq 0, \quad \sum_j g_{ij}P_j - I_{\Delta,i} \leq 0, \\ &\lambda_i\left(\sum_j g_{ij}P_j - I_{\Delta,i}\right) = 0 \quad \forall i. \end{aligned} \tag{5}$$

The solution has the form $P_j = (\sum_i \lambda_i \cdot g_{ij})^{-1}$ where the Lagrangian multiplier λ_i is positive if the ith constraint is binding. Otherwise, $\lambda_i = 0$. The PF scheme allocates the transmit power levels so that each transmitter takes an equal fraction out of the aggregate interference margin at the binding points. Unfortunately, for complex secondary network geometries and noncontiguous TV coverage areas, it is difficult to identify the binding points in advance.

One can show that the Hessian matrix of the objective function is negative definite and thus the optimization function is concave. Since the constraints are linear functions of transmit power levels, the optimization problem (4) is convex. The globally optimal solution can be found by using standard convex optimization tools. When the number of constraints and optimization parameters are high, the computational complexity may prohibit a real-time computation in the spectrum allocation database. Note that the database may need to reallocate the transmission power levels in frequent time intervals. The secondary transmitters can be mobile or new transmitters can send spectrum access requests.

4. Simplified Proportional Fair Power Allocation Scheme

We propose associateing each transmitter with the TV test point where its generated interference is maximized. In this way, we end up with a subset D of TV test points that experience the highest interference levels. We call it the set of dominating TV test points. Obviously, it is sufficient to control the generated interference only at the TV test points belonging to the dominating set.

We denote by J_i the set of transmitters dominated by the $i \in D$ TV test point. Also, let us assume that each transmitter generates mean interference level equal to p_0 at its dominating point, $y_{ij} = p_0$, $j \in J_i$, $i \in D$. Essentially, we propose a PF power allocation scheme for secondary transmitters belonging to the same set. Next, we show how to compute the parameter p_0.

The generated interference at the kth TV test point due to the $j \in J_i$ secondary transmitter can be written as a fraction of the interference p_0:

$$y_{kj} = p_0 \cdot \exp\left(\frac{\sigma_{kj}^2 - \sigma_{ij}^2}{2\xi^2} + \frac{L_{kj}^{(db)} - L_{ij}^{(db)}}{\xi}\right), \quad j \in J_i. \tag{6}$$

The mean interference I_i at the ith TV test point is the sum of the interference from all secondary transmitters:

$$I_i = \sum_j y_{ij} = \sum_{j \in J_i} y_{ij} + \sum_{k \neq i} \sum_{j \in J_k} y_{kj}. \tag{7}$$

Since each transmitter $j \in J_i$ generates interference equal to p_0 at the $i \in D$ test point, $\sum_{j \in J_i} y_{ij} = p_0 \cdot |J_i|$ where $|\cdot|$ denotes the cardinality of a set. Also, by using (6) in (7) the aggregate interference I_i can be read as $I_i = p_0 \cdot \omega_i$ where $\omega_i = |J_i| + \sum_{k \neq i} \sum_{j \in J_k} \exp((\sigma_{ij}^2 - \sigma_{kj}^2)/2\xi^2 + (L_{ij}^{(db)} - L_{kj}^{(db)})/\xi)$. For protecting the TV receivers the mean interference should be kept under the margin, $I_i \leq I_{\Delta,i}$. By enforcing the inequality to be tight, the parameter p_0 can be selected as the minimum over all test points belonging to the dominating set:

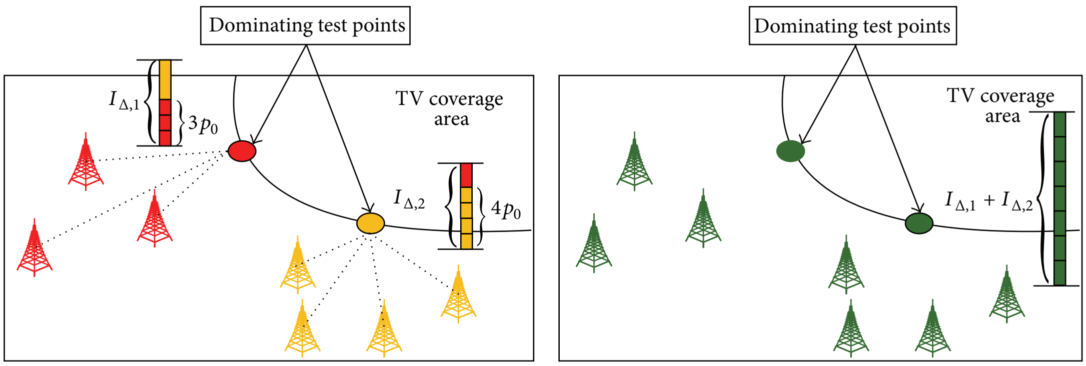
$$p_0 = \min_{i \in D} \left\{\frac{I_{\Delta,i}}{\omega_i}\right\}. \tag{8}$$

With the parameter p_0 at hand, we can identify the transmit power level P_j after replacing y_{ij} by p_0 into (3): $P_j = p_0 \cdot e^{-\sigma_{ij}^2/2\xi^2} \cdot 10^{-L_{ij}^{(db)}/10}$, $j \in J_i$, $i \in D$ where the value for the distance-based pathloss $L_{ij}^{(db)}$ and the standard deviation σ_{ij} must be taken from the test point that dominates the jth transmitter. By using (8) and (2) the allocated power level can also be written as

$$P_j = \min_{i \in D} \left\{10^{(S_i^{(db)} - \gamma_t^{(db)} - L_{ij}^{(db)} + Q^{-1}(1-O_t)\sigma_{\mathrm{TV},i} - (\sigma_{ij}^2/2\xi) - 10\log_{10}(\omega_i))/10}\right\}. \tag{9}$$

In Figure 1 it is assumed that both TV test points belonging to the dominating set are also binding; that is, all their interference margin is filled in by the secondary transmissions. According to the simplified PF scheme each transmitter generates mean interference p_0 at its dominating test point. The remaining interference headroom is filled in by the secondary transmitters dominated by the other test point. According to the PF scheme the aggregate interference margin $I_{\Delta,1} + I_{\Delta,2}$ is divided equally among the secondary transmitters.

The two schemes are characterized by different implementation complexity. The complexity to identify the set of dominating test points in the simplified scheme is $\mathcal{O}(N \cdot (N_p -$



(a) Simplified proportional fair power allocation

(b) Proportional fair power allocation

FIGURE 1: Comparison of simplified PF and PF power allocation schemes.

1)) while the complexity to identify the minimum over the computed values for p_0 is $\mathcal{O}(|D| - 1)$. Since $|D| \ll N_p$ the overall complexity can be approximated by $\mathcal{O}(N \cdot (N_p - 1))$. In order to get insight on the complexity for solving (4) by using interior-point methods we use the complexity bound $\mathcal{O}(N^2 \cdot N_p^{3/2})$ [24]. Besides the lower implementation complexity, the simplified scheme allows power allocation to mobile UE with lower signalling overhead in comparison with the PF scheme. This is the topic of the next section.

5. Power Allocation for Mobile Users

The power allocation scheme proposed in Section 4 is applicable to secondary transmitters with fixed and known locations, for example base stations (BSs). The secondary transmitters can also be mobile user equipment (UE). If the number of UE is high, the communication signaling overhead for updating their locations in the database at frequent time intervals would be high too. Fortunately, the simplified PF algorithm can be modified to allow decentralized power allocation with reduced signaling overhead. Next, we show how the simplified scheme can group secondary pixels and control the interference from each group instead of doing it on a per-pixel basis. UE can move within pixels belonging to the same group without the need to inform the database about their locations.

Following the ECC approach, we discretize the secondary deployment area into pixels. We assume that the UE inside each pixel is distributed according to a Poisson point process (PPP). The density of the process in the jth pixel is equal to the number N_j of UE times the activity factor ν. The mean interference due to the transmissions originating from the jth pixel to the ith TV test point is [25]

$$y_{ij} = w_j \cdot P_j \cdot e^{\sigma_{ij}^2/2\xi^2} \cdot \sum_n 10^{L_{ijn}^{(db)}/10}, \qquad (10)$$

where the index n is used to integrate over the area A_j of the jth pixel, P_j is the transmit power level for UE located inside the jth pixel, and $w_j = (\nu N_j A_\epsilon)/A_j$ where A_ϵ is the integration element. The w_j describes the average number of active UE inside the integration element of the jth pixel. The $L_{ijn}^{(db)}$ stands for the distance-based pathloss between the nth integration element of the jth pixel and the ith test point.

Similar to the power allocation rule described in Section 4, we group together pixels dominated by the same test point. The mean interference level from the group J_i to the ith TV test point is $p_0|J_i|$. (Note that the parameter value p_0 and the set D of dominating TV test points are in general different for the secondary transmitters with fixed locations described in Section 4 and for the secondary pixels described in this section. In order not to introduce unnecessary complexity we keep the same notation and provide the related explanation when needed.) The interference headroom $p_0|J_i|$ can be divided among the secondary pixels belonging to the group J_i by using any rule. For PF allocation each pixel takes an equal amount of resource, p_0. In that case, pixels with low user density allocate higher power levels to the UE compared to pixels with high user density. One alternative way is to divide the interference headroom $p_0|J_i|$ proportionally to the user density of pixels belonging to the set J_i. In that case, the transmission power level for UE inside the jth pixel becomes

$$P_j = \frac{p_0 \cdot |J_i|}{\sum_{j \in J_i} w_j} \cdot e^{-\sigma_{ij}^2/2\xi^2} \cdot \left(\sum_n 10^{L_{ijn}^{(db)}/10} \right)^{-1}, \quad j \in J_i,\ i \in D. \qquad (11)$$

The parameter p_0 can be calculated based on (8) after computing the parameter ω_i as

$$\omega_i = |J_i| + \sum_{k \neq i} \sum_{j \in J_k} \exp\left(\frac{\sigma_{ij}^2 - \sigma_{kj}^2}{2\xi^2} + \frac{10}{\xi} \left(\log_{10} \sum_n 10^{L_{ijn}^{(db)}/10} - \log_{10} \sum_n 10^{L_{kjn}^{(db)}/10} \right) \right). \qquad (12)$$

The transmission power level P_j calculated based on (11) does not depend on the particular population density in the jth pixel. Only the total amount of UE $\sum_{j \in J_i} N_j$ inside the group J_i has to be known. Because of that, the UE can freely move between pixels belonging to the same group without the need to recalculate their transmission power levels at the database. Each UE just has to know the pixel where it belongs and set its transmission power level based on (11). The database has to recompute the parameter value p_0 and the transmission power levels only if the total number of UE in a group of pixels changes.

Allowing UE mobility within a group $J_k : k \neq i$ may violate the protection criteria at the ith TV test point. One way to protect the ith test point is to recompute the parameter ω_i in (12) based on the worst case interference scenario. That refers to the case where all UE inside the group J_k is concentrated in the pixel generating the highest interference at the ith TV test point. In that case the parameter ω_i becomes

$$\omega_i = |J_i| + \sum_{k \neq i} |J_k| \cdot \max_{j \in J_k} \left\{ \exp\left(\frac{\sigma_{ij}^2 - \sigma_{kj}^2}{2\xi^2} + \frac{10}{\xi} \left(\log_{10} \sum_n 10^{L_{ijn}^{(db)}/10} - \log_{10} \sum_n 10^{L_{kjn}^{(db)}/10} \right) \right) \right\}. \quad (13)$$

The flexibility introduced with (13) does not come for free. In the worst case, the distribution of UE minimizes the interference at the ith TV test point whereas (13) assumes maximum interference.

Thus far, the transmission power levels for BS and UE have been calculated assuming that the full interference margin is available to BS and UE, respectively. When the BS and the UE are simultaneously active, the power allocation algorithm may have the following steps:

(1) allocate some fraction q of the interference margin to the BS, $I_{\Delta,i}^{(\mathrm{BS})} = q \cdot I_{\Delta,i}$, for all i,

(2) compute the parameter p_0 for the BS transmissions after replacing $I_{\Delta,i}$ by $I_{\Delta,i}^{(\mathrm{BS})}$ in (8),

(3) compute the BS transmission power levels P_j by using (9),

(4) by using the identified BS transmission power levels compute the remaining interference margin $I_{\Delta,i}^{(\mathrm{UE})} = I_{\Delta,i} - \sum_j y_{ij}$ at the TV test points where the y_{ij} is calculated from (3),

(5) group the secondary pixels and identify the transmission power level for UE in each pixel by using (11). The parameter p_0 is computed after replacing $I_{\Delta,i}$ by $I_{\Delta,i}^{(\mathrm{UE})}$ in (8). For supporting UE mobility within groups of pixels (13) must be used instead of (12).

6. Numerical Illustrations

6.1. Parameter Settings. For testing the proposed power allocation rule we select a study area in Jyväskylä in Finland where the Vihtavuori TV transmitter operates at 546 MHz. The minimum required median field strength for fixed TV reception at 64 QAM and 2/3 code rate is 52.5 dbuV/m at 500 MHz [26, pp.185]. For other frequencies f in MHz the correction factor $20\log(f/500)$ should be added resulting in 53.3 dBuV/m at 546 MHz.

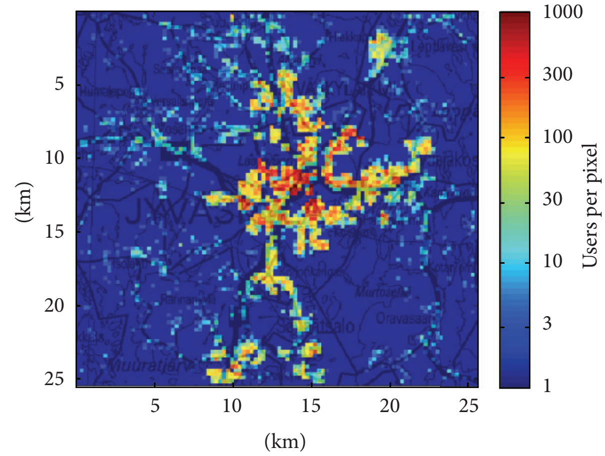


Figure 2: Secondary UE density map in the study area.

In order to identify the TV coverage area we cover the full study area with square pixels with side equal to 250 m. A pixel belongs to the TV coverage area if the median field strength is higher than 53.3 dBuV/m. The TV field strength at the center of each pixel has been calculated by using the Longley-Rice propagation model with terrain data implemented in Splat! [27]. The slow fading standard deviation of the TV signal is $\sigma_{\mathrm{TV},i} = 5.5$ dB for all i. The TV self-interference is not considered and the noise power level is −106 dBm. The protection criteria of TV receivers are $\gamma_t = 17.1$ dB and $O_t = 10\%$ motivated from [2].

For testing power allocation for mobile UE, the population density map of the area is utilized; see Figure 2. The antenna height for the UE is 1.5 m. Their activity factor is 10%. The locations of secondary BS are fixed and known. They are placed at a square lattice with 2 km side and their antenna height is 3 m. For modeling the distance-based propagation pathloss of secondary transmissions we utilize the modified Hata model for suburban areas [28]. The slow fading standard deviation for BS and UE is $\sigma_{ij} = 8$ dB for all i, j.

6.2. Results. First, we compare the allocated transmit power levels of secondary BS by using PF and simplified PF power allocation rules. For PF rule the power levels are obtained by solving (4) while for simplified PF rule (9) is utilized. For illustration purposes the dominating TV test points and the locations of secondary BS are depicted in Figure 3 for protection distance equal to 3 km. The distributions of BS power levels for different protection distances are plotted in Figure 4. One can see that the simplified scheme almost achieves the optimal solution. In general, the PF scheme allocates higher transmission power levels for the BS located close to the TV protection area. Also, we notice that the set of dominating test points has different cardinality for

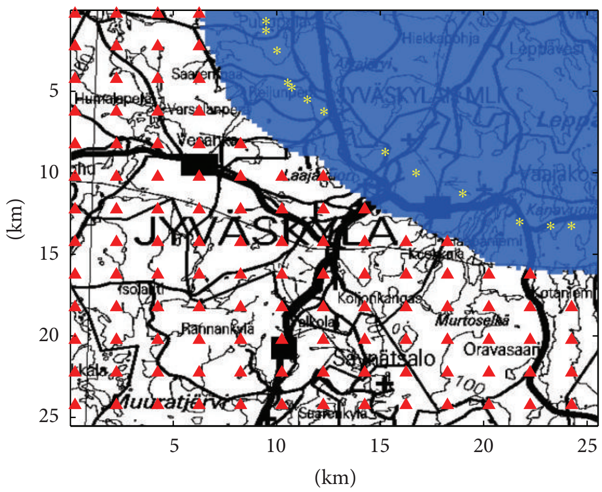


Figure 3: TV protection area (blue-shaded area), secondary BS (red triangles), and dominating TV test points (yellow stars).

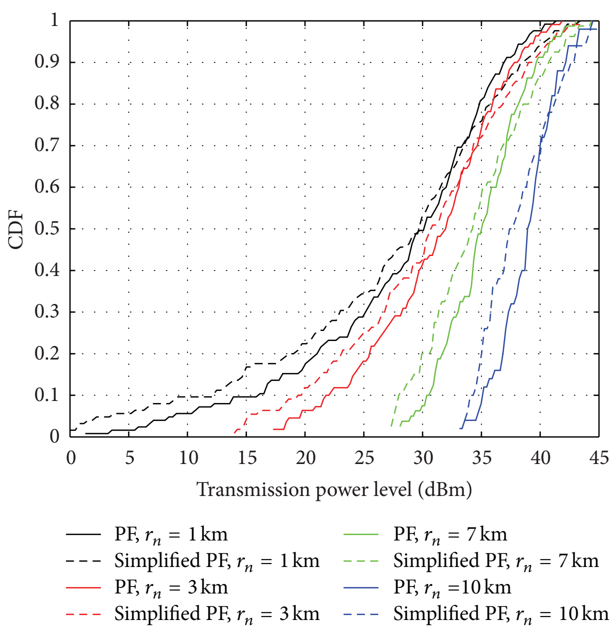


Figure 4: Distribution of transmission power levels by using PF and simplified PF schemes for different protection distances. The locations of secondary transmitters are fixed and known.

different protection distances and only a single test point is binding. Hereafter, the simplified PF scheme is utilized and it is referred to as the proposed power allocation method.

Next, we compare the proposed power allocation method with other existing methods. If we are to use equal transmit power for all secondary transmitters [6–10], the maximum permitted levels are $\{14, 26, 33, 38\}$ dBm for protection distances $\{1, 3, 7, 10\}$ km, respectively. As a result, the common power allocation rule is conservative for secondary transmitters located far from the TV coverage area especially when the protection distance is small. Also, if the sumpower is maximized [11], a single transmitter is essentially favored: the transmitter located furthest away from the TV coverage area has the smallest link gain and can dominate the sum-power utility by using high transmit power level. The power level for the rest of the transmitters is practically zero. As a result, the sum-power utility is extremely unfair in our system setup.

Next, we compare our method with the existing SE43 proposal. The transmission power level for each BS by using the SE43 rule is [2, page 24]

$$P_j = \min_{i \in D} \left\{ 10^{\left(S_i^{(db)} - \gamma_t^{(db)} - L_{ij}^{(db)} + Q^{-1}(1-O_t)\sqrt{\sigma_{\mathrm{TV},i}^2 + \sigma_{ij}^2} - \mathrm{SM} - \mathrm{MI}\right)/10} \right\}, \tag{14}$$

where SM and MI are the safety and the multiple interference protection margin, respectively.

Instead of using protection margins one can scale the transmission power of each BS with the total number N of active BS. The modified SE43 rule allocates transmission power level equal to [29]

$$P_j = \min_{i \in D} \left\{ 10^{\left(S_i^{(db)} - \gamma_t^{(db)} - L_{ij}^{(db)} + Q^{-1}(1-O_t)\sqrt{\sigma_{\mathrm{TV},i}^2 + \sigma_{ij}^2} - 10\log_{10}(N)\right)/10} \right\}. \tag{15}$$

The TV SINR distribution at the test point experiencing the highest interference level is depicted in Figure 5 for protection distance 10 km. The protection margins for the SE43 rule are taken equal to SM = 10 dB and MI = 6 dB as proposed in the ECC report [2]. One can see that the existing and the modified SE43 rules fail to protect the TV service. The same behaviour is observed for other protection distances too. One could maintain the TV SINR target by using, for instance, a higher value for the safety margin in (14). This approach requires an iterative type of power allocation algorithm implemented in the database. On the other hand, the proposed rule has low complexity and protects the TV system in all cases.

The proposed rule can also be used to allocate the transmission power levels to the UE (11). UE mobility between pixels belonging to the same group is allowed if (13) is used instead of (12). This flexibility comes at the cost of reduced transmission power level at the UE. However, the loss is negligible especially for a large protection distance; see Figure 6.

Finally, we consider simultaneous BS and UE transmissions and the power allocation algorithm described in Section 5. In Figure 7 one can see the distribution of UE transmit power levels for different fractions q of allocated interference margin to the BS. When 75% of the margin is allocated to the BS its transmission power levels are between 36 dBm and 48 dBm while the UE power levels lie between 10 dBm and 30 dBm. At the same time, the TV SINR target is satisfied at all the dominating test points.

7. Conclusions

In this paper we proposed a power allocation algorithm for multiple secondary transmitters in the TVWS that protects the TV service in the cochannel. The proposed rule can incorporate secondary transmitters with different antenna

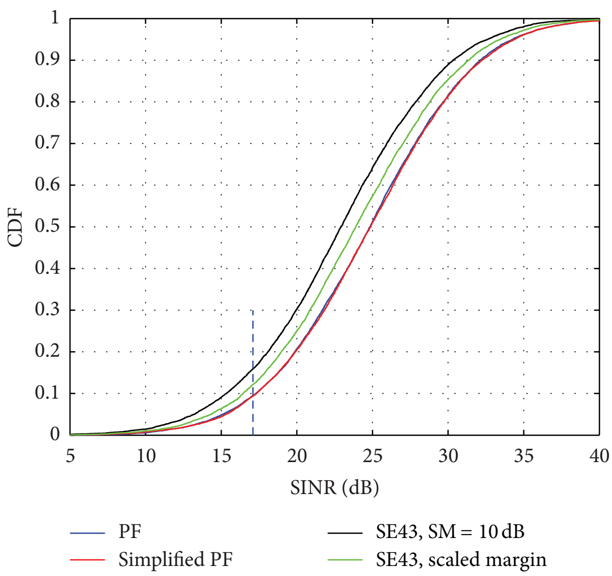


FIGURE 5: TV SINR distribution at the dominating test point experiencing the highest secondary interference level by using different power allocation rules and protection distance 10 km.

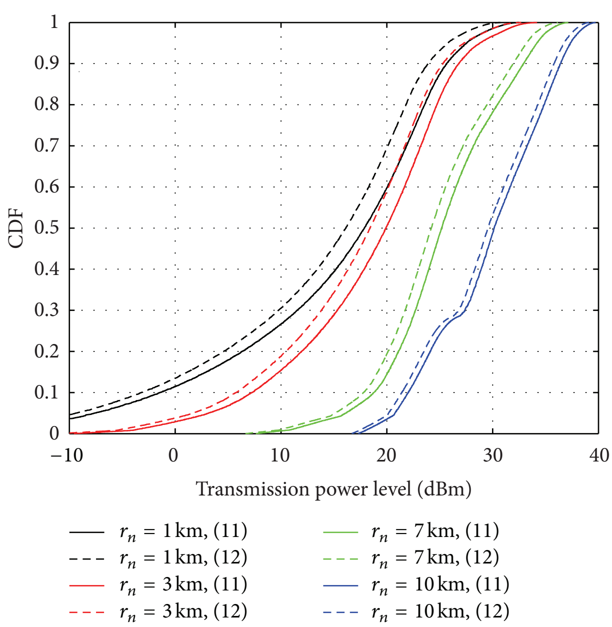


FIGURE 6: Distribution of UE transmission power levels by using the simplified PF power allocation rule for different protection distances. The power allocation scheme (12) is compared with the power allocation scheme supporting mobility within groups of pixels (13).

heights, for instance, base stations and mobile UE. The impact of terrain morphology can be considered by using different slow fading standard deviations for transmitters located at different pixels. The proposed rule allows reducing the communication signaling overhead between the UE and the spectrum allocation database with the reason being that the database groups secondary pixels and controls the aggregate

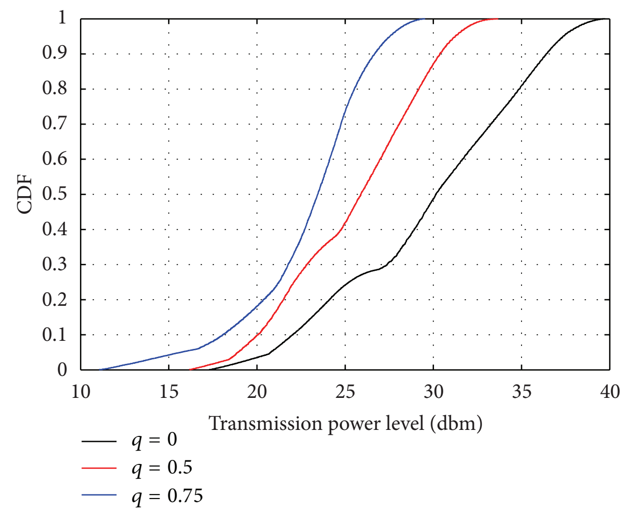


FIGURE 7: Distribution of UE transmission power levels for different fractions q of interference margin allocated for BS transmissions. The simplified PF power allocation rule supporting mobility within groups of pixels (13) is utilized. The protection distance is 10 km.

interference from each group instead of doing it on a per pixel basis. The proposed rule outperforms the existing SE43 rule because it protects the TV service in all cases and results in smaller communication signalling overhead. However, it does not consider the scenario where some of the secondary transmitters fall inside the coverage area of an adjacent TV channel. The SE43 rule takes into account the protection of adjacent channel TV service by using reference coexisting geometries. The reference geometry rule is conservative particularly at low user densities [30]. Extending the proposed rule to incorporate adjacent channel TV protection can be an area of future work.

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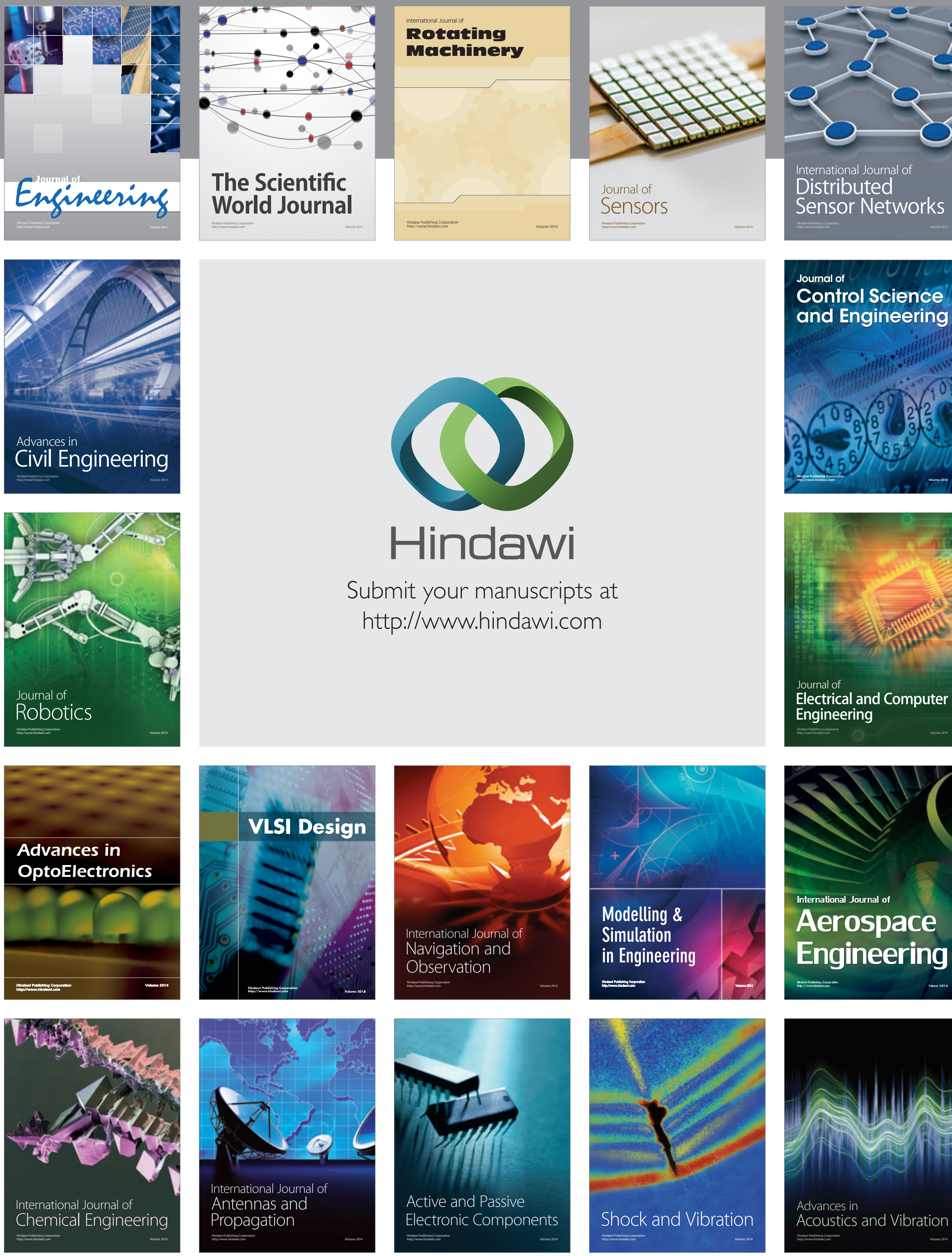
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