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TECHNICAL CONFIGURATION OF TV WHITE SPACE DEVICES: A CONCEPTUAL VIEW

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Abstract: As it is known, to eliminate interference, the frequency reuse approach is followed in digital TV (DTV) planning similar to cellular networks, avoiding the use of the same channel in two neighboring allotments. There are large areas where certain groups of TV channels are not deliberately used. They are called white spaces in TV spectrum (TVWS). Considering the great economical value of TV spectrum, it was proposed to use TVWSs for low-power wireless networking on non-interfering (secondary) basis with the licensed (primary) DTV service.

At the same time, restrictions imposed on white space devices (WSDs) to protect primary users should not devaluate spectrum for secondary use. The lack of knowledge about the locations of primary receivers, as well as the unreliable estimation of the aggregate interference impact caused by the large number of secondary devices accessing the spectrum are reported to be among the key challenges for the use of TVWSs.

In our view, parameters for the protection of primary system should be based on the determination of minimum separation distance, which by all means should be observed at a certain area. A required shadow margin, as well as a multi-user margin should be calculated for such a minimum safety range. To reuse spectrum efficiently, mobile/portable WSDs should support dynamic power control ability which has to play a key role in sensing and operate with the lower power??? when a TV signal is weak. Except for providing WSDs with a list of available channels, the geolocation database should contain recommended parameters for path loss calculations, as well as minimum distances which could be ensured for a certain inhabited locality.

Key words: TV white space; cognitive radio; white space device; spectrum sensing; geolocation database; opportunistic spectrum access; secondary use; aggregate interference; LTE over TVWS.

1. Digital TV, “white” spectrum, cognitive radio

As a result of the Regional Radiocommunication Conference (RRC06) being held in Geneva in June 2006, TV bands IV–V (470-862 MHz) were assigned to DVB-T usage and divided into 49 channels, each one 8 MHz wide. Region 1 was divided into geographical allotments and into the sets of frequency assignments for each of them. To eliminate interference, the frequency reuse approach is followed in DTV planning similar to a cellular network, avoiding the use of the same channel in two neighboring allotments [1]. So, there are always vast unused frequency bands between used TV channels. These areas are called “white spaces” in a television spectrum (TV white spaces, or TVWS: that is how they look like at a bandmap). DTV allocations are much larger than the size of cells in mobile communication, and as usual cover areas of several hundred square kilometers. Considering the economical value of TV spectrum due to perfect propagation characteristics and reasonable size of antennas, it was proposed to use these “white” frequency bands for low-power low-range wireless networking on non-interfering (secondary) basis with the licensed (primary) DTV transmissions.

The US Federal Communications Commission was a pioneer in developing the concept of using TVWS. In Europe these tasks are carried out by the CEPT Spectrum Management Group and the CEPT Spectrum Engineering Working Group (WGFM and WGSE). ETSI Reconfigurable Radio Systems Technical Committee is responsible for standardization efforts. Thus, increased spectral efficiency and great savings of spectrum after the transition to DTV makes a profit not only for broadcasting. Many services and applications could benefit from the secondary use of TVWS [2], for example:

- Wireless low power networks for hotspots and premises in TV bands, as an alternative to the highly congested industrial, scientific, and medical (ISM) band.
- Regional-area networking, especially suited to providing the Internet in areas with poor wireline infrastructure.
- 3G/4G networks extension over TVWS, complementing licensed spectrum usage: in particular, in femtocells to minimize interference to own macrocells.
- Short Range Devices, and others.

For the effective exploitation of TVWS it is necessary to develop mechanisms for determining TV channels which could be occupied by this or that secondary device and maximum effective isotropic radiated power (EIRP) allowed. This is the idea of so-called opportunistic spectrum access where mechanisms, employed by the network of such devices (White Space Devices, WSD) is a feature falling in the more general category of Cognitive Radio.

For these, two principal mechanisms were proposed: spectrum sensing and geolocation [3]. In the first, a node of a secondary wireless network is equipped with the receiver which periodically scans the TV band searching for locally unused channels and estimating a signal level that could be permitted for its transmitter. Distributed sensing is also possible, where several nodes exchange their data to increase sensing accuracy.

Due to static locations, service areas and frequency assignments of licensed DTV transmitters, one can create a database containing the map of TV channels assigned to each location along with a permissible power level for corresponding WSDs. These devices determine current locations via built-in GPS receivers thus finding sets of channels with their corresponding permissible power levels in the database to avoid interference with primary users. Geolocation-based spectrum allocation can be applied simultaneously or together with spectrum sensing.

The approaches mentioned above were implemented in a number of standards/specifications [4]. Thus, IEEE 802.22 defines the physical (PHY) and medium access control (MAC) layers of a regional cognitive radio access network. Here channel allocation is centralized and based on geolocation approach, while sensing is also used to check the presence of the TV signal [5]. We should mention, among others, IEEE 802.11af, developed for opportunistic unlicensed operation in TV bands, IEEE 802.16h which defines WiMAX adopted to work in the TVWS in a cognitive manner, ECMA-392, IEEE P802.19.1 and cognitive IEEE 802.15.4 Zigbee.

2. Problems of deploying TVWS radio networks: the protection of primary services

Licensed primary users must be reliably protected against potential secondary interference. Digital TV receivers require special protection: only few percent of them is allowed not to reach their signal-to-interference ratio (SIR) targets. At the same time, restrictions imposed on secondary devices should not lead to the devaluation of the white spectrum blocs to such extent which makes opportunistic secondary access to them useless.

The main source of interference to primary systems considered in the literature is emissions from TVWS users (typically out-of-band) that fall in-band for the licensed receiver. There are also in-band emissions from the WSD that fall outside but close to licensed band and couldn't be filtered properly in the TV receiver. In practice interference is a combination of these two factors.

There are two principal categories of TVWS devices: fixed and portable WSD. The first includes base stations (BS) operating from a known, fixed location with effective isotropic radiated power (EIRP) up to 4W, as well as 100 mW consumer premise equipments (CPEs) [6]. Within the second category, personal/portable devices are allowed a maximum EIRP in a range of 40÷100 mW. Devices of both categories can use spectrum sensing and could retrieve a list of available channels from some authorized database.

Planning a BS within the protected contour is simplified by a number of factors:

– channels with less critical protective ratios can be allocated for more powerful fixed devices;

– fixed WSD antenna can be oriented towards the center of protected contour co-directionally to antennas of nearest TV receivers (so any BS must be located on the edge of a certain concentric figure within that contour);

– the opportunity to implement cross-polarization isolation between the secondary system and TV.

Thus, in future the technical parameters of unpredictable and ubiquitous portable WSDs will probably be the most critical issue for compatibility with the digital TV services.

In the common cognitive-radio approach it is assumed that secondary devices will find free spectrum by sensing the signals of primary users. However, in some publications low efficiency and poor spectrum-utilization of sensing is alleged [7]. Among the major reasons for this we should mention the following:

1. Secondary device may fail to detect TV signals because of buildings or other surrounding obstructions even though the TV channel is occupied (a so called "hidden node problem"). Using the channel according to wrong sensing result causes severe interference to the DTV reception.

2. The lack of information about the location of the primary receiver is the key problem. Detecting the signal from the primary (DTV) system transmitter by the secondary receiver does not provide reliable information regarding neither the propagation path between the secondary transmitter and the TV receiver, nor the primary user's desired path gain.

3. There is no reliable way for the secondary device to assess the aggregate interference caused by the large number of other WSDs accessing the spectrum – consequently the first one cannot determine its own maximum allowed transmission power.

Indeed, the unknown location of the primary receiver is a great difficulty for the secondary use of spectrum due to high interference margin needed for the protection of an incumbent application. According to [7], scanning has little sense in the presence of a geolocation database which could indicate the occupancy of TV channels in the relevant geographical area in a much more reliable way. At the same time, the database containing certain information about the location of TV receivers is unlikely to appear. It was stated that the secondary reuse of TVWS is impractical unless the powers and the data rate transmitted at secondary user's end is extremely low [7].

Such a conclusion was largely predetermined by the interference scenario taken for analysis. The propagation loss between the primary transmitter and receiver is calculated as

$$L_1 = L_{12} + (1-\beta) \cdot X_1 ,$$

where the constant $\beta \in \{0;1\}$ is the measure of the correlation between the observed level of primary signal on the input of secondary (sensing) receiver and the same signal on the TV receiver input [7];

L_{12} is a measured value of the pass loss between the primary transmitter and the sensing receiver;

X_1 is a random value representing the uncertainty related to the unknown distance between the TV transmitter and TV receiver. In our view, a study that have been conducted for two boundary correlation values, for $\beta = 0$ (where sensing does not make sense at all) and $\beta = 1$ (where L_1 and L_{12} are related in a deterministic way, i.e. the location of a primary receiver is definitely known) is not a sufficient one.

Our important assumption for the future findings is about the existence of some minimal distance from which we start addressing the issue of primary receiver protection. In other words, we assume that in the typical TV antenna position secondary devices cannot approach it by an arbitrarily small distance.

3. Interference Model and Secondary Access Scenario

Let us start with the assumption that the portable secondary device does not cause harmful interference to TV receiver from some minimal distance specific for this settlement. Then let's assume that the power P_1 of the primary transmitter Tx1 is known at the secondary device Tx2, thus the path losses L_{12} between them can be accurately estimated (Fig. 1). DVB-T external antennas are assumed to be placed on roofs (usually over 10 meters high) and have no directional properties with respect to secondary transmitters. The signal-to-interference ratio (SIR) in the primary receiver Rx1 is then (in dB)

$$SIR = S_1 - I_2 = (P_1 - L_1) - (P_2 - L_{21}) = P_1 - P_2 - L_1 + L_{21} ,$$

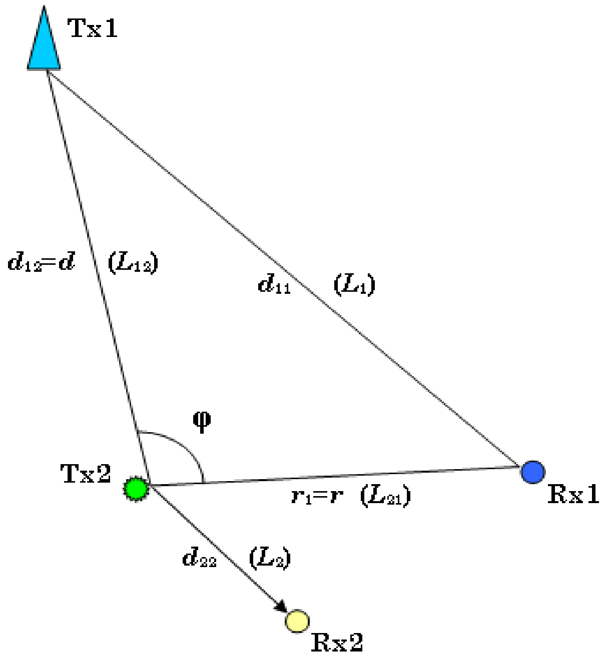
where $L_1 = L_{12} + X_1$ is the path loss prediction between the transmitter and receiver of the primary system;

$$L_{21} = \overline{L}(r) - X_2 = \overline{L}(r_0) + 10 n \log\left(r_1 / r_0 \right) - X_2 ,$$

(we have used a simple propagation model, where the mean loss in dB follows the inverse n power law dependence of distance [7, 8]). A zero-mean Gaussian random value X_2 has standard deviation 6÷10 dB for the TV band (the maximal measured value was 11.8 dB according to [8]);

$\overline{L}(r)$ is the deterministic propagation path loss between the secondary transmitter and primary receiver, and a log-normal random value X_2 presents shadow-fading path loss component. Thus, $SIR = P_1 - P_2 - L_{12} + \overline{L}(r) - (X_1 + X_2)$, wherefrom

$$P_2 + X = P_{Rx1} + \overline{L}(r) - SIR . \quad (1)$$



Tx1/Rx1 – primary transmitter/receiver;
Tx2/Rx2 – secondary transmitter/receiver;
L_1, L_2, L_{12}, L_{21} – propagation losses;
d_{11}, d_{22}, d_{12}, r – corresponding distances.

Fig. 1. The secondary use and interference scenario.

Let *SIR* be the minimal value of wanted-to-unwanted signal ratio at the primary receiver input, so that desirable reception quality is achieved at the output. For specified conditions (frequency offset), it will be a co-channel (adjacent channel, etc.) protection ratio. Then P_2 is the median value of secondary transmitter power which provides required *SIR* at the primary receiver input. The primary signal value measured at the input of the secondary receiver should be taken as primary signal estimate at the TV receiver input (considering TV antenna gain): $P_{Rx1} = P_1 - L_{12}$. We assume that the secondary transmitter Tx2 which is the nearest to the TV receiver Rx1 (and which is located at a distance r_1 from it) is the main interferer. In the following, we evaluate the aggregate interference caused by other WSD. According to the Law of Cosines, $d_{11}^2 = d_{12}^2 + r_1^2 - 2 \cdot d_{12} \cdot r_1 \cdot \cos\varphi$, where $\varphi \in [0; 2\pi]$. Let's $\Delta = d_{11} - d_{12}$, then $\Delta \cdot (d_{11} + d_{12}) = r_1^2 - 2 \cdot d_{12} \cdot r_1 \cdot \cos\varphi$, and $\Delta \approx \frac{r_1^2 - 2 \cdot d_{12} \cdot r_1 \cdot \cos\varphi}{2 \cdot d_{12}} = \frac{r^2}{2d} - r \cdot \cos\varphi$.

It follows

$$\mathrm{M}[\Delta] = \frac{r^2}{2d}, \text{ and } \sigma_\Delta^2 = \left\langle \left|\Delta - \mathrm{M}[\Delta]\right|^2 \right\rangle =$$

$$= \mathrm{M}\left[\frac{r^4}{4d^2} - 2\frac{r^2}{2d} \cdot r \cdot \cos\varphi + r^2 \cdot \cos^2\varphi\right] - \frac{r^4}{4d^2} = .$$

$$= \mathrm{M}\left[r^2 \cdot \cos^2\varphi - \frac{r^3}{d} \cdot \cos\varphi\right] = \frac{r^2}{2}.$$

Since $X_1 = 10 \cdot n \cdot \log\left(\frac{d + \Delta}{d}\right)$ and $\frac{\Delta}{d} < 1$, we obtain

$$X_1 = \frac{10 \cdot n}{\ln(10)} \cdot \left(\frac{\Delta}{d} - \frac{\Delta^2}{2d^2} + \frac{\Delta^3}{3d^3} - \frac{\Delta^4}{4d^4} + \frac{\Delta^5}{5d^5} - \ldots\right) \quad (2)$$

Taking into account $\sigma_\Delta = r/\sqrt{2}$, $\Delta \approx r$ (several tens of meters for urban area [6]), and $d_1 \approx d_2$ (minimum 0.5÷1.5 km from TV tower, while 15÷50 km is the typical DVB-T coverage range) we conclude $\frac{\Delta}{d} \le 10^{-2}$. If we take the first term in (2), so that $X_1 = \frac{10 \cdot n}{\ln(10)} \cdot \frac{\Delta}{d}$, the relative error will unlikely exceed a few percent of X_1 actual value. From the aforementioned it follows $\mathrm{m}_{X_1} = \frac{10 \cdot n}{\ln(10)} \cdot \frac{r^2}{2d^2} \approx 0$, $\sigma_{X_1}^2 \approx \left(\frac{10 \cdot n}{\ln(10)}\right)^2 \cdot \frac{r^2}{2d^2}$ and $\sigma_{X_1} = \left(\frac{10 \cdot n}{\sqrt{2}\ln(10)}\right) \cdot \frac{r}{d}$.

Even at extremely large r (hundreds of meters) and the minimal d (a few km), the mean square of X_1 will be about 1 decibel. This value is much smaller in practice. For instance, for $d \approx 5$ km, $r = 50$ m and $n = 4$, we find $\sigma_{X_1} \approx 0.123$ dB. Obviously, X_1 is relatively small compared to X_2. It follows that the uncertainty of the receiver location is unlikely to be a critical factor for the interference scenario which we selected for studying.

Since Δ depends on a number of random factors which are mostly comparable in terms of their impact, the random variable X_1 has nearly log-normal distribution, and what is much more important, it is small compared to X_2. In this way, we should consider the variable $X = X_1 + X_2$ to be normally distributed (in dB) with the largest possible RMS within $\sigma_X = 9...12$ dB.

4. Basic relations and results

According to (1), the desirable reception quality is achieved for the given conditions and with a given probability Pr. Namely, the right side of (1) is a threshold $P_L = P_{Rx1} - PR + \overline{L}(r)$ which should not be exceeded in a certain percentage of the time for a some median power P_2 of the secondary transmitter. Considering normal distribution of X, one could write $\Pr(P_2 + X \le P_L) = 1 - Q\left(\frac{P_L - P_2}{\sigma_X}\right)$, where $Q(z) = \frac{1}{\sqrt{2\pi}} \int_z^{+\infty} \exp\left(-\frac{x^2}{2}\right) dx$. For instance, for 95 % of time we have $Q\left(\frac{P_L - P_2}{\sigma_X}\right) = 0.05$, or $\frac{P_L - P_2}{\sigma_X} = Q^{-1} = 1.65$, where Q^{-1} is the reverse meaning of Q-function). From that we have

$$P_2 = P_{Rx1} - PR + \overline{L}(r) - Q^{-1} \cdot \sigma_X \quad (3)$$

Knowing the DVB-T antenna gain G_A, secondary device can estimate the power of TV signal at its input. We could express this as a product of antenna effective aperture and average magnitude of the Poynting vector

$$P_{Rx1} = \Pi \cdot S_{eff} \cdot G_A = G_A \cdot \frac{E^2}{120\pi} \cdot \frac{\lambda^2}{4\pi} = \frac{G_A}{480\pi^2} \cdot \lambda^2 \cdot E^2$$

Being represented in decibel notation (where field strength is expressed in dBμV/m, power in dBm and frequency in MHz) this formula takes the form:

$$P_{Rx1} = E + G_A - 20 \cdot \log f - 10 \cdot \log\frac{160\pi^2}{3} - 50 \quad (4)$$

Since the main lobe of the DTV receiving antenna is looking away from the omni-directional WSD transmit antenna, we assume the off-axis antenna discrimination equal 14 dB [6]. Let the minimum nominal distance r_0 be 10 m, corresponding to a free space loss of 50 dB at 800 MHz. According to (3), $P_2 = P_{Rx1} - PR + \overline{L}(r) - Q^{-1} \cdot \sigma_X$. Then considering (1), (4) and [8] we obtain the estimation of the maximum permissible power for the secondary user

$$P_2 = E + G_A - 10\left(\log\frac{160(\pi f)^2}{3} - n\log\frac{r}{r_0}\right) - PR - Q^{-1} \cdot \sigma_X \quad (5)$$

This approach [7] is based on the assumption that the levels of a primary signal at both receivers are nearly the same (strongly correlated). It most cases however, the primary signal is typically experiencing a greater attenuation at the WSD input than that for fixed TV reception (where antenna location is specifically chosen). This sometimes results in the underestimation of permissible power of the secondary transmitter. Indeed, DVB-T reception is usually realized with directive roof-top antennas whose main lobe is looking away from the nearest omni-directional WSD transmit antenna (off-axis antenna discrimination is assumed to be 14 dB [6]). The situation may also happen to be different when the secondary device is working somewhere on the upper floors of the building on the side of the street opposite to the primary one. In this case, the off axis antenna discrimination between the DTV receiving antenna and the WSD transmitting antenna is not ensured.

Distances needed to protect the primary users from the different values of secondary transmitter power (for minimum median field strength 56 dBμV/m and DVB-T receiver antenna located at a height of 10 m [1]) are presented in the Table I.

Table 1

Protection distances in meters: WSD/DVB-T (99%)

channel (*PR*)	*n*	*EIRP of secondary transmitter*			
		40 mW	100 mW	400 mW	1 W
N (23 dB)*	3	2300	3200	5000	6800
	4	880	1120	1600	2000
N±1 (-30 dB)	3	70	90	150	200
	4	40	50	75	95
N±2 (-42 dB)	3	27	36	60	80
	4	15	18	27	33

* 64-QAM 3/4, fixed roof-level reception

These distances were determined in accordance with (5) for two types of zones: high density urban area (*n*=4), and medium density urban / suburban environment (*n*=3) [8]. Protection ratios for co-channel and adjacent channels interference were obtained by averaging the corresponding values for DVB-T/DVB-T2 receivers provided in [9-12]. We also make the pessimistic assumption that secondary devices operate over the entire 8 MHz bandwidth of TV channel [13].

From Table I it follows that the co-channel mode requires protection distances from several hundreds of meters up to kilometers even for small power devices. Adjacent channel protection distances range from 40 up to 70 meters for the secondary transmitter with power about 40 mW. This distance may also be reduced to 20-27 meters at the expense of less stringent requirements for primary receiver protection (95% availability). We assume this distance to be a minimum nominal separation distance between the DTV receiving antenna and the WSD transmitting antenna required for urban environment. In such circumstances operating on adjacent channels is allowed for portable WSDs whose maximum conducted output power does not exceed a few tens of milliwatts (the protection ratio for adjacent channel is assumed to be –33 dB) [6].

Minimum median field strength or protected $E_{\min}$ is the lowest field strength value permitting the given standard of reception to be achieved. Therefore, $E_{\min}$ has to be provided at the edge of the coverage area. In practice, the variation range of DVB-T median field strength inside the protected contour is about 50 dB. For a large amount of statistics, measurements show a log-normal distribution of the DVB-T signal samples. The measured median value of received field strength is about 63 dBμV/m (Fig. 2) [14].

The GE06 Agreement specifies the standard deviation inside large areas equal to 5.5 dB. Variations may be short-term and noticeable even during the day time period depending on changing weather conditions. Thereby according to (5) permissible power of secondary transmitter will also have a log-normal distribution. Figure 3 shows the probability density of P_2 for different conditionally named types of environment (where low densities of TV-receivers in industrial districts are also taken into consideration).

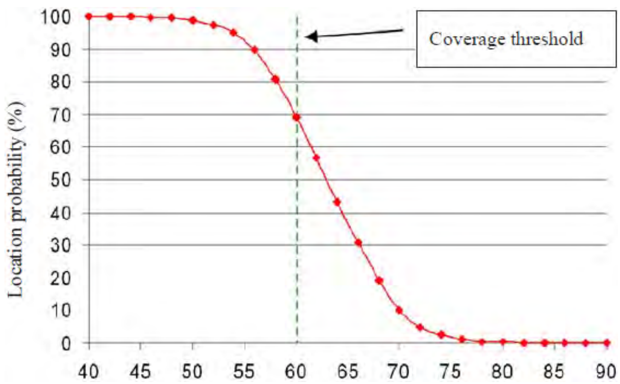


Fig. 2. Location probability vs. received field strength (fixed reception) [14].

For environments differing by housing density, as well as by average building height (such as suburban and urban areas), the difference in median permissible power is about 3 dB at the distance of 20 m between the WSD and TV receiver, and up to 7 dB at the distance of 50 m (see curves 1 and 2). Reducing from 50 to 20 meters the separation distance between WSD and TV decreases the permissible power of secondary transmitter by 16 dB. On the contrary, reducing the requirements for primary receiver protection (from 99% to 95% availability of primary service) increases the permitted power for about 8 dB.

The FCC has allowed portable TVBDs to operate on adjacent channels within the DTV protected contour only if their maximum conducted output power does not exceed 40 mW [6]. But in densely populated areas with a large number of households (curve 2 in Fig. 3) even the

WSD with the power of 40 mW is a potential source of interference for most of receivers: it is shown that the 16 dBm value exceeds at least 96% of all power values which could be permitted for a certain location (see "A", Fig. 3). On the other hand, in non-residential or sparsely populated areas (for instance hotspots in business centers) the same portable device operates with power 10 dB less of median permissible value being even located at a considerable distance from the victim TV receiver ($r_{\min}$=50 m: curve 3). Obviously, this results to the underutilization of available spectrum resource.

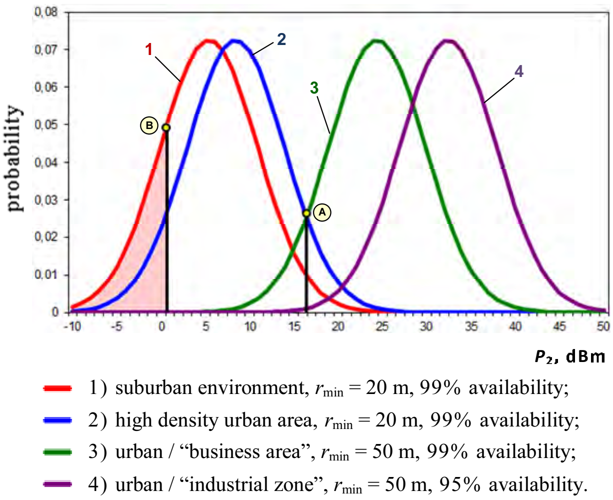


Fig. 3. Permissible power of secondary transmitters.

Thus, the operation in a fixed power mode is usually far from optimal for the WSD. However, the evaluation of P_2 based on some propagation pattern without sensing is unlikely to provide a much better result. For instance, according to (5) for E=56 dBμV/m we get $P_2 \approx 0$ dBm (see "B", Fig. 3). In that case, about 16% of WSDs operate with power exceeding the recommended level and 84% of them with power less than this value. This means that the available spectrum resource is underused in terms of coverage and data rate. As it was expected, limited knowledge/flexibility regarding the current system parameters leads to large safety margins for the secondary-spectrum use and poor spectrum utilization [7].

To use spectrum efficiently, mobile/portable WSDs should support the ability of dynamic power control. The geolocation approach is unlikely to be an effective solution, since the minimum distance between the WSD and the victim TV receiver is much smaller than the typical pixel size (100×100 m ÷ 250×250 m). Therefore, measurements made with the special receiver within the pixel are not correlated sufficiently with the primary signal on the input of the TV receiver.

In these circumstances sensing made by secondary device seems to be a natural source of information about the local electromagnetic environment. By estimating the median power of primary signal at the input of the potentially nearest TV receiver, the WSD evaluates the EIRP of its own transmitter, implementing Open Loop Power Control scheme in the secondary system.

5. Evaluation of aggregated interference effect

Secondary access is commercially attractive only when it is scalable and can support a sufficient amount of secondary traffic in a large area. This means that the primary spectrum is reused by multiple secondary users. However, there are still no unified guidelines for evaluation of the multiple secondary users' impact and correspondently this issue has not been properly addressed in the existing regulatory approaches [7].

In ECC Report 159, a method for regulating transmission powers of secondary users in TV white spaces is proposed [3]. In brief, the main idea is to divide a service area into many pixels. In each of them the maximum allowed transmission power for a secondary user is calculated with the constraint of the TV coverage probability, as follows:

$$\Pr\lfloor PX_P \ge PX_{P,\min} + I_{TV} + I(P_{S,\max}) + IM \rfloor \ge q \,,$$

where q is the required TV-coverage probability, RX_P is the power of the primary signal at the input of the TV receiver, $RX_{P\min}$ is the minimum TV-receiver sensitivity, I_{TV} is the interference from other TV transmitters and $I(P_{S,\max})$ is the interference from the secondary user as a function of $P_{S,\max}$. The safety margin and multi-user margin for considering the effect of multiple secondary users are accounted for by the term IM. However, a harmonized generally accepted method for obtaining the proper IM value has not been adopted yet [7]. The conservative value of IM results in poor spectrum utilization, while the insufficient multi-user margin leads to the risk of failing TV receiver's protection. Nevertheless, we consider this approach to be quite appropriate when there is the dominant source of interference, so that a multi-user margin can be determined as a scaling factor.

Let $P_{\text{Rx1}}^{(1)} = P_2 - 10n\log r_1$ be the median power of signal from the nearest WSD measured at the input of the TV receiver. The interference from other WSDs is, respectively, $P_{\text{Rx1}}^{(2)} = P_2 - 10n\log r_2$; … ; $P_{\text{Rx1}}^{(k)} = P_2 - 10n\log r_k$ ($P_{\text{Rx1}}^{(k)} = P_2 / r_k^n$ in a linear scale).

Let's consider a scenario example 1, where secondary devices are located at distances $r_1 = r$; $r_2 = 2r$; … $r_k = k \cdot r$ from the TV receiver (Fig. 4), so that $P_{\text{Rx1}}^{(k)} = \frac{1}{k^n} \cdot \frac{P_2}{r^n} = \frac{1}{k^n} \cdot P_{\text{Rx1}}^{(1)}$.

Accordingly, the aggregate interference power is $I_\Sigma = \sum_{k=1}^{\infty} P_{\text{Rx1}}^{(k)} = P_{\text{Rx1}}^{(1)} \cdot \sum_{k=1}^{\infty} \frac{1}{k^n}$. The last sum is known as the Riemann zeta function [15]: $\sum_{k=1}^{\infty} \frac{1}{k^n} = 1 + \frac{1}{2^n} + \frac{1}{3^n} + ... = \zeta(n)$ (where $n>1$), thus $I_\Sigma = P_{\text{Rx1}}^{(1)} \cdot \zeta(n)$. According to Euler, the values of the Riemann zeta function at even positive integers are expressed in terms of the Bernoulli numbers [15] which in their turn can be found from the recurrence relation

$$\zeta(2k) = (-1)^{k+1} \frac{(2\pi)^{2k}}{2(2k)!} B_{2k}, \sum_{j=0}^{k} \binom{k+1}{j} B_j = 0,\ k \geq 1 . \quad (6)$$

As it follows from (6), B_0=1, B_1=–1/2. The value of ζ(3) is known as Apéry's constant [16], while the value of ζ(5), being also one of the widely known mathematical constants, was published in [17]. In this case, a few initial values of ζ(n) have significance.

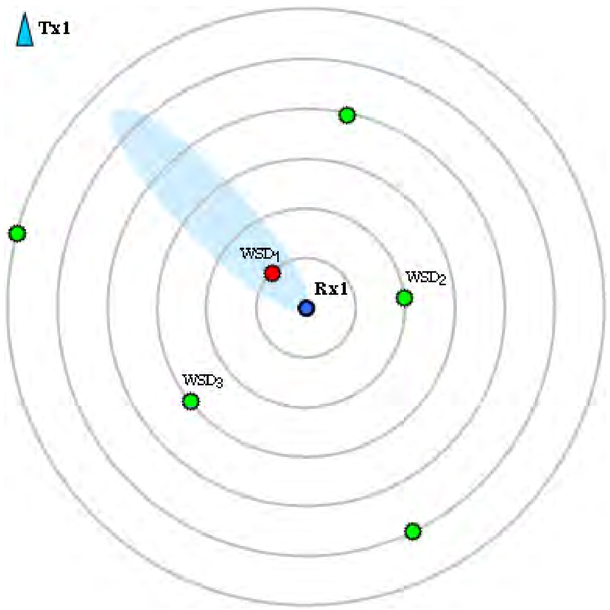


Fig.4. Aggregate interference scenario 1.

The second scenario presents uniform discrete distribution, with distances between the TV receiver and WSDs relating to each other as the series of natural numbers. The nearest of these devices is at the critically small distance r_1=r from the primary receiver (at the minimal distance specified for this location), the other devices are located at distances twice (three times, etc.) greater. Thus their amount increases proportionally to the square of the radius from the TV receiver and this asymptotically leads to uniform spatial distribution. The directional properties of the antennas change the contribution of different transmitters in the aggregate interference, but do not affect their total power.

Let r_k^2 be the total number of secondary users within the range of distances [0; r_k] from a certain TV receiver (the scenario implies the density $\frac{1}{\pi \cdot r_1^2}$ of simultaneously active WSDs which is about 127 devices per 1 km^2 for r_1=50 m. This considerably exceeds the density of active IMT users accepted for compatibility studies in the frequency band 790-862 MHz [18]). One could roughly define their number at a distance $r \approx r_k$ as $r_k^2 - r_{k-1}^2$. It follows $I_\Sigma = \sum_{k=1}^{\infty} P_{\text{Rx1}}^{(k)} = P_{\text{Rx1}}^{(1)} \cdot \sum_{k=1}^{\infty} \frac{k^2-(k-1)^2}{k^n}$.

Since $\sum_{k=1}^{\infty} \frac{k^2-(k-1)^2}{k^n} = \sum_{k=1}^{\infty} \frac{2k-1}{k^n} = 2 \cdot \sum_{k=1}^{\infty} \frac{1}{k^{n-1}} - \sum_{k=1}^{\infty} \frac{1}{k^n}$, we get $I_\Sigma = P_{\text{Rx1}}^{(1)} \left(2\zeta(n-1) - \zeta(n)\right)$. To take into account the impact of aggregate interference, an additional “multiuser” safety margin

$IM = 2\zeta(n-1) - \zeta(n)$ of about 3 dB or even less is needed (see Table II). This table also shows that this impact depends on the propagation environment. It should not be neglected for slowly attenuating pass loss open areas e.g., rural or suburban. However, this effect is not significant for the medium with the rapid attenuation (n=4÷5), so using the multi-user margin may not be necessary.

Table 2

Multiuser margin for different environments

n	3	4	5	6
$2\zeta(n-1) - \zeta(n)$	2.087818	1.321776	1.127726	1.056496

For this scenario, Table III shows the dependence of the allowed WSDs power on the distance between the TV receiver and nearest secondary device (where primary service availability is assumed to be 95% or 99%).

Table 3

Maximum allowed transmission power for channel N±1

Surroundings	%	***minimum safety distance between the WSD and DTV***			
		20 m	**30 m**	**40 m**	**50 m**
Urban area	95%	33 mW	170 mW	0.5 W	1.2 W
	99%	5 mW	25 mW	85 mW	200 mW
Suburbs	95%	33 mW	100 mW	250 mW	450 mW
	99%	8 mW	25 mW	65 mW	130 mW

Here we consider high-density (n=4) urban environment with the maximum shadow-fading standard deviation σ=12, as well as low-rise buildings / suburbs (n=3, σ=9) to be the reference medium. Assuming 20 meters to be a minimum potential distance between the WSD and TV set, we notice the aggregate interference decrese the allowed power of WSD to the value smaller than nominal 40 mW [6].

6. The Technical Configuration of WSDs

Even in the case of mass deployment in the future, WSDs are unlikely to be the cheapest devices for providing locally available services, highly localized in time and space. No doubt license-exempt networking will contribute in reducing the cost of services, but from the consumer's point of view this reducing can hardly recover all shortcomings mentioned above. If WSDs are saled as individual devices, it will hardly allow the manufacturer to benefit from the economies of scale in a reasonable term. That is why the implementation of the WSD functionality as a special module of 3G/4G user equipment could be considered as the one of the possibilities to ensure its market success (TVWS can particularly be utilized by femtocells for minimizing the interference to macrocells). In such alliance white space device will obtain free GPS capability, as well as an independent wireless channel connecting it to geolocation database with the channel tables while a smartphone acquires a supplementary frequency band with perfect propagation characteristics.

The key issue to be solved via access to the geolocation database is to provide secondary devices with the consistent list of protected services for given location and locally available channels. The low frequency of changing this information allows updating it via the main portable equipment interface 3G/4G with the periodicity of a weather forecast or even via USB when recharging from the user's PC. The database could also contain recommended parameters for calculations of the propagation loss (taking into account the actual terrain morphology) as well as nominal minimum safety distances associated with each location (them both could gradually be specified in-service after introducing the cognitive network into operation).

White space devices should operate at variable power levels using the lower power in areas of poor availability of the TV services. The key task of cognitive spectrum sensing has to be power control, where each portable device is responsible for determining allowed transmission power. The Open Loop Power Control scheme operates on the estimate of median value of primary signal at the input of WSD receiver and uses the value of minimum recommended distance for current location. Obviously, with this approach the hidden terminal problem will never occur. If there exists a reliable data source (a geolocation database) indicating that the channel is used, a low (or undetectable) level of this channel at the input of WSD informs the last regarding the adverse reception conditions for the TV receiver nearest to it. This permits the secondary device to evaluate correctly its maximum allowed transmission power.

Long Term Evolution (LTE) with its advanced power control and flexible deployment in terms of bandwidth and carrier aggregation features looks like beinig a good choice as the physical layer for implementation of white space devices. At today's radio equipment market we can see LTE devices capable to operate in at least six different bands, including the 791-821/832-862 MHz band. It would be useful if the combined terminals extended LTE operational mode over the TVWS and will operate in the digital dividend I and II bands (790÷862 MHz and 694÷790 MHz) both on the primary, as well as the secondary basis. After the expected allocation of the digital dividend II to mobile service at the World Radio Conference-2015, an imbalance of needs in the DTV and mobile services in different countries will probably remain. So equipment being able to change the operational mode (primary to opportunistic and vice versa) will provide flexibility regarding the coordination procedures in border areas for neighboring countries which follow different priorities in the use of spectrum.

Sharing spectra is effective if the requirements for the use of primary system spectrum differ sufficiently from the usage pattern of the secondary system. The secondary systems should also get accurate information about the technical features and usage pattern of the primary system (including the location of transmitters, local relief, building characteristics and relevant propagation losses). This information is inaccessible if concerning wireless microphones, video cameras and other program making and special event equipment due to liberalized nature of their application. Some administrations suggest localizing their operation within one or two TV channels as the solution to the problem. In particular, Ofcom has licensed the channel 38 for exclusive access by wireless microphones and other PMSE equipment. If it is not a large event with several dozen microphones in use, primary users could operate other channels as well. These devices are registered in a database temporarily. The WSD periodically interrogates the database to find out which channels are free (typically updates occur every 2 hours) [2].

7. Conclusion

The instability of propagation environment and limited accuracy of pass loss predictions makes reasonable the dynamical setting of margin for primary receiver protection. The study presented in this paper unveils the necessity for revising functions associated with sensing abilities (as well as, to some extent with the geolocation) in the cognitive radio system. The geolocation database provides secondary devices with a list of locally available channels, as well as with parameters for path loss calculations and minimum safety distance, which should be observed at a given location. The key role of spectrum sensing is to implement a power control scheme, whereby each portable device evaluates its allowed transmission power. This evaluation is based on estimation of the median primary signal value at the input of the WSD receiver as well as minimum safety distance for current location.

Parameters for protecting the primary system should be based on the determination of minimum separation distance, which should be observed at a certain area. The multi-user margin is calculated for this minimum safety range as a scaling factor in reference to the dominating interference source. At this approach the uncertainties of TV receivers location will not limit dramatically the accuracy of calculating the WSD power margin needed for TV protection.

Optimization of spectrum sharing implies significant differences in usage patterns of the primary and secondary systems. The last one should have accurate information about the technical features of the primary system, including location of transmitters, local relief and building characteristics. This information on PMSE devices is not accessible due to liberalized nature of their application. Therefore it is advisable to ensure their interference-free operation by localizing this equipment within one or two channels) exclusively allocated to them.

We do not expect the sales of WSDs as individual devices will allow a manufacturers to benefit from the economies of scale in a reasonable term. At the same time, the implementation of WSD as a special module of the 3G/4G cellular user equipment is an attractive solution for the market. For instance, LTE equipment which is able to operate both on the primary and secondary basis could provide the necessary spectrum use flexibility after the expected allocation of the digital dividend II band to mobile service at the WRC-2015.

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ТЕХНІЧНА КОНФІГУРАЦІЯ КОГНІТИВНИХ РЕЗ, ЩО ФУНКЦІОНУЮТЬ У «БІЛИХ ПЛЯМАХ» ТЕЛЕВІЗІЙНОГО СПЕКТРА: КОНЦЕПТУАЛЬНЕ ДОСЛІДЖЕННЯ

Ігор Гепко

У цій статті запропоновано метод кодування для зниження рівня позасмугових випромінювань у комунікаційних системах із сигналами з багатьма носіями.

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