Dimensioning of secondary cellular system in TVWS

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***Abstract*—The attractiveness of TV white space depends on the cost of secondary network. The cost mainly depends on the number of deployed cell sites. Traditionally, the required number of sites is estimated at the dimensioning stage of the network planning process. However, in TVWS the amount of available spectrum and the allowed transmission powers are not known beforehand. In this paper we propose to use an iterative dimensioning process. Initially secondary cell sizes are selected based on the user density. In the cells where the capacity is not sufficient, we either reduce the cell size or increase the transmission power. In TVWS, the strict limitations on the allowable transmission power significantly constrain the capacity of large cells. The power is mainly limited by the reference geometry used for protecting adjacent channel TV reception. Even a slight increase of the allowed power will significantly improve the secondary cellular system capacity.**

I. Introduction

The usage of mobile data traffic has been rapidly growing during recent years. The growing demand requires more frequency allocations to the mobile systems. Instead of dedicated spectrum blocks, future mobile systems could share same frequency with other systems. One such candidate spectrum is the TV white space (TVWS). TVWS has been studied extensively during recent years, however, the achievable secondary capacity varies significantly depending on the country and secondary system. Whether a TVWS will be opened up for secondary use depends on its economical attractiveness. In this paper we assess the TVWS suitability for a cellular system.

Traditional cellular system is dimensioned to meet the users demand [1]. Usually the amount of frequencies allocated for the system is fixed and the demand is met by selecting appropriate cell sizes: smaller cells in areas with high traffic density, larger cells in areas with lower traffic density. Compared to the traditional network planning, the design of a system using TVWS has a different nature. In TVWS the entire spectrum is not available for secondary use. In TVWS the available bandwidth and transmission powers depend on the coverage areas of the TV transmitters and on the WS usage rules. This means, that the capacity of the cellular system using TVWS frequencies cannot simply be estimated by using the cell sizes. The secondary network has to be dimensioned around an unknown amount of spectrum.

Previous studies of the amount of TVWS mainly present the number of available channels or capacity for single link, which cannot be used for cellular case. However, few previous studies are analyzing the TVWS cellular capacity taking into account interference from primary system and secondary system self-interference. In [2] and [3] secondary capacities are computed for uniform cell sizes, but also cellular network dimensioned according to population density is very briefly discussed. These papers use the secondary usage rules outlined by the Federal Communications Commission (FCC) [4]. In [5] FCC rules are compared with the proposed rules provided by Electronic Communications Committee (ECC) [6], but again only uniform cell sizes are used. Now this study is continued by including detailed population information to the analysis and by analyzing the results from network's and users' perspectives.

In this paper we study a TVWS cellular system that is dimensioned according to the user density in the cells. Instead of following the classical dimensioning approach where the cell size is a variable and selected such that the cell throughput meets the demand in the cell, we set the cell size to contain certain amount of demand and compute the data rate in each cell. The data rate computation takes into account the available TVWS spectrum and allowed power level in each cell. We do the analysis for TVWS spectrum usage rules outlined FCC and ECC.

The analysis outlined in this paper is intended as a part of the TVWS system dimensioning method. We illustrate how the cells, designed based on the proposed method, are able to satisfy the users demand. Also, we compare the capacity of the TVWS system with a system that can use the whole spectrum, all the spectrum in all locations. Such comparison illustrates how the primary system reduces the capacity of the secondary system.

The paper is organized as follows. In section II we describe the dimensioning process, in section III we describe how the amount of TVWS channels is estimated, in section IV we describe how a cell capacity is computed, in section V illustrate the TVWS capacity per user in Finland and section VI concludes the paper.

II. Dimensioning process

In the dimensioning process we determine the cell sizes that are required to meet the offered demand. In TVWS we do not know the available spectrum beforehand and

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TABLE I
USED CELL SIZES, THEIR COVERAGE AND AMOUNT IN NON-UNIFORM CELLULAR LAYOUT

Name	Size	Coverage	Number
small	1km x 1km	1 km^2	1744
medium	4km x 4km	16 km^2	5459
large	32km x 32km	1024 km^2	327

therefore we propose to start the dimensioning process by selecting the cell sizes based on the user density. Our dimensioning process steps are:

1) User density based cell size selection.
2) Channel and power allocation based on TVWS usage rules.
3) Computation of the service quality (e.g. capacity per user).
4) If desired quality target is not met, split cells or increase power.

We compare the performance of the cellular network designed based on the above described steps with the network having uniform (constant) cell size.

As a case study we use TVWS information and user density information in Finland and cover the country with cellular network. In the covering we use rectangular shaped cells. Rectangular structure simplifies analysis when different sized cells are used. At the same time, it provides a good estimate of the cells density and the actual network capacity.

Three sizes of square shaped cells were chosen to be used in the analysis: small, medium and large cells with sides of 1km, 4km and 32km, respectively. The cell size allocation algorithm is simple. First, country wide coverage is done with large cells. The large cells that have more than 10000 users in their coverage area are split into medium size cells. In the second step we consider the medium size cells. The medium size cells covering more than 10000 users are split further into small cells. The resulting cellular layout is shown in Figure 1 and information about the sizes and their amounts are presented in Table I.

From network operator's point of view it is essential that reasonable amount of capacity can be provided in each cell. Due to power constraints in the WS operation, the capacity especially in large cells can in some locations be very modest. The capacity per area can be increased by introducing smaller cells or by allowing higher transmission powers. The density of the smaller cells can be identified by the iterative splitting process described above. In large cells the power is usually limited by the need to protect the TV receivers in adjacent channels. Accordingly to ECC spectrum using rules, such protection is defined by the reference geometry, the distance to the nearest TV receiving antenna. Higher power can be allowed if larger reference geometry is assumed.

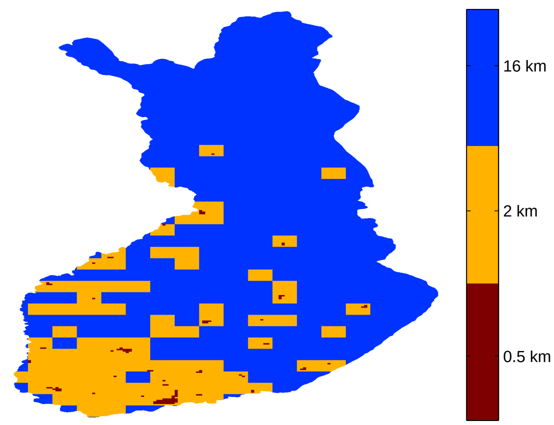

Fig. 1. Non-uniform cellular layout in Finland when cell sizes are selected based on population density

III. CHANNEL AVAILABILITY

The actual available TVWS spectrum depends on the applied spectrum usage rules. Currently there are two TVWS usage approaches, in Europe the rules are proposed by ECC and in the United States by FCC. Below we describe both of the TVWS usage rules and the parameters we were using while applying those rules.

We consider a TV channel to be available in the cell if it is available in the whole cell area. In case of FCC rules, it means that the cell should be outside of the protection area surrounding the TV coverage area. Figure 2 shows the density of available channels in each cell when FCC rules are applied and Figure 3 the density when the ECC rules are applied.

FCC rules prohibit using both, co- and adjacent channels inside certain protection distance whereas ECC rules allow using the adjacent channels everywhere. Therefore with FCC ruling the number of available channels is considerably lower. In some cells only one channel can be used, whereas with ECC rules in every cell there are at least 10 available channels. However, since the allowed transmission power is also different, the number of available channels does not directly indicate the available capacity.

A. *FCC usage rules*

The FCC allows the operation of both portable and fixed unlicensed devices in the TV bands [4]. In the fixed operational mode, FCC specifies the maximum allowable EIRP of secondary transmissions to be equal to 4 W. In addition, the secondary transmitter must be located at least a certain distance away from the coverage area of a TV station when using co-channel or the closest adjacent channels. Other adjacent channels do not impose any restrictions. FCC uses different protection distances for different secondary antenna heights. Compared to a

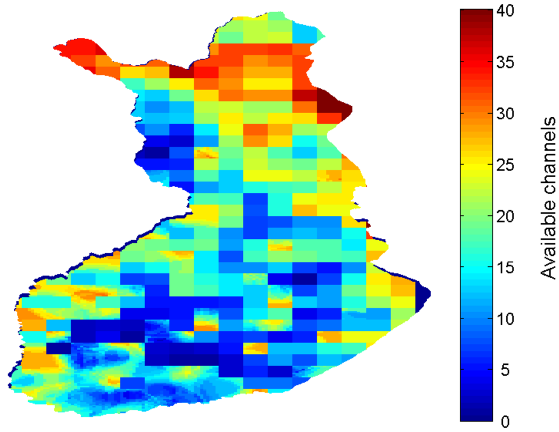

Fig. 2. Available channels per cell when FCC rules are applied, non-uniform cellular layout

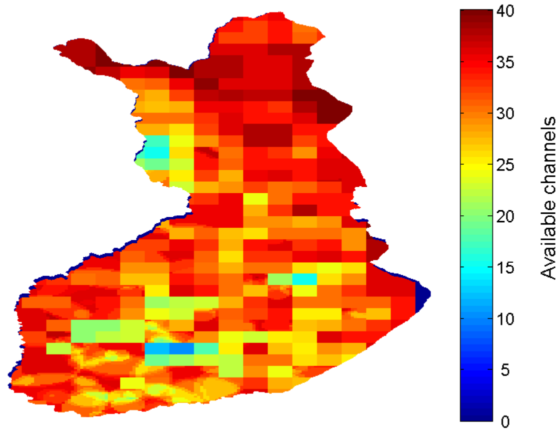

Fig. 3. Available channels per cell when ECC rules are applied, non-uniform cellular layout

low antenna height, signal from a high-located antenna faces less environmental clutter. Such antenna will potentially generate more interference and TV receivers need better protection. FCC does not explicitly consider multiple secondary transmitters. It assumes that the specified protection distances are sufficient to keep the aggregate interference under control.

B. ECC usage rules

According to the ECC rules [6], all adjacent channels can be used everywhere. The co-channels can be used only outside of the TV coverage area. In ECC specification the allowed secondary power is calculated as

$$P_{SU} = \mu_{TV} - \mu_G - \gamma_{D|U} + q\sqrt{\sigma_{TV}^2 + \sigma_{SU}^2} - MI - SM - M \tag{1}$$

where μ_{TV}, σ_{TV} are the mean and standard deviation respectively of the TV signal, μ_G is the mean secondary pathloss, $\gamma_{D|U}$ is the protection ratio in dB due to the frequency offset between the TV receiver and the secondary device, $q = Q^{-1}(1 - O_n)$ is the Gaussian confidence factor and the Q^{-1} is the inverse Q-function.

In (1) all the means and standard deviations are expressed in dB. Additionally, the margin MI is used to account for multiple secondary interference, the margin SM is a safety margin and the margin M contains all the parameters not directly expressed in (1) such as antenna gain and antenna directivity discrimination.

TV receivers are protected by selecting the secondary transmission powers based on (1). From (1) one can deduce that the secondary transmission power is not fixed but it depends on the location of the unlicensed device. The closer the device is to the TV cell border the less power it can transmit. The equation is also used for computing the allowable power when transmitting on adjacent channel within a TV coverage area. We assume that the nearest TV receiver is 22 m or 100 m away and has line of sight connection to the secondary transmitter. For such distances free space path losses are -53.3 dB and -66.4 dB at 500 MHz, respectively. ECC rules protect the TV receivers from multiple secondary transmitters' interference by using a margin MI. The current proposal contains three different margin values MI = 3; 5; 6dB for 2; 3 and 4 secondary interferers respectively. For more interferers we can use the additional safety margin SM specified in (1). In our computations we use only one interference margin (IM) that includes all the margins.

IV. Cell capacity computation

The number of available channels does not give realistic overview of the usability of TVWS. In a cellular system we are rather interested in the capacity the system is able to provide. Cellular TVWS capacity is affected by channel exclusions, allowed transmission power, interference and noise. Interference is caused by primary system as well as self-interference from other secondary transmitters.

Capacity for a secondary cell is calculated by first computing the secondary SINR:

$$SINR_{SU,i} = \frac{P_{SU,i} g_{SU}}{\sum\limits_j P_{TV,j} g_{TV,j,i} + \sum\limits_{k \neq i} P_{SU,k} g_{SU,k,i} + P_n} \tag{2}$$

where $P_{SU,i}$ is the secondary transmission power at the ith cell, $g_{TV,j,i}$ is the pathloss attenuation from the jth TV transmitter to the ith secondary cell, $\sum_j P_{TV,j} g_{TV,j,i}$, describes the aggregate interference from the co channel TV transmitters to the ith secondary cell test point and $\sum_k P_{SU,k} g_{SU,k,i}$ describes the secondary network self interference. Naturally, when calculating capacity of standalone network, the interference from TV is removed. By applying Shannon capacity formula to the SINR we get the capacity:

$$C = BW \log_2 (1 + SINR) \quad (3)$$

where C is the resulting capacity on a channel and BW is the channel bandwidth. The average capacity in each cell is calculated by taking the mean over 32 test points inside each cell.

Based on the population data of Finland, we precisely know the number of inhabitants living inside each secondary cell. Population density varies significantly throughout Finland. We assume that in each cell there is at least one user. Capacity per user is computed by dividing the average cell capacity by the number of people living in each cell.

V. Cellular TVWS capacity in Finland

In this section we illustrate the cellular system capacity in TVWS in Finland. The capacity is evaluated by selecting the cell sizes to follow the user density, each cell is selected to have 10000 or less users. Otherwise the computation parameters are the same as in our previous study [5]. The computed capacity is compared to the capacity of a cellular system that has the same cells but use a dedicated spectrum. The compared networks are: *a*) network using one TV channel everywhere in the country, *b*) network using 20 MHz bandwidth like a LTE system *c*) network using all the TV channels everywhere in the country.

Compared to TVWS case, in dedicated system, there are no limitations on transmission powers and not interference from TV transmitters. Interference is caused only by other cells in the network, self-interference. We limit the maximum transmission power to be 10 W at each BS. This is enough to keep transmitted signal well above noise level at cell edges.

We compute the capacity from, user and network perspectives. Population density is taken into account when allocating the non-uniform cells and when calculating the capacity per user in each cell.

A. Capacity per user

For the non-uniform cellular structure results are shown in Figure 4. User capacities from FCC and ECC methods are close to each other. ECC method gives slightly better capacity in general, but in the lowest 10th percentile FCC method gives more capacity. Using 4dB larger margin (4dB lower transmission powers) in ECC method has only marginal effect to the user capacity results. Compared to standalone network with 20 MHz BW, the TVWS secondary usage with non-uniform cell structure gives up to 10-times more capacity per user.

When the cellular structure is uniform throughout the country (no adoption to the users density), the user capacity is again about 10-times larger when using cells with 1km radius. When larger cells with 5 km radius are used, the capacity is about 2-times larger. This is shown

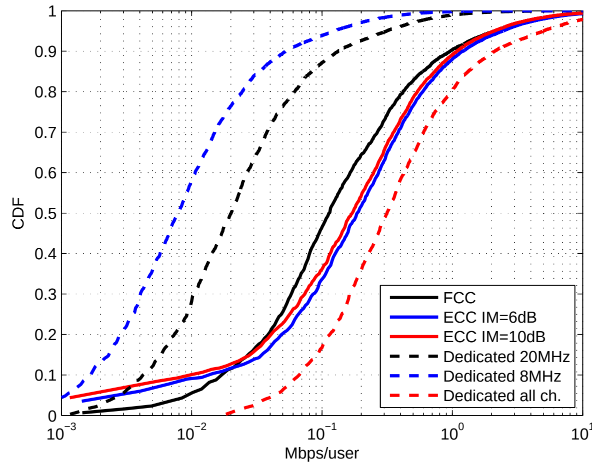

Fig. 4. Average capacity per user distribution with non-uniform cellular layout calculated for FCC rules, for ECC rules with different margins and for dedicated system with different bandwidths

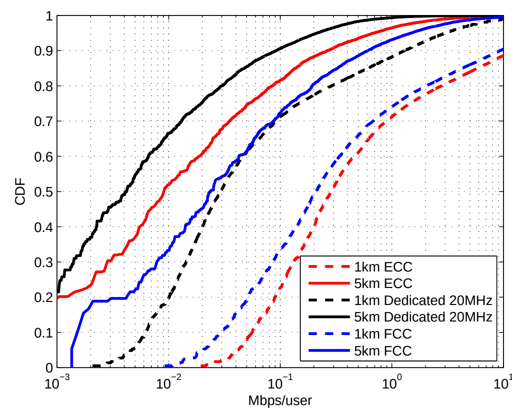

Fig. 5. Average capacity per user distributions with uniform cells having cell radii of 1km and 5km, calculated for FCC rules, for ECC rules and for dedicated system with 20MHz bandwidth

in Figure 5. The relatively smaller increase in the larger cells can be explained by power limitation of the cells.

B. Capacity per cell

From operator's point of view, the capacity per cell is an important metric. It tells where it is reasonable to use TVWS cells. For the non-uniform cell structure, average capacity per cell distributions is shown in Figure 6. TVWS use gives 10-times more capacity in small cells and about 5-times more capacity in medium sized cells compared to stand-alone network. In large cells TVWS network provides more capacity in 75% of the cells than stand-alone network. This suggests that the main potential of TVWS usage is on small and medium sized cells.

When cellular layout is uniform, the difference between ECC and FCC method can be seen clearly as shown in Figure 7. For 1 km cells, ECC method gives slightly more capacity than FCC, but with 5 km cells FCC gives more capacity per cell. This is again caused by the fact that ECC method has more available channels, but the allowed transmission powers are in most locations smaller than what FCC allows. In fact, cell size has very little effect to the cell capacities in FCC and stand-alone networks. As expected, in the stand-alone case, almost all cells give the same amount of capacity. However, small portion of the cells that are located at the border areas can provide higher capacity, due to fewer interfering cells. Average capacities in stand-alone network are about 60 Mbps per cell, whereas in the WS networks median average capacities are over 500 Mbps per cell, except for the ECC method with 5 km cells the median capacity is about 250 Mbps per cell.

C. Increasing capacity in Large cells

Unlike in a traditional cellular network, network operating on TVWS has strict power limitations. As can be seen from Figure 6 this causes noticeable effect in large cells. Power limitations cause cells to become noise limited, resulting to significant capacity decrease. We assessed two different methods for increasing capacities in large cells. One option is to split the cells that have low capacity into smaller ones. We split cells that had average capacity less than 100 Mbps into 4 smaller ones and then recomputed the capacity. About 60% of the large cells are split.

Other option is to increase transmission power. In ECC method the power is usually limited by the reference geometry which means the expected distance to the closest TV receiver. This distance is considered to be 22 meters in the ECC rules. In our analysis, large cells are located in rural areas where population density is low. Therefore it is reasonable to assume that this distance can be higher. In rural areas base stations can also be more freely located further away from buildings having TV receivers.

Capacity results for large cells before and after the splitting, and with larger 100 meter reference geometry are shown in Figure 8. By splitting the chosen cells, the lowest 10th percentile capacity moves from 4Mbps up to 20Mbps. By redoing the splitting, capacity can be naturally further increased. However, in low population density areas, it might not be economically attractive solution since more cells are needed. From operator's perspective more tempting is to assume larger 100m reference geometry. Now, the lowest 10th percentile capacity moves up to 45Mbps, which is over 10-times better than with 22m reference geometry.

VI. Conclusion

In this paper we discussed the dimensioning process of secondary cellular network operating in TVWS. Secondary operation causes constraints to transmission power and channel availability, that don't exist in traditional cellular system. As a result, the capacity is not known beforehand. We select cell sizes for each location by using information about population density. Based on our capacity computations it can be seen that the TVWS usage rules cause low capacity, especially in large cells. In large cells the capacity is noise limited. The capacity conditions can be improved by replacing the large cells with smaller cells or by increasing the allowed transmission power. In the first case we split the cells with low capacity and compare it to the second method where more transmission power is allowed. We see that assuming 100m reference geometry instead of 22m improves capacity more than cell splitting. Cell splitting can naturally be done several times, but building more small cell cites into rural area is not economically attractive solution.

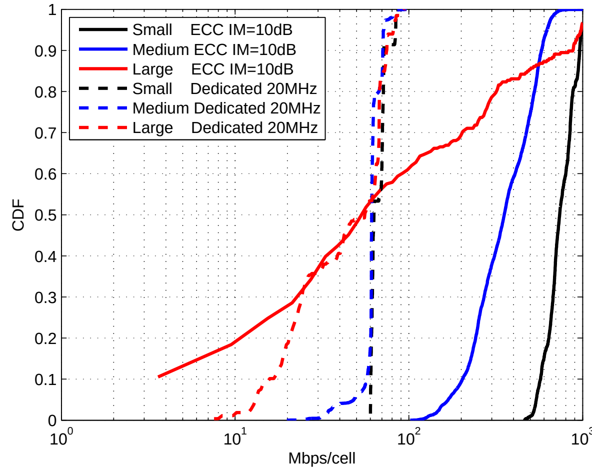

Fig. 6. Average capacity per cell distribution with non-uniform cellular layout calculated for ECC rules with 10dB margin and for dedicated system with 20MHz bandwidth

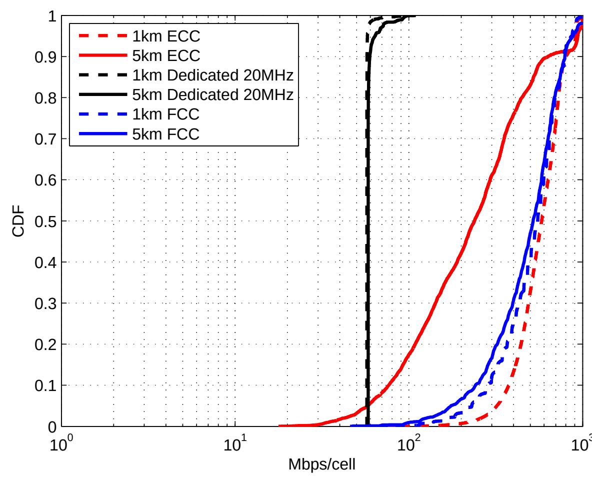

Fig. 7. Average capacity per cell distribution with uniform cellular layouts having cell radii of 1km and 5km, calculated for FCC rules, for ECC rules with 10dB margin and for dedicated system with 20MHz bandwidth

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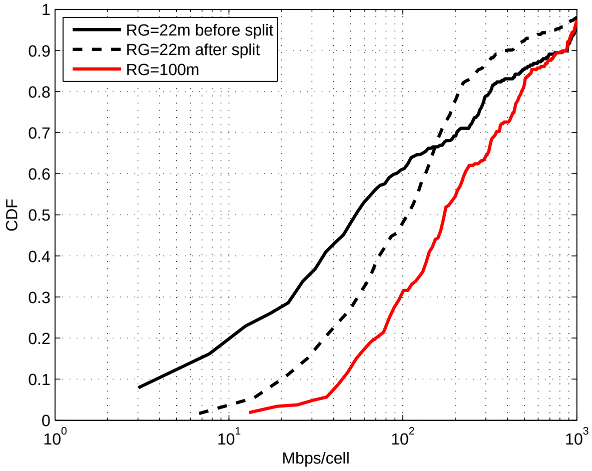

Fig. 8. Average capacity per cell distributions with non-uniform layout, calculated for large cells only with 22m reference geometry before and after cell splitting and 100m reference geometry, ECC rules with 10dB margin used

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