Modeling of the Secondary System's Generated Interference and Studying of its Impact on the Secondary System Design

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Abstract. *In this paper we study how much capacity a cellular secondary system can achieve if the interference to the TV system is kept under control. The interference is modeled and controlled in a slow fading environment. The secondary system's capacity is computed for the adjacent and for the co-channel (with respect to the TV channel). We study the behavior of the system capacity while changing the size of the no transmission area surrounding the TV coverage area. It turns out that for most of the secondary cell sizes the network with adjacent channel is in interference limited mode and the network with co-channel is in noise limited mode. Since in the co-channel we can not use very high power it is recommended to use in bigger cells only adjacent channel.*

Keywords

Secondary spectrum usage, interference, capacity.

1. Introduction

One of the most promising frequencies for secondary spectrum sharing are the TV frequencies. The TV signal is transmitted from relatively sparsely located high power transmitters. There is a large space between the transmitters where the TV frequency is unused. The spectrum can be more effectively utilized if low power secondary transmitters could populate that space.

How the secondary users (SU) can transmit depends on their aggregate interference on the TV receivers. In this paper we combine two sides of this problem: how to compute the amount of aggregate interference the secondary system can generate and given this interference constraint how different network designs impact the secondary network achievable capacity.

By adding secondary transmitters we increase the interference level at the TV receivers. In a non fading environment it is relatively easy to estimate how much additional interference the SU can generate [1]. How to estimate the same thing in a fading environment is a more challenging task. In this paper we propose an equation describing the interference condition in the presence of log-normal fading.

The analyzed secondary system has cellular structure. For a cellular network we know how to compute the data rate corresponding to the worst SINR condition. The data rate can be expressed analytically and we use it as the optimization criterion.

We have various ways for controlling the secondary system generated aggregate interference. In this paper we look at two different methods for controlling the secondary system generated aggregate interference: we can control the transmission power of secondary transmitters or we can adjust the size of the no transmission area around the TV coverage area.

The impact of secondary system transmission power on the aggregate interference has been studied before [2], [3], [4]. The impact of the no transmission area on the aggregate interference is examined, for instance, in [5]. In this paper we not only look at the relationship between the transmission power, the no transmission area and the aggregate interference, but we also study how these parameters impact the secondary system capacity.

Our purpose is to estimate the capacity available to the secondary spectrum users. The amount of available secondary spectrum has been estimated before [6]. The [6] contains few interesting claims but the analysis leading to these claims overlooks the impact of aggregate interference. In this paper we develop a technical analysis that allows to put these claims on stronger foundation. For example we can confirm the result from [6] that near to the TV cell border the secondary system should use smaller cells.

The developed models are relatively versatile and can be used to describe different secondary system properties. For example we study the trade off between the power allocation on the adjacent and the co-channel. The TV receiver filters are not fully able to remove the adjacent channel interference. The model in our paper allows to estimate the capacity by constraining the aggregate interference generated from all available channels. The proposed model allows to make more realistic assessment about available spectrum and can augment the analysis carried out in [6].

The intentions of the paper can be summed up as following: We derive an equation that describes how much interference the SU can generate in a fading environment. By using this equation we study different secondary system cellular structures that meet the given interference constraint. By using secondary system capacity description we optimize the power allocation between the adjacent and the co-channel. The same equations are used for illustrating the impact of the TV protection area size on the SU system capacity.

2. System Model

We consider a high power TV transmitter located in the center of a circular TV coverage area. At the cell border the TV signal should satisfy the SINR target, γ_t. For protecting the TV receivers located close to the TV cell border, the coverage area is surrounded by the no transmission area (or protection area). Outside of this area the spectrum can be reused. We have two different protection areas, one for the co-channel Δ_c and one for the adjacent channel Δ_a (Fig. 1).

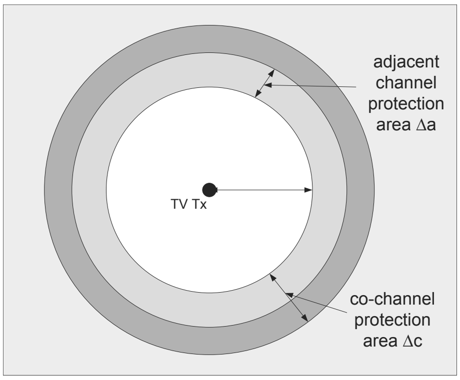

Fig. 1. Considered system model. The TV coverage area is surrounded by secondary users using adjacent channel and co-channel.

The secondary system uses hexagonal cells. In the center of each cell there is a base station (BS) and all the BS use the same power levels. Inside a cell, the uplink and downlink connections are arranged by using time division duplexing.

The secondary system could transmit either on adjacent channel, on co-channel or on both adjacent and co-channel. If both channels are used we control the aggregate interference from them by selecting transmission power P_{SU_a} for adjacent channel and power P_{SU_c} for co-channel. The power levels P_{SU_a} and P_{SU_c} are common for all secondary transmitters. This assumption helps us to keep the equations simpler and more intuitive. The equations outlined here can be easily modified to control the interference in case of unequal secondary transmitters' powers.

The attenuation in the channel g is described by the mean path loss and the shadow fading component

$$g = 10^{(m+x)/10} \tag{1}$$

where m is the mean path loss in dB and x is the the shadow fading that is modeled as a Gaussian random variable with zero mean and standard deviation σ also in dB. The simplest mean path loss model is a "power law" model $m = 10\log_{10}(r^{-\alpha})$ where α is the channel attenuation constant.

3. Problem Description

We define the problem as following:
For the given secondary system cell size and no transmission areas Δ_a, Δ_c we want to maximize the secondary system capacity by selecting appropriate powers P_{SU_a} and P_{SU_c} such that the interference constraint is satisfied.

The secondary system capacity C is computed as the capacity the system can provide on its cell border

$$C = B\log_2(1+\gamma_{SU,b}) \tag{2}$$

where B is the system bandwidth and $\gamma_{SU,b}$ is the minimum SINR on cell borders. The $\gamma_{SU,b}$ calculation is outlined in Sec. 5.

While maximizing the capacity we control the mean aggregate secondary system interference $\bar{I}$ on TV receivers. The aggregate interference is computed as the sum of the interfering powers from all the secondary transmitters. It turns out that under shadow fading this sum can be limited as

$$\bar{I} \le \exp\left(-\frac{\sigma^2}{2\xi^2}\right)\left(\frac{1}{\gamma_t}\exp\left(Q^{-1}(1-O)\frac{\sigma_{TV}}{\xi}+\frac{m_{TV}}{\xi}\right)-P_N\right) \tag{3}$$

where O is the TV signal outage probability, $Q^{-1}(\cdot)$ is the inverse of the Q function, m_{TV} is the mean TV signal level in dB at the TV coverage border, σ_{TV} is the standard deviation describing the fading of TV signal, σ is the standard deviation of the secondary signals fading, P_N is total noise power in the system and $\xi = \frac{10}{\ln(10)}$ relates ln to $\log_{10}$. Detailed derivation of (3) is given in the next Section.

4. Interference Margin

The interference margin describes the amount of aggregate interference the secondary system can generate at the TV receiver. We compute the interference margin as the difference between the TV signal SINR at the TV cell border and the SINR target γ_t.

The SINR γ_{TV} at a TV receiver located at the TV coverage border can be expressed as

$$\gamma_{TV} = \frac{S}{I_{TV}+I_{SU}+P_n} = \frac{S}{I_{SU}+P_N} \tag{4}$$

where S is the received TV signal, I_{TV} is the interference from other TV stations, P_n is the noise power and I_{SU} is the

SU generated aggregate interference. The analysis here does not account for the interference from other TV stations. We could simplify the model by incorporating TV interference into common noise floor $P_N = I_{TV} + P_n$.

The interference I_{SU} contains contribution from the co channel, I_{SU_c}, and the adjacent channel, I_{SU_a}. The interference is modeled by scaling the transmission powers $P_{SU_k}, k \in \{a,c\}$ with channel attenuation g

$$\begin{aligned} I_{SU} &= I_{SU_c} + I_{SU_a} = \sum_{k\in\{a,c\}} G_k \sum_n P_{SU_k} g^{TV}_{k,n} \\ &= P_{SU_c} \sum_m g^{TV}_{c,m} + P_{SU_a} G_a \sum_n g^{TV}_{a,n} \end{aligned} \tag{5}$$

where G_k is the rejection coefficient describing how much this interference is suppressed by the TV receiver's filter. For co-channel $G_c = 1$. The attenuations $g^{TV}_{c,m}$ and $g^{TV}_{a,n}$ are computed between the transmitter and the point where the SINR is evaluated.

The SU transmission always increases the interference level. Such increase will not deteriorate the TV reception if at the coverage border the TV signal SINR is kept above the quality target $\gamma_{TV} - \gamma_t > 0$.

The amount of interference the SU system can contribute can be estimated from (4) by inserting $\gamma_{TV} = \gamma_t$

$$I_\Delta = \frac{1}{\gamma_t}(S - \gamma_t P_N) \tag{6}$$

where we call I_Δ the interference margin and it describes how much interference the secondary system can generate if to assume a constant path loss only, $g = r^{-\alpha}$ (no fading). For the mean path loss the I_{SU} is expressed by the term

$$\bar{I} = P_{SU_a} G_a \sum_n r^{-\alpha}_{a,n} + P_{SU_c} \sum_m r^{-\alpha}_{c,m}. \tag{7}$$

In mean path loss channel the interference constraint is satisfied as long as

$$\bar{I} \le I_\Delta. \tag{8}$$

For computing the interference margin in fading environment we express the aggregate interference from the outage probability equation

$$O = \Pr(\gamma_{TV} < \gamma_t) \tag{9}$$

where O is the target outage probability and γ_t is selected such that the probability of γ_{TV} falling under γ_t is O.

For computing the interference margin we express γ_{TV} as function of $\bar{I}$ insert it into (9) and invert it.

The distribution of γ_{TV} is computed by inserting (1) into (4). The random variable (RV) $I_{SU} + P_N$ is a sum of log-normal distributed interferers and noise power. We use the Wilkinson method to approximate the sum of lognormal RVs, $I_{SU} + P_N$, with a single lognormal RV $10^{z/10}$ that has the same first two moments as the initial variable

$$I_{IN} = (I_{SU} + P_N) \to 10^{z/10} = 10^{(m_{IN} + x_{IN})/10} \tag{10}$$

where m_{IN} is the mean of the new variable z in dB and x_{IN} is a Gaussian random variable with zero mean and variance equal to σ^2_{IN} (calculated in (15)).

By using the variable z in (9) the outage probability is

$$\begin{aligned} O &= \Pr\left(\frac{10^{\frac{1}{10}(m_{TV}+x_{TV})}}{10^{z/10}} < \gamma_t\right) \\ &= \Pr\left(10^{\frac{(x_{TV}-x_{IN})}{10}} < \gamma_t 10^{\frac{-m_{TV}+m_{IN}}{10}}\right) \\ &= 1 - Q\left(\frac{10\log_{10}(\gamma_t) + \mu}{\sqrt{\sigma^2_{TV} + \sigma^2_{IN}}}\right) \end{aligned} \tag{11}$$

where $-\mu = m_{TV} - m_{IN}$ describes the mean SINR value (m_{TV} is the mean path loss of the TV signal in dB) and $\sigma^2_{TV} + \sigma^2_{IN}$ is the variance of the random variable $x_{TV} - x_{SU}$. The variance of SINR is composed by summing the fading variances of the TV signal and of the interfering signal.

For extracting $\bar{I}$ from (11) we have to express both m_{IN} and σ^2_{IN} as functions of $\bar{I}$. Next, we compute two first moments of interference plus noise and use moment matching for describing z's distribution. If all different interfering signals have the same fading variance σ^2 we have a simple expression for the first two moments of I_{IN}

$$E\{I_{IN}\} = \exp\left(\frac{\sigma^2}{2\xi^2}\right) \cdot \bar{I} + P_N, \tag{12}$$

$$var\{I_{IN}\} = \exp\left(\frac{\sigma^2}{\xi^2}\right)\left(\exp\left(\frac{\sigma^2}{\xi^2}\right) - 1\right)(\bar{I}_n)^2 \tag{13}$$

where $\bar{I}$ is from (7) and $(\bar{I}_n)^2$ describes the sum of the squares of each element in the sum $\bar{I}$.

After moment matching we describe z by

$$m_{IN} = \xi \ln(E\{I_{IN}\}) - \frac{\sigma^2_{IN}}{2\xi}, \tag{14}$$

$$\sigma^2_{IN} = \xi^2 \ln\left(1 + \frac{var\{I_{IN}\}}{E\{I_{IN}\}^2}\right). \tag{15}$$

By inverting (11) we can express the mean

$$m_{IN} = Q^{-1}(1-O)\sqrt{\sigma^2_{TV} + \sigma^2_{IN}} - \xi \ln(\gamma_t) + m_{TV}. \tag{16}$$

By using (16) in (14) we calculate the $E\{I_{IN}\}$ in terms of the outage constraint O and use it in (12) to get

$$\bar{I} = \exp\left(-\frac{\sigma^2}{2\xi^2}\right)\left(\exp\left(\frac{m_{IN}}{\xi} + \frac{\sigma^2_{IN}}{2\xi^2}\right) - P_N\right). \tag{17}$$

The right-hand side of (17) is the interference margin I_{Δ_f} in fading environment. Unfortunately this right hand side is a complex function that depends also on the secondary system standard deviation σ_{IN}. By omitting the impact of the secondary system parameters we get interference margin

I_{Δ_f} lower bound that is only a function of primary system parameters. We replace $m_{IN} \to m'_{IN}$

$$m'_{IN} = Q^{-1}(1-O)\sigma_{TV} - \xi \ln(\gamma_t) + m_{TV}. \qquad (18)$$

By using the simplified bound the aggregate interference is limited as

$$\bar{I} \leq I_{\Delta_f} = \exp\left(-\frac{\sigma^2}{2\xi^2}\right)\left(\exp\left(\frac{m'_{IN}}{\xi}\right) - P_N\right). \qquad (19)$$

This bound is true in case

$$O < Q\left(\frac{\sigma^2_{IN}}{2\xi\sqrt{\sigma^2_{TV}+\sigma^2_{IN}}}\right). \qquad (20)$$

That conditions holds usually in secondary spectrum using systems where $\sigma_{IN} < \sigma_{TV}$ and O is relatively small.

One can notice the I_Δ can be satisfied for different cell sizes. For smaller cell sizes we can use less power and for bigger cells more power. While describing the secondary system we are free to select any cell size as long as we satisfy

$$\bar{I} \leq I_{\Delta_f}. \qquad (21)$$

5. Secondary System Analysis

So far we have calculated the interference margin in fading (21) and non fading (8) environment. In this Section we describe the optimization criterion for SU system design. That is the data rate the SU system can provide at the cell border.

We do not involve any medium access scheme and look only at the radio interface throughput. The cell border capacity is the minimum data rate that can be guaranteed to any user in the system. It is used to describe the lower limit to the radio interface throughput in the cell.

We employ conventional network planning assumptions. All the SU cells are similar: they have the same size and same transmission power. The SINR is computed for a simple link with one transmitter and one receiver. The SINR depends on the self-interference and the TV signal interference. For the co-channel the SINR is

$$\gamma_c = \frac{P_{SU_c} r_{c,i}^{-\alpha}}{\sum_j P_{TV_j} r_{c,j}^{-\alpha} + \sum_{m\neq i} P_{SU_c} r_{c,m}^{-\alpha} + P_n} \qquad (22)$$

and for adjacent channel it is

$$\gamma_a = \frac{P_{SU_a} r_{a,i}^{-\alpha}}{G_{TV}\sum_j P_{TV_j} r_{a,j}^{-\alpha} + \sum_{n\neq i} P_{SU_a} r_{a,n}^{-\alpha} + P_n} \qquad (23)$$

where G_{TV} stands for the attenuation of the TV due to the input filter of the SU adjacent channel receiver. We use notation i to index the SU cell where the SINR is computed.

In a cellular network we will have different interference situation in the uplink and the downlink. For simplicity we describe both of them by the downlink cell border capacity. This approach overestimates the capacity in uplink. Despite that, it supposes not to change the results of our optimization problem since the impact is similar for both co-channel and adjacent channel.

6. Power Allocation Optimization

The capacity equation (2) expresses secondary system's capacity if only one channel is used. If the secondary system uses both, adjacent channel and co-channel, we have to consider the capacity over both channels. Below we outline a method that allows to optimize the joint capacity of adjacent and co-channel given the interference constraint (21) (or (8)).

The joint capacity with both channels is

$$C(P_{SU_a}, P_{SU_c}) = \sum_{k\in\{a,c\}} B\log_2(1+\gamma_k) \qquad (24)$$

where for γ_c γ_a we can use (22) and (23).

We maximize the capacity (24) given the the constraint (8) (or (21)) by using Lagrange multiplier. The Lagrangian of the optimization problem is

$$L(P_{SU_k}, \lambda) = \sum_{k\in\{a,c\}} B\log_2(1+\gamma_k) + \lambda(\bar{I} - I_\Delta). \qquad (25)$$

For finding the maximum we take the partial derivative with respect to P_{SU_a}, P_{SU_c} and set them to zero. By using (22) and (23) in (25) and taking the derivative with respect to P_{SU_c} we have

$$\frac{\partial L}{\partial P_{SU_c}} = \frac{B r_{c,i}^{-\alpha} P_N}{\ln(2)} \frac{1}{f(P_{SU_c})} + \lambda G_c \sum_m (r_{c,m}^{TV})^{-\alpha} = 0 \qquad (26)$$

where

$$f(P_{SU_c}) = a_c P_{SU_c} + b_c P_{SU_c} + P_N^2,$$

$$\begin{aligned} a_c &= \sum_{m\neq i} r_{c,m}^{-\alpha}\left(r_{c,i}^{-\alpha} + \sum_{m\neq i} r_{c,m}^{-\alpha}\right), \\ b_c &= P_N\left(r_{c,i}^{-\alpha} + 2\sum_{m\neq i} r_{c,m}^{-\alpha}\right). \end{aligned}$$

Similarly one can calculate the derivative with respect to P_{SU_a}.

After rearranging the terms we have a set of equations

$$\begin{aligned} \frac{B P_N r_{a,i}^{-\alpha}}{G_a \sum_n (r_{a,n}^{TV})^{-\alpha}}\left(a_a P_{SU_a}^2 + b_a P_{SU_a} + P_N^2\right) &= \frac{1}{\lambda}, \\ \frac{B P_N r_{c,i}^{-\alpha}}{G_c \sum_m (r_{c,m}^{TV})^{-\alpha}}\left(a_c P_{SU_c}^2 + b_c P_{SU_c} + P_N^2\right) &= \frac{1}{\lambda}, \qquad (27) \\ P_{SU_a} G_a \sum_n (r_{a,n}^{TV})^{-\alpha} + P_{SU_c} G_c \sum_m (r_{c,m}^{TV})^{-\alpha} &= I_\Delta. \end{aligned}$$

One can notice that (27) resembles a well known water-filling problem [7]. The difference is that instead of linear problem we are dealing with second order polynomials. Since the size of the problem is relatively small we can solve it by using simple substitution.

7. Numerical Examples

By using the equations above we investigate how the size of the no transmission area impacts the capacity of the secondary system. We do this analysis for co-channel, adjacent channel and also for the two channels together.

For numerical illustrations we use a system model with TV station using P_{TV} 200 kW, the TV cell size is 140 km, $10\log_{10}(\gamma_t) = 15.4$ dB, system bandwidth is $B = 8$ MHz, noise temperature is 290 K, outage target is $O = 0.1$, the channel path loss constant is $\alpha = 3.2$, adjacent channel suppressions are $G_a = G_{TV} = 10^{-5}$. We allocate the hexagonal secondary cells outside of the TV no transmission area and do the computations for three different secondary cell sizes $\{100, 1000, 10000\}$ m.

In Fig. 2 the secondary system capacity is illustrated if only one of the channels (either adjacent or co-channel) is used. We change the size of the no transmission area, compute the power P_{SU_a} (or P_{SU_c}) that satisfies the interference constraint (21), and evaluate the cellular system capacity given this power. The cellular system capacity is computed as following: set the cell size, cover the secondary system area with hexagonal cells and evaluate the SINR at each cell border. The capacity is computed from (2) by using minimum SINR over all the cells.

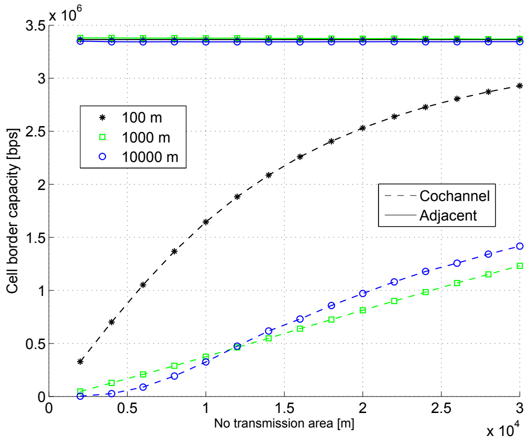

Fig. 2. Adjacent and co-channel capacity for different no transmission area when the capacity is computed for both channels separately. One channel is 8 MHz TV channel.

In Fig. 2 we see that the adjacent channel is sufficiently uncoupled from the TV channel. SU can use in that channel enough power to turn the secondary system into interference limited mode. By increasing the no transmission area we can allow even higher power but that does not lead to any significant additional capacity increase.

The co-channel SU network operates in noise limited mode. The co-channel can not be filtered away and the only method for allowing higher power for SU transmission is to move the SU transmitters away from TV coverage border. By increasing the no transmission area size the secondary cells could use more power and there is a visible increase in the network capacity. In order to reach the interference limited mode the no transmission area has to be very wide. Smaller SU cell sizes achieve that mode for smaller no transmission area. This result confirms the claim from [6] that near to the TV cell border it is preferable to use small cells.

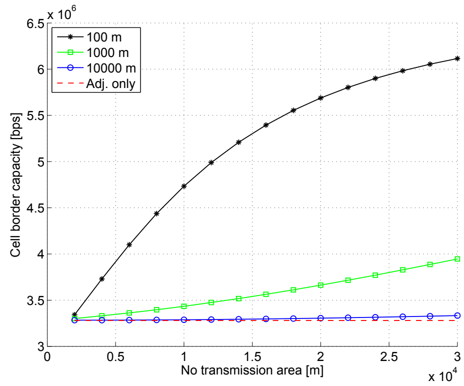

Fig. 3. Adjacent and co-channel capacity for different size of no transmission area when the capacity is optimized for both channels together. One channel is 8 MHz wide, the adjacent and co-channel together use 16 MHz of bandwidth.

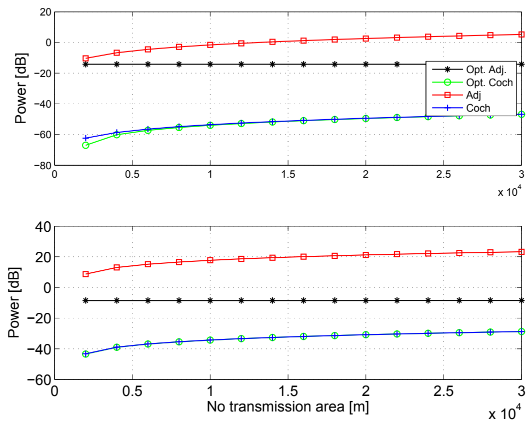

Fig. 4. Power sharing between the adjacent channel and the co-channel. Upper figure for the SU cell size $R = 100$ m, lower figure $R = 10$ km. Optimized case represent power allocations done on both channels simultaneously. The comparison is made with the normal case when the power is allocated only on one of the channels.

The analysis of the power allocation between co-channel and adjacent channel is illustrated in Fig. 3. The equation (27) has four sets of solutions but we present only the one leading to the highest capacity. The corresponding power allocations are seen in Fig. 4. With dashed line we represent the adjacent channel capacity (the same that is on the Fig. 2). It is observed that for a large cell size it is better to generate most of the interference from the adjacent channel. There will be not much power allocated on the co-channel and therefore its contribution to the total capacity is very little. Since all channels are co-channels to some TV stations based on those results one would question whether large secondary cells are at all feasible.

The simulation results indicate that the cellular network in adjacent channel is in most times interference limited while the co-channel cells are noise limited. This observation suggest to use bigger cells with adjacent channel and small cells with co-channel.

8. Conclusions

We have derived the equation describing the aggregate secondary system interference to the TV system in a fading environment. We use this equation for constraining the power a secondary system can use in its cellular base stations. By using the aggregate interference constraint and the capacity of a cellular system we analyzed the impact of no transmission area on the capacity of the secondary system.

When allocating the powers together on the adjacent and on the co-channel it is better to use only adjacent channel when large secondary cells are used. By allocating the power on the co-channel we generate relatively more interference than we gain in capacity. This is because the cells with adjacent channel can operate mostly in interference limited mode while cells with co-channels are noise limited. For large cells even a no transmission area of 30 km was not enough to allow sufficient power on co-channel to move it to interference limited mode. The SU cells using co-channel can be pushed into interference limited regime only if the cell size is relatively low. We could confirm the claim from [6] that near to the cell border it is favorable to use small cells.

All the TV frequencies are co-channels to some of TV stations. Since it is not beneficial to allocate much power to a co-channel, it seems that it is very difficult to introduce large cells into TV white space. Essentially, for providing enough power for big secondary cells we have to create large no transmission area. For such large no transmission area there will not be much space left. There will be very little area where secondary transmitters can be deployed.

Acknowledgement

The authors would like to thank the European Union from providing partial funding of this work through the EU FP7 project INFSO-ICT-248303 QUASAR.

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