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SECONDARY TERRESTRIAL USE OF BROADCASTING SATELLITE SERVICES BELOW 3 GHZ

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ABSTRACT

Secondary use of the satellite spectrum by a terrestrial system is studied in this paper, focusing on broadcasting satellite services. Both spectrum sensing based access and database based access are discussed. Link budget analysis is used to define operational limits for spectrum sensing and transmission power control when the primary system is a digital video broadcasting – satellite services to handheld devices (DVB-SH) system. The results show that cognitive radio techniques should be applied with caution in satellite bands. The energy detection method does not support well spectrum sharing in the studied band. Rather the sensing should be based on the feature detection or matched filter detection. The results show that only short-range transmission can be used on a secondary basis in many environments when the secondary spectrum use is based on the sensing.

KEYWORDS

Cognitive Radio, Dynamic Spectrum Access, Mobile Network.

1. INTRODUCTION

Emergence of cognitive radio (CR) techniques has had a significant role in the wireless research during the last decade. CR techniques have been proposed to improve the spectrum occupancy by exploiting the unused parts of the spectrum without interfering with the primary users (PU) having either higher priority or legacy rights [1], [2]. The CR research work has focused strongly to the terrestrial systems, identifying solutions to spectrum awareness, resource management, and interference problems. Even though the work has progressed considerably, it is estimated that CRs will be adopted by mainstream only after 10+ years [3]. One of the key factors slowing down the adoption process is the difficulty in defining suitable bands for secondary operation.

There are several interesting spectrum band candidates for the secondary spectrum use, including e.g., TV bands due to the deterministic traffic and the suitable penetration characteristics. However, many other bands need to be studied carefully to find space for the ever-increasing demand for wireless services. Satellite communications and bands have not been explored much in the CR research literature. However, cognitive radio techniques could be applied in satellite communication systems in several different ways. A secondary system can operate at the satellite bands using the cognitive principles to avoid interfering with the primary satellite system. The satellite system itself can be made more intelligent by applying cognitive techniques in it. It is even possible that the satellite system accesses the band used by another communication system and operates as a secondary user in that band [4].

The purpose of our paper is to study the secondary terrestrial use of the satellite DVB-SH spectrum, focusing especially on the spectrum sensing requirements and transmission power limits for the secondary system while assuming realistic models for propagation. A part of our

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work done in the satellite downlink is reported in [4]. However, our previous paper studies only satellite downlink sensing. Since spectrum sensing performance partly defines the transmission power of the secondary system, we consider here the research question: *What transmission power levels are supported by which spectrum sensing techniques/detection thresholds?* That information is used to define what kind of secondary systems could operate in this band.

The studied DVB-SH system can be seen as a general broadcasting scenario in frequencies below 3 GHz and thus the carried research provides useful information on the applicability of CR techniques in related scenarios as well. Both the indoor and outdoor scenarios in the urban and suburban environments are considered. The proposed estimation method does not require exact channel knowledge between the primary transmitter and the secondary sensor. We focus on the terrestrial part of the hybrid satellite-terrestrial system. In addition to sensing related investigation, we will also discuss about the possibility to use databases for spectrum sharing between systems.

The organization of the paper is as follows. Related work is presented in Section II and the system model in Section III. Achieved results concerning link budget and spectrum sensing ranges are shown in Section IV. Transmission power limits are estimated in Section V. The database approach is reviewed in Section VI and finally the paper is concluded in Section VII.

2. RELATED WORK

Spectrum sharing in satellite bands has been discussed by regulation authorities actively, e.g., in [5], [6] where Worldwide Interoperability for Microwave Access (WiMAX) and International Mobile Telecommunications-Advanced (IMT-Advanced) systems were considered. The results of [5] show that criteria where the fixed satellite services (FSS) antennas cannot co-exist with WiMAX systems range from 50 km to over 200 km. Use of adaptive antennas is shown to remarkably reduce the range requirements in [6].

There is a growing interest in spectrum sharing in satellite bands in the research community. Secondary use of terrestrial spectrum by a satellite system in the Ka band using highly directed antennas was considered in [4]. An extension of a terrestrial 3GPP Long Term Evolution (LTE) network by a satellite LTE system to provide coverage in areas where building infrastructure is too expensive was also investigated in [4]. Both the satellite and terrestrial components were operating in the 2.6 GHz band. Load-balancing in satellite-terrestrial wireless networks was investigated in [7]. Other hybrid satellite terrestrial systems have been proposed in [8] and [9]. The idea in these papers is to use the satellite to assist the terrestrial secondary network. In [8], the satellites are used to connect the terrestrial cells, which are operating as secondary users of the spectrum, to each other. The base station sends uplink data towards satellite. Downlink data are in both scenarios received by the base stations. In the architecture described in [9], the satellite is the central controller; i.e., it is in charge of the spectrum allocation and management.

It is shown in [10] that cyclostationary features of satellite signals help secondary operation in the same spectrum. Cyclostationarity affects both the secondary signal design and reliable detection of the satellite signals. A recent paper [11] proposes a satellite-based multi-resolution compressive spectrum detection algorithm to help the coexistence of a mobile satellite system and an infrastructure based wireless terrestrial network. Secondary use of satellite spectrum is considered also in [12]. The article investigates power allocation strategy for cognitive radio terminals which are using the spectrum of a primary DVB-SH system. In the proposed strategy it is assumed that the secondary system is able to collect all the relevant propagation information of both secondary and primary systems. In reality, the exact PU system information might not be available.

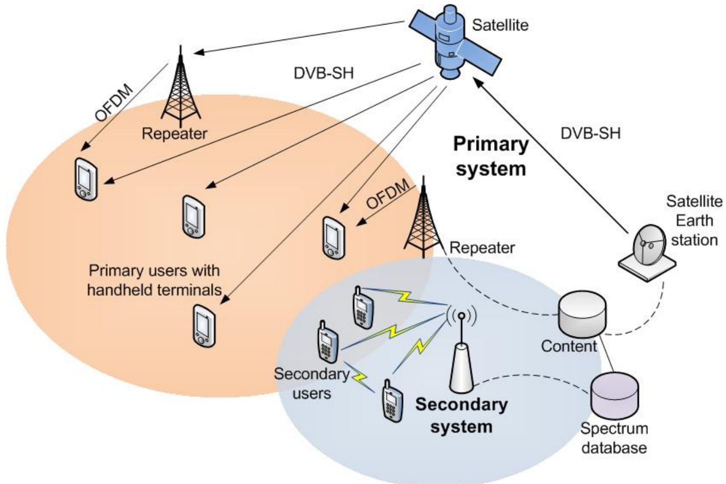

Figure 1. A secondary spectrum use scenario with a DVB satellite.

3. SYSTEM MODEL

Fig. 1 presents the system model for the studies. A terrestrial secondary system provides data transmission for its users. The secondary network operates in the same frequency band and geographical area with the primary DVB-SH satellite system. The primary system architecture is a hybrid one combining a satellite component and where necessary, terrestrial repeaters to complement reception in areas where the satellite reception is difficult. Repeaters may send information from the local content or from the satellite signal. The system can transmit either an orthogonal frequency division multiplexing (OFDM) or a time-division multiplexing (TDM) signal over the satellite link or an OFDM signal over the terrestrial link. The frequency band is the S band between 2.17 GHz and 2.2 GHz.

The secondary system is using the spectrum resources that are available, without interfering with the primary satellite system that is located in the geosynchronous earth orbit (GEO). The secondary network uses either spectrum sensing or database access to spectrum that it is using at times and locations where the primary user is not present. Fig. 2 describes the spectrum sensing task inside the satellite spot both for the terrestrial signal sent by the DVB-SH repeater and for the satellite signal. Sensing can be performed either via mobile devices or via fixed sensing stations with high-gain antennas.

Energy detection is a simple method that can be used to detect any signals in the band with a fast manner. However, it is not a suitable method for detection in the very low SNR regime. The limitations of the real energy detection equipment have been reported in the literature. For example, in the article [13] the sensing threshold of a commercial energy detection device is 10 dB above the noise floor that is already a rather sensitive threshold. Very low threshold causes significant amount of false alarms, i.e., the sensor claims that there is a user in the band even if there is no user at all. In addition, detection of weak signals requires a longer integration time than the detection of strong signals in the band. However, the sensor cannot detect signals below a fundamental limit called SNR wall, no matter how long it can observe the channel. The SNR wall for energy detection is -3.3 dB when the noise uncertainty is 1 dB [14].

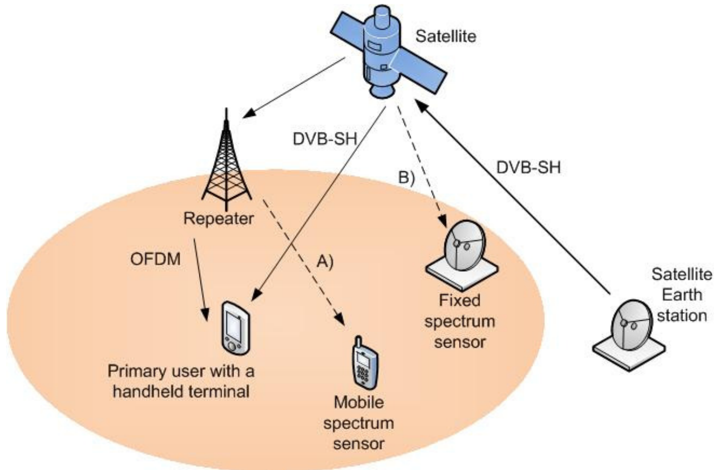

Figure 2. Spectrum sensing of A) terrestrial signal and B) satellite downlink signal inside the satellite spot.

The performance of sensing can be increased with the knowledge of the primary signal. The feature detection requires partial knowledge of the signal whereas the matched filter detection needs a perfect knowledge on the signal. For example, reliable sensing of the DVB-T signal can be achieved at SNR = -20dB even with a hardware implementation [15]. The matched filter detection can provide even better performance since it is the optimal detection method for a known signal. The feature detection method seems to be very promising for the satellite DVB-SH signal detection as well.

It was shown in [4] that portable sensing devices can be used for downlink sensing only if the sensing method itself is good enough. The feature detection and especially matched filter detection can perform reliably in the satellite downlink signal sensing even with portable devices. Separate sensing stations with high gain antennas are required if energy detection is used for the same purpose. An interesting task then is to define requirements both for the sensing and transmission power of the secondary system when the terrestrial component of the DVB-SH system is considered as well.

4. SENSING RANGES OF DIFFERENT METHODS FOR TERRESTRIAL TRANSMISSION

The requirement to detect the terrestrial DVB-SH transmission in decibel domain is

$$P_{\mathrm{dvb}} - \alpha_{\mathrm{rs}} \geq S_{\mathrm{s}} \quad (1)$$

where P_{dvb} is the transmission power of the terrestrial repeater, α_{rs} is the attenuation between the repeater and a sensing radio, and S_{s} is the detection threshold of the CR. If no detection occurs, there is no signal present or it is attenuated so much that it cannot be sensed. From (1) we can define

$$\alpha_{\max} = P_{\mathrm{dvb}} - S_{\mathrm{s}} \quad (2)$$

for the maximum path loss. Usual transmission power P_{dvb} for the repeater given in EIRP is 55.1 dBm [16]. Assuming shadowing margins calculated for the 95 % coverage in [16] we can now define the values for the sensing. Link budget for sensing is presented in the Table 1.

Table 1. Terrestrial link budget with interference margins and spectrum sensing link budget for terrestrial signals.

		Indoor with interference		Outdoor with interference	
Parameters	**Unit**	**Urban**	**Suburban**	**Urban**	**Suburban**
Useful bandwidth	MHz	4.75	4.75	4.75	4.75
Modulation		QPSK	QPSK	QPSK	QPSK
EIRP	dBm	55.1	55.1	55.1	55.1
Required C/N	dB	2.8	2.8	2.8	2.8
Rx antenna gain	dB	-3.0	-3.0	-3.0	-3.0
Noise figure	dB	4.5	4.5	4.5	4.5
Rx noise level	dBm	-102.7	-102.7	-102.7	-102.7
Minimum Rx level at the antenna, R_s	dBm	-96.9	-96.9	-96.9	-96.9
Avg. building penetration loss	dB	16.0	14.0	0.0	0.0
Shadow fading margin	dB	11.6	11.6	8.7	8.7
SFN network gain, G	dB	4.7	0.0	4.7	0.0
Minimum signal level	dBm	-74.0	-71.3	-92.9	-88.2
Maximum path loss, L_m	dB	129.1	126.4	148.0	143.3
Interference margin	dB	0.5 or 1.0	0.5 or 1.0	0.5 or 1.0	0.5 or 1.0
Cell range, COST231-HATA model	km	0.519	0.987	1.786	2.978
Cell range, 0.5 dB margin	km	0.502	0.955	1.727	2.882
Cell range, 1.0 dB margin	km	0.486	0.924	1.672	2.789
Sensing parameters					
Detection threshold	dBm	S_s	S_s	S_s	S_s
Combined losses L_c	dB	27.6	25.6	8.7	8.7
Maximum path loss, L_m	dB	$55.1–27.6+G–S_s$	$55.1–25.6+G–S_s$	$55.1–8.7+G–S_s$	$55.1–8.7+G–S_s$

The Cost231-HATA model that was also adopted in [16] has been used in calculations. The standard median path loss L in urban areas is given by [17]

$$L_{50}\ (urban) = 46.3 + 33.9 \log f - 13.82 \log h_B - a(h_R) + (44.9 - 6.55 \log h_B) \log d + C, \quad (3)$$

where f is the frequency (in MHz), h_B is the effective transmitter (base station) antenna height (in meters) ranging from 30 m to 200 m, h_R is the effective receiver (mobile) antenna height (in meters) ranging from 1 m to 10 m, d is the distance between the transmitter and the receiver (in km), and $a(h_R)$ is the correction factor (in dB) for an effective mobile antenna height which is a function of the size of the coverage area. The correction factor for a small to medium sized city is

$$a(h_R) = (1.1 \log f - 0.7)\ h_R - (1.56 \log f - 0.8) \quad (4)$$

and for a large city, it is given as

$$a(h_R) = 8.29(\log 1.54\ h_R)^2 - 1.1 \text{ for } f \leq 300 \text{ MHz} \quad (5a)$$
$$a(h_R) = 3.2(\log 11.75\ h_R)^2 - 4.97 \text{ for } f \geq 300 \text{ MHz}. \quad (5b)$$

To obtain the path loss in a suburban area, the equation (3) is modified as

$$L_s = L_{50}(urban) - 2[\log (f / 28)]^2 - 5.4. \quad (6)$$

The factor C = 0 dB for a medium sized city and suburban areas and C = 3 dB for metropolitan areas. The building penetration loss and a larger shadowing margin are applied in the indoor environment scenarios.

The maximum median path loss L_m for the signal to be detected in the urban environment, defining the attenuation to be used in the sensing range calculations is

$$L_m = \alpha_{max} - L_c + G \quad (7)$$

where α_{max} is defined in (2) and L_c defines the combined losses in the signal path such as the building penetration loss and the shadowing margin. Parameter G is the network gain that is 4.7 dB in case of a single frequency network (SFN) that is used in the urban area [16]. The same equation can be used in the cell range calculations when a small modification is made. Parameter S_s in (2) needs to be changed to the minimum required power level at the receiving antenna of the primary node, parameter R_s, i.e., $\alpha_{max} = P_{dvb} - R_s$.

Fig. 3 shows the sensing results for the urban indoor scenario. Sensing thresholds exactly at the noise floor and -20 dB below the noise floor are set as examples in the figure. It can be seen that the energy detector able to operate exactly at the noise floor level would provide roughly 750 m sensing range. If the sensor can detect signals 20 dB below the noise floor, the sensing range is increased by 2 km. The lower threshold allows a better operational environment for the secondary system that starts to use the band when the DVB signal is not present at that location. Higher transmission powers can be used without interfering with the DVB-SH receivers.

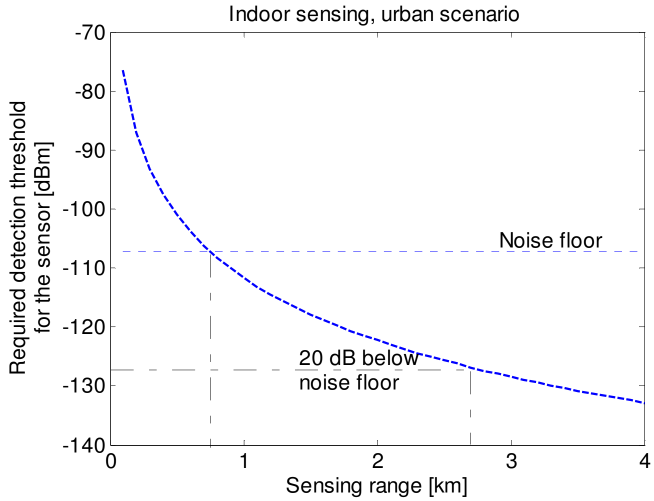

Figure 3. Spectrum sensing of terrestrial DVB-SH transmission in urban environment, sensor located indoor.

5. TRANSMISSION POWER LIMITS

The interference caused by simultaneous transmission at the same band causes interference if the coexisting system is located too close. The interference management in the spatial domain in sensing-based system [18] is shown in Fig. 4. The red circle with a red receiver represents the primary DVB-SH system whereas the secondary system is shown with the blue colour. Communication ranges of the primary and secondary systems are marked with r_t and r_d, respectively. Inside the communication range, the signal-to-noise ratio (SNR) is large enough to decode transmitted data. Transmission power of the transmitter, together with the channel, defines both the communication range and the interference range of the system. When the secondary transmitter is sending data, it is interfering with the victim receivers up to the interference range of $r_i > r_d$. The interference range of the primary system is r_w.

A cognitive radio can only detect the local situation around it. The sensing range of the secondary system, i.e., the maximum range to detect the primary transmission is r_s and is defined using (2) and (3). The range should be $r_s \geq r_i + r_t$ to protect the PU from interference.

The Table I includes also estimates on the cell sizes for the different interference margins. The interference range of the secondary transmission system can be calculated using the 1 dB or 0.5 dB coexistence criterion, i.e., signal power received at the DVB-SH receiver by secondary transmission P_{sp} should be 6 dB below the noise floor to decrease C/N by 1 dB or 9 dB below the noise floor to decrease C/N only by 0.5 dB. Now,

$$P_{sp} \leq N + N_F - X \text{ dB}, \tag{8}$$

where N is the noise floor and N_F is the noise figure of the primary receiver, and X is either 6 dB or 9 dB. Because the CR system does not receive any information from other systems we assume the worst case scenario to guarantee interference-free communication for the primary system. Thus, there is only path loss between the secondary transmitter and the primary receiver but fading between the primary transmitter and the secondary receiver as well as in the secondary link. Inequality (8) can be written as

$$P_{sp} = P_{su} - \alpha_{rs} \leq N + N_F - X \text{ dB}. \tag{9}$$

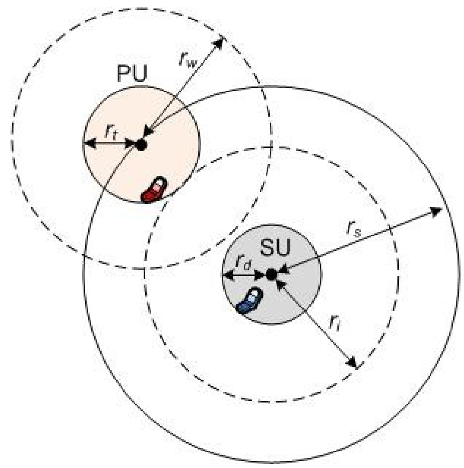

Figure 4. Interference, sensing, and communication ranges in a primary-secondary scenario.

We can now define the limit for the secondary transmission power as

$$P_{su} \leq L_{50}(r_s - d_c) + N + N_F - X \text{ dB}, \quad (10)$$

where r_s is the sensing range of sensor, d_c is the cell range of the terrestrial DVB-SH repeater and the path loss L is calculated using (3).

In order to allow 0.5 dB or 1 dB degradation to the SNR level, new cell ranges need to be calculated for the primary system. This means that in the edge of the cell, we allow either 0.5 dB or 1 dB attenuation to the signal due to interference. Calculations can be done with the modified version of (7) as discussed in the section below the equation. Now we will increase the minimum required power level at the receiving antenna by 0.5 dB or 1.0 dB for calculations. The estimated cell ranges are shown in the Table I. The results show that the reduction in the cell size is in the order of 3 % with the 0.5 dB margin and 6 % with the 1 dB margin.

Estimations for the transmission power limits for the secondary user are shown in Figs. 5–8. Typical transmission power levels of a WLAN access point (20 dBm) and the LTE base station (43-48 dBm) are marked in the figures as reference points. The results are calculated for a single transmitter in several different scenarios. Indoor and outdoor scenarios in urban and suburban environments are considered.

In Fig.5 the sensor is located indoor in the urban environment. The sensing threshold should be clearly below the noise level to allow even a WiFi type transmission on the same frequency band. The result means that energy detection cannot be used here but more powerful methods such as the matched filter detection are needed. The situation changes clearly when the suburban environment is considered as can be seen in Fig. 6. Now the sensor able to detect signals a few dB above the noise floor is enough for WLAN type transmission. Even LTE powers could be possible in the suburban indoor scenario with a sensor that can operate reliably more than 10 dB below the noise level. It should be remembered that the reported thresholds for implemented energy detectors are e.g., 10 dB above noise floor. Thus, these devices would not allow even short-range transmission in the studied scenario.

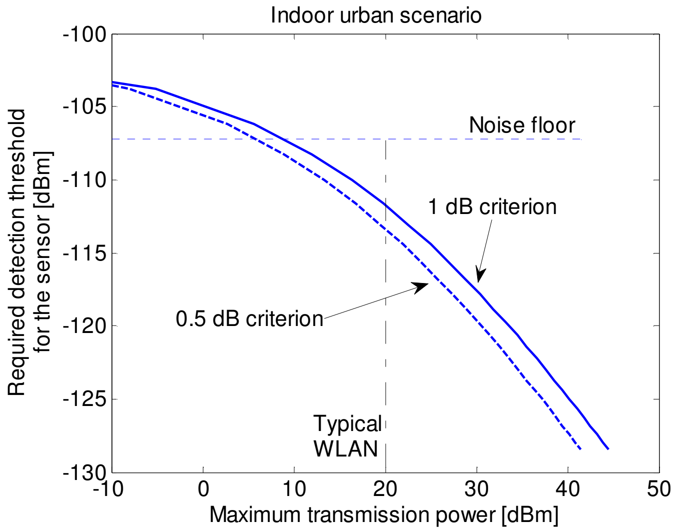

Figure 5. Maximum transmission power of a secondary user in urban environment, sensor located indoor.

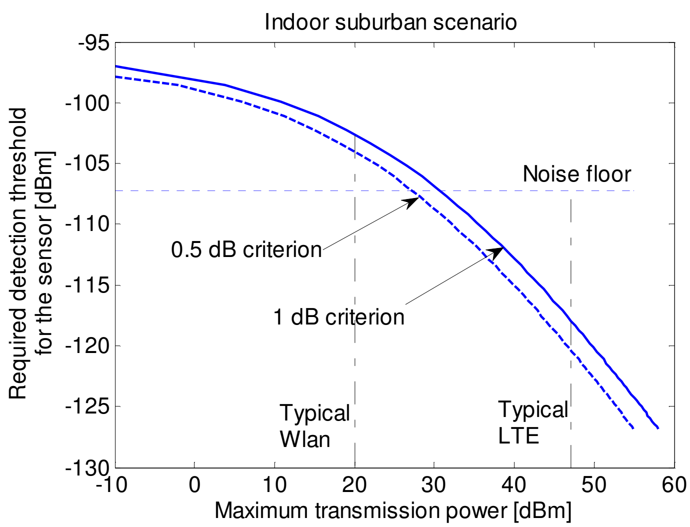

Figure 6. Maximum transmission power of secondary user in suburban environment, sensor located indoor.

Fig. 7 and Fig. 8 show results for outdoor scenarios that are much easier for the spectrum sensing. In the suburban environment even the energy detectors with a sensing threshold 10 dB above the noise floor would allow WLAN type secondary transmission in the spectrum. In the urban environment the sensor has to be able to detect signals reliably 10 dB below the noise floor to make LTE type transmission possible. In the suburban case the threshold needs to be only slightly below the noise level.

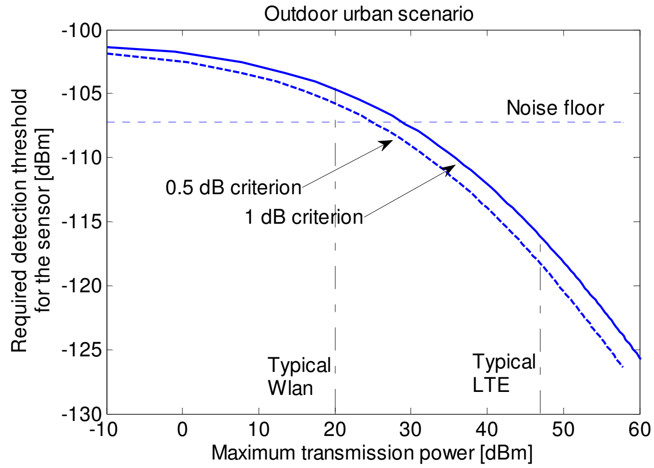

Figure 7. Maximum transmission power of secondary user in urban environment, sensor located outdoor.

The most difficult environment is the urban case where the sensor is located indoor. The sensing threshold should be clearly below the noise level to allow even WiFi type transmission on the same frequency band. The only scenario where the conventional energy detector could support even the short range transmission is the suburban outdoor scenario. In other cases, more powerful sensing methods are needed. The difference between the transmission power limits is 3 dB with the same detection threshold for the two considered coexistence criterions (0.5 dB and 1.0 dB).

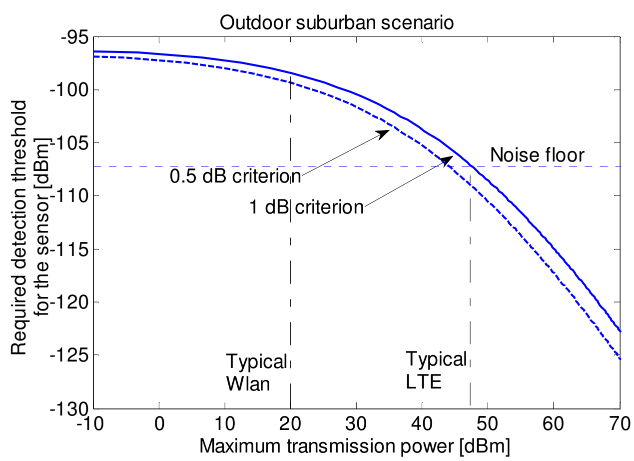

Figure 8. Maximum transmission power of secondary user in suburban environment, sensor located outdoor.

The shown figures are restricted to a single secondary user case. Already these results show well that spectrum sensing should be used with caution for the spectrum access in the studied satellite band. In a more realistic situation, aggregate interference of several secondary users should be taken into account as well. A very rough estimate for the interference addition is to use constructive interference principle, i.e., assuming same parameters for all secondary transmitters and adding the interference powers together. The interference power is then increased by 10log (N) dB where N is the number of interferers. This means the correspondent reduction in the allowed transmission power for the secondary users.

However, this is not a very realistic model. More accurate would be to use statistical models such as the Poisson-point process used in [19] for the secondary node placement and include the probability to sense the PU signal at certain location in the analysis. Cooperative sensing brings additional gain to the sensing, affecting also the aggregate interference value. Based on this discussion, we might assume that reduction of some decibels in the transmission power might be enough to handle the aggregate interference issue. This is a good topic for further studies.

6. DATABASE APPROACH

Other approaches for spectrum sharing need to be considered since spectrum sensing, especially if energy detection is used, cannot support well secondary operation. The database method is a promising approach for spectrum sharing between the hybrid DVB-SH system and a terrestrial secondary system. Frequencies used by the licensed system as well as unused frequencies can be seen from the database. Spectrum databases are currently heavily supported in many terrestrial scenarios, including TV white space operation [20].

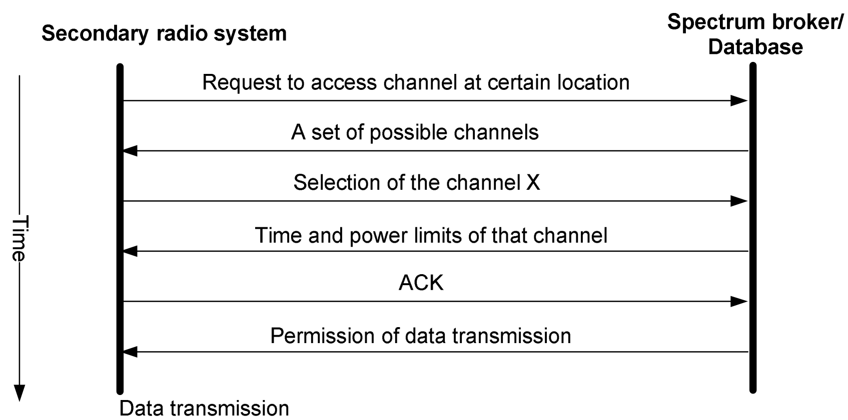

Figure 9. Spectrum access with a database.

When the secondary system needs to transmit, it requires spectrum from the spectrum broker that is governing the database, and available band is given for it. Other secondary users in the area can then see that this particular band is occupied. Thus, the method can be used to spectrum sharing among secondary systems as well. The proposed method for the spectrum access using a database is shown in Fig. 9. First the secondary system sends the request to access the spectrum to the spectrum broker governing the spectrum use in that area. The location information of the requesting device is attached. The spectrum broker sends back a set of possible channels that could be used in the secondary transmission. This set is idle at the request time.

Then, the secondary device selects a channel X to be used in the transmission and informs the broker about the choice. This band is reserved to the secondary system in the database so that it will not be offered to other requesting secondary users. The broker sends information about the time and power limits of the channel. The secondary system acknowledges it has received the restrictions regarding the channel use. Finally, it receives permission to use that channel and starts data transmission.

Interference management and avoidance are easier with databases than with the spectrum sensing. However, the database method is not as dynamic and fast as sensing and this can restrict the way to operate. In addition, the use of this approach requires an extra infrastructure for the operation. Unlike spectrum sensing, it cannot be used straight away with the existing satellite systems. When the database operation is considered, the satellite system needs to play its part in sharing, i.e., provide the needed information for the operation.

A clearly advantageous feature of this type of spectrum sharing is the possibility to keep the situation in control. When the sharing of spectrum between the terrestrial and the satellite system is controlled, the systems can experience the predictable quality of service (QoS). The passive spectrum awareness helps the secondary system to avoid chaotic situations since the passively received spectrum use pattern shows the spectrum opportunities in advance. Instead on reactive operation, it helps the secondary user to be proactive.

In addition, leasing the spectrum enables the primary user to get financial advantage of the secondary operation at the same frequencies. Actually, guaranteed QoS requirements can be met for both primary and secondary users only if primary users promise not to interfere. This is most likely only true for a fee. All these features strongly support the use of database/broker based access to the spectrum.

The following requirements and open issues can be seen in this operation. 1) *Location awareness*. The secondary nodes need to have location information available. Otherwise they are not allowed to use the spectrum database for accessing the S band. 2) *Satellite system/operator provides information to spectrum broker*. Without the knowledge on the current spectrum use the broker cannot allocate resources to the users requesting it. 3) *Analysis and experiments are needed to provide time and power limits for secondary operation.* What are the acceptable transmission powers and continuous tranmission times when the database access is used? How much mobility affects to these in satellite bands? How often the secondary user needs to connect to the database to update the information?

7. CONCLUSIONS

We have investigated the secondary use of the spectrum in a satellite band below 3 GHz. Primary system is a DVB-SH hybrid network that is operating in the S band between 2170 MHz and 2200 MHz. Both a sensing based access method and a database based access method were described. We have calculated link budgets for the system in several different indoor and outdoor scenarios. Requirements for the spectrum sensing and transmission power control for the secondary system in these scenarios have been provided. Following conclusions can be drawn.

1) With sensing, short range communication is preferred, especially in the urban scenario.
    a. The sensing threshold and the environment where the secondary system is operating have significant effects to the allowed transmission power level.
    b. Energy detection with the same kind of devices that are used nowadays cannot be used at all in many scenarios even when low power short range secondary operation is considered.
    c. Matched filter detection and the feature detection are needed especially when the secondary transmitters are using higher transmission powers.
    d. Only a single secondary transmitter was considered. If the aggregate effect of several transmitters is considered, even better performing sensors are needed to fulfil the secondary power requirements. The effects might be different in each of the studied scenario.

2) Based on the analysis and the related uncertainties, database information/passive spectrum awareness should be prioritized when possible.
    a. Use of these can guarantee the QoS of both the secondary and the primary systems.
    b. In addition, business models for this are easier to develop.

Several issues need to be still considered before the use of cognitive radios can be allowed in the satellite bands. Possible topics for future studies include: A) What bands are most promising for spectrum sharing? B) How the selection of terrestrial channel model affects the performance? C) How reliably the sensor needs to be able to detect transmission? We used 95 % value for the sensing analysis but higher values might be needed in practice. D) Open issues for the database approach described in Section V need to be investigated.

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REFERENCES

[1] J. Mitola III and G. Q. Maguire, Jr., "Cognitive radio: Making software radios more personal," *IEEE Personal Communications*, vol. 6, pp. 13–18, Aug. 1999.

[2] S. Haykin, "Cognitive radio: Brain-empowered wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 25, pp. 201–220, Feb. 2005.

[3] Gartner, "Hype cycle for wireless networking infrastructure," S. Fabre (eds.), Jul. 2011.

[4] M. Höyhtyä, J. Kyröläinen, A. Hulkkonen, J. Ylitalo, and A. Roivainen, "Application of cognitive radio techniques to satellite communication," in *Proc. DySPAN*, pp. 517–528, Oct. 2012.

[5] S. Ames, A. Edwards, and K. Carrigan, "Field Test Report WiMAX Frequency Sharing with FSS Earth Stations", Feb. 2008.

[6] Rep. ITU-R M.2109. Sharing studies between IMT-Advanced systems and geostationary satellite networks in the fixed-satellite service in the 3 400-4 200 and 4 500-4 800 MHz frequency bands. 2007.

[7] M. Ali, P. Pillai, and Y. F. Hu, "Load-aware radio access selection in future generation satellite-terrestrial wireless networks," *International Journal of Wireless & Mobile Networks*, vol. 4, pp. 35–54, Feb. 2012.

[8] S. Kandeepan *et al*., "Cognitive satellite terrestrial radios," In *Proc. Globecom*, Dec. 2010.

[9] D. Gozupek, S. Bayhan, and F. Alagöz, "A novel handover protocol to prevent hidden node problem in satellite assisted cognitive radio networks," In *Proc. ISWPC*, May 2008.

[10] Y. H. Yun and J. H. Cho, "An orthogonal cognitive radio for a satellite communication link," in *Proc. PIMRC*, pp. 3154–3158, Sep. 2009.

[11] H. Li, Q. Guo, and Q. Li, "Satellite-based multi-resolution compressive spectrum detection in cognitive radio networks," in *Proc.* IMCCC, pp. 1081–1085, Dec. 2012.

[12] E. Del Re *et al.*, "Power allocation strategy for cognitive radio terminals," in *Proc. CogART* , pp. 1–5, Feb. 2008.

[13] J. Lehtomäki, R. Vuohtoniemi, K. Umebayashi, and J. P. Mäkelä, "Energy detection based estimation of channel occupancy rate with adaptive noise estimation," *IEICE Transactions on Communications*, vol. E95-B, No. 4, p. 1076–1084, Apr. 2012.

[14] R. Tandra and A. Sahai, "SNR walls for signal detection," *IEEE Journal of Selected Topics in Signal Processsing*, Vol. 2, pp. 4–17, Feb. 2008.

[15] C. Song, M. A. Rahman, and H. Harada, "New robust sensing methods for DVB-T signals," in *Proc. Crowncom*, Jun. 2011.

[16] ETSI TS 102 584 V1.2.1, "DVB-SH Implementation guidelines," Jan. 2011.

[17] COST 231, "Urban transmission loss models for mobile radio in the 900 and 1800 MHz bands (Revision 2)," Sep. 1991.

[18] M. Höyhtyä, T. Chen, and A. Mämmelä, "Interference management in frequency, time, and space domains for cognitive radios," in *Proc. WTS conference*, Apr. 2009.

[19] A. Ghasemi and E. Sousa, "Interference aggregation in spectrum-sensing cognitive wireless networks," *IEEE Journal of Selected Topics in Signal Processing*, vol. 2, Feb. 2008.

[20] M. Nekovee, T. Irnich, and J. Karlsson, "Worldwide trends in regulation of secondary access to white spaces using cognitive radio," *IEEE Wireless Communications*, vol. 19, pp. 32–40, Aug. 2012.

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