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Interference Analysis of Coexistence Scenarios in TV White Spaces

Robson D. Vieira, Edgar B. Souza, André M. Cavalcante
Nokia Technology Institute (INdT)
Manaus, Brazil
{robson.domingos,edgar.souza,andre.cavalcante}@indt.org.br

Riku Pirhonen, Padam Kafle, Andrei Malkov, Zexian Li
Nokia
Dallas, USA
{riku.pirhonen,padam.kafle,andrei.malkov,zexian.li}@nokia.com

***Abstract*—Broadband wireless systems in TV White Spaces have gained considerable attention since FCC started the process in 2004 and later 2008 published the first rules for TV band devices. Several companies, mainly in the US, are looking at the new opportunities and are putting efforts to develop standards in industry forums and IEEE. Since white spaces spectrum is accessed in opportunistic way, it can be seen as a step towards the deployment of cognitive networks. In order to evaluate the benefits and challenges for technologies which may operate in the TV white spaces spectrum, the analysis of radio frequency issues has an important role. Out of band emissions and intermodulation products from other channels are examples of RF impairments that should be considered in the interference analysis. When some of the requirements are not fulfilled, cell coverage and spectral efficiency can be reduced. In this paper, an interference analysis, taking in account the RF impairments, was done for several coexistence scenarios in the White Spaces (WS) context. The analysis was done not only considering the FCC rules but also investigating other RF parameters.**

***Index Terms*—TV band, white spaces, interference analysis**

I. INTRODUCTION

The requirements for the future broadband wireless networks have generated not only a series of new technical challenges but also questions concerning the traditional spectrum utilization rules. Peak rate, aggregate throughput and greater bandwidth flexibility are the key factors that distinguish the current from the forthcoming broadband networks.

In order to fulfill the peak data rate targets, bandwidth on higher frequency bands is being extended from the 20 MHz up to 100 MHz. However, the “good” available spectrum, considering propagation problems, is scarce and expensive. Hence, features such as flexible spectrum usage and dynamic spectrum allocation have appeared for spectrum sharing of users and for opportunistic spectrum allocation, respectively. The success of the features will depend on the spectrum utilization rules and on the change from the traditional ones, where each part of spectrum is defined for a specific service, to a dynamic one where secondary users can utilize any frequency hole of the spectrum or share the resource with other users, but in both cases respecting rules of interference over the primary users.

In the US, valuable White Spaces (WS) spectrum in the underused broadcast TV channels became available after the DTV transition and it can be used to expand the bandwidth available for traditional wireless communications. The usage of WS requires coexistence technologies to ensure that incumbent users, such as TV broadcasters and wireless microphones, are not inadvertently subjected to harmful interference. With strong advances in radio technology, engineering solutions to the coexistence challenge are under study and development. Several consumer electronics industries are working with Federal Communications Commission (FCC) [1] to develop and test these coexistence technologies and bring them to market when they are proven and mature [2].

Several other countries are also looking into the possibility of opening up the WS to new applications and devices. In the U.K., the U.K. communications regulator Ofcom [3] has foreseen significant benefits. Ofcom has decided to move forward and is studying technology approaches to coexistence. CEPT SE43 [4] is studying how the European Union can best take advantage of the opportunities posed by the WS in order to create important steps towards providing a regulatory framework for the utilization of WS.

Therefore, the analysis of radio frequency issues represents an important role to evaluate the possible benefits and challenges for technologies which may operate in the TV white spaces spectrum. The spectrum sharing among other secondary users is not mature yet. Secondary users can easily cause interference due to obstructed coverage or errors in sensing. Some coexistence studies in the DTV spectrum have been started in literature. In [5] a mechanism of WRAN self-coexistence was performed and analyzed. In [6], a simple interference analysis method was proposed trough a coexistence scenario between WRAN and DTV.

The main purpose of this paper is to provide a study of interference on practical coexistence scenarios, when there is an effective common use of the spectrum among networks of secondary systems. Additionally, the proposed interference analysis takes into account the main RF aspects existing in a coexistence scenario, being investigated through some numerical calculations and link budget evaluations.

This paper is organized as follows. In Section II, the modeling and assumptions of the main RF impairments presented in the coexistence context are described. The interference analyses on the proposed coexistence scenarios are presented and discussed in Section III. Finally, the conclusions are summarized in Section IV.

II. MODELING OF RF IMPAIRMENTS

Generally, the standards define the minimum RF performance requirements for base stations and user equipments. The requirements are essential since they facilitate the mutual coexistence of systems without coordination. The standard requirements have been derived from either regulatory requirements or coexistence studies performed by standardization entities.

The coexistence of systems needs to be studied using system scenarios that, together with implementation issues, reflect the environments in which technologies are expected to operate. Besides, the radio transmission and reception characteristics need to be considered in these studies as well. There are several basic concepts that are commonly used in coexistence studies and some of them will be described in this section.

A. Out of Band/Spurious Emissions

Normally, wireless communication standards define spectrum masks for limiting their transmitter’s emitted power in frequency spectrum. The transmit spectrum mask defines the maximal allowed power spectral density in dBr, i.e., dB relative to the maximum spectral density of a signal. The considerable overlapping of the spectrum mask of neighboring carriers leads to harmful interference on adjacent channels. The transmitter spectrum consists of the three basic components: emissions within the occupied bandwidth, Out Of Band (OOB) emissions and far out Spurious Emissions (SE) domain [7]. While the occupied bandwidth is defined as the bandwidth containing 99% of the total integrated mean power of the transmitted spectrum on the assigned channel, the OOB and spurious emissions are unwanted emissions outside the nominal transmission bandwidth observed in the receive band. OOB are emissions immediately outside the transmitter bandwidth originated from the modulation process and power amplifier nonlinearities. On the other hand, SE are persistent unwanted spectral components including harmonic and parasitic emissions, inter-modulation and frequency conversion products which dominate the emissions beyond the OOB frequency domain.

B. Adjacent Channel Power Ratio

Adjacent channel power ratio (ACPR) is defined as the ratio of the transmitter mean power centered on the assigned channel frequency to the mean power centered on an adjacent channel frequency [8]. The ACPR provides the amount of interference that a transmitter could cause to a receiver operating in the adjacent channel.

The wireless systems spectrum emission masks (SEM) are designed in order to coexist with other wireless systems. Hence, it is possible through a specific SEM to determine the ACPR and consequently the interference power in adjacent channel. The transmit filter attenuation in adjacent channel is inferred from SEM and represents the ACPR values that are defined by the measurement bandwidth resolution. Hence, the power spectral density (PSD) of the signal transmitted by an aggressor is given by:

$$ACPR = 10\log_{10}\left(\sum_{k=1}^{K} 10^{\left(\frac{P_{aggr}-L-ACPR_k}{10}\right)}\right), \quad (1)$$

where K is the number of subbands of the SEM within an adjacent channel. It is obtained by dividing the total adjacent bandwidth by the measurement bandwidth, P_{aggr} is the transmission power of the aggressor, L is the path loss between the aggressor and the victim, and $ACPR_k$ is the effective attenuation of the SEM in a given subband k.

C. Adjacent Channel Selectivity and Blocking

A non-ideal receiver will experience blocking from a transmitter due to the receiver's non-ideal adjacent channel selectivity and blocking in the first or in the second adjacent channel [9]. Therefore, interference power due to receiver imperfections or rejection capability needs to be estimated.

Adjacent channel selectivity (ACS) is defined as the ratio of the receive filter attenuation on the assigned channel frequency to the receive filter attenuation on the adjacent channel frequency. ACS is a measure of the receiver ability to receive a wanted signal in the presence of an adjacent channel signal, i.e., it verifies the selectivity on the adjacent channel. On the other hand, blocking requirement is a measure of the receiver ability to receive a wanted signal at its assigned channel frequency in the presence of an unwanted interferer, excluding the adjacent channel. The in-band blocking can also be called adjacent channel selectivity for the second adjacent channel.

The wireless systems rejection capabilities are also designed in order to coexist with other wireless systems. Hence, it is possible through a specific rejection capability to determine ACS and blocking and, consequently, the interference power in the first and second adjacent channels. The receive filter attenuation capability in first and second adjacent channels represents ACS and blocking values and they are defined by the measurement bandwidth resolution. So, the total interference due to ACS and blocking is given by the following equation:

$$ACS = 10\log_{10}\left(\sum_{m=1}^{M} 10^{\left(\frac{P_{aggr}-L-ACS_m}{10}\right)}\right), \quad (2)$$

where M is the number of subbands of the receive filter within an adjacent channel. It is obtained by dividing the total adjacent bandwidth by the measurement bandwidth, P_{aggr} is the transmission power of the aggressor, L is the path loss between the aggressor and the victim, and ACS_k is the effective attenuation of the receive filter in a given subdand m.

D. Intermodulation Distortion

Intermodulation Distortion (IMD) can be generated by any intermodulation product (IMP) that is created at the receiver due to any order of mixing of primary communication carriers [10]. Normally, third order intermodulation products are the most relevant ones, because they happen to be stronger and closer to the fundamental frequencies than the other products.

In this paper it is considered only intermodulation distortion generated at unlicensed devices due to DTV signals transmitted by co-sited stations. It is assumed that DTV stations operate at channels with center frequencies f_A and f_B, and the unlicensed device operates at channel f_C such that $f_C = 2 * f_A - f_B$. Then, intermodulation distortion in dB due to third order products is given by:

$$IMD = 2 * P_{f_A} + P_{f_B} - 2 * IP3, \quad (3)$$

where P_{f_A} and P_{f_B} are received powers from DTV stations that operate in channels with center frequencies f_A and f_B, respectively, and $IP3$ is the third-order intercept point. The later characterizes the linearity of the unlicensed device and is an indication of the largest input signal the receiver can tolerate before running into issues related to nonlinearities.

E. Receiver Desensitization

Receiver desensitization is defined as the degradation in the receiver sensitivity due to an increase in the receiver noise floor by the interfering OOB/spurious emission, IMP and receiver imperfections. The most significant case is when the transmit frequency of the interfering system is adjacent to the receive frequency of the victim system, where OOB emissions (referred to adjacent channel interference) will be largest.

In the coexistence studies the degradation of receiver performance when a transmit signal of one system generates interference in the receiver of another system is a major issue. Generally, two aspects are considered:

- The direct noise rise of the victim due to the aggressor's out-of-band emissions in the adjacent channel and;

- Degradation of the receiver's performance due to blocking mechanisms.

Let S_I and S_N be the sensitivities of the receiver with and without the additional interference component, respectively, I be the additional interference and N_{floor} the receiver noise floor. The receiver desensitization in dB is given by:

$$DeSens = S_I - S_N = 10\log_{10}\left(1 + 10^{\frac{I - N_{floor}}{10}}\right). \quad (4)$$

III. INTERFERENCE ANALYSIS

A. Coexistence Scenarios

In a coexistence scenario two (or more) unlicensed wireless systems operate in the TV white spaces. The secondary systems have to satisfy FCC rules and several scenarios (indoor, outdoor or outdoor-to-indoor) and different types of radio technologies can be considered.

According to FCC rules [11], inside the protected TV noise-limited contour, called Grade B contour, the unlicensed systems are not allowed to operate in the co-channel and the first adjacent channel of an active DTV channel. Hence, if there is a DTV station transmitting in channel N in the UHF band, then the unlicensed systems located inside the Grade B contour must not operate on channel N neither $N + 1$. The unlicensed systems can only operate in channels $N + i$ for $i \geq 2$ if and only if the effective isotropic radiated power (EIRP) is below certain levels to avoid interference to nearby DTV receivers.

On the other hand, unlicensed systems located outside the TV Grade B contour and operating on channel N or $N + 1$ must be separated from the DTV station by a minimum distance called the *keep out distance* [12]. This distance depends on the channel separation between the unlicensed systems and the DTV channel and on the type of the unlicensed device, because FCC allows different levels for the maximum EIRP of fixed and mobile devices.

Three case studies are considered:

- *Home scenario*: coexistence between DTV and indoor Wireless LAN is investigated inside the DTV noise limited contour;
- *Town center scenario*: coexistence between DTV and outdoor unlicensed systems is investigated inside the DTV noise limited contour;
- *Wide (rural) area scenario*: the coexistence between DTV and outdoor LTE eNodeB is investigated outside the DTV noise limited contour assuming co-channel operation.

B. Results

First of all we present the assumptions of the wireless LAN system that is used in TV white spaces spectrum. Since the standardization of specification for WLAN variant for WS use has not started yet, no specific physical layer design is available up to this date. However, the best guess would be to assume an OFDM based system like 802.11a or 802.11n, but modified for smaller channel widths for the TV channel bandwidths. The IEEE 802.11 specification already has provided an OFDM PHY design when using 5 and 10 MHz bandwidths in Clause 17.

Hypothetical design and timing parameters for 5 MHz were considered. For instance, it was assumed 53 subcarriers (48 data, 4 pilot and 1 dc subcarrier) with frequency spacing equal to 78.1 kHz. Due to FCC ruling, the spectrum mask requirements for WS variant system are more stringent (-55 dBr to adjacent channel), which will likely require some changes to signal design as well but it is yet to be investigated.

The use of WLAN in WS spectrum has showed some advantages such as higher cell ranges compared to the operation on the current unlicensed bands as shown in downlink link budget in Figure 1. In this calculations it was assumed the COST 231 one slope propagation model. In simple WLAN indoor coverage analyses showed an increasing of the coverage ranges in white spaces spectrum of 4 and 3 times, compared to the ones obtained in the original bands used by 802.11g and 802.11a systems, respectively.

It is seen that the coverage range decreases substantially for same modulation order for 5 GHz WLAN compared to that of 2.4 GHz. There is about 7 dB extra path loss in 5 GHz compared to 2.4 GHz just because of higher carrier frequencies. From these results, it is seen that the coverage range when using the same transmission power (20 dBm) in WS band can be substantially increased compared to that of 802.11g or 802.11a systems. Path losses due to the use of lower carrier frequency itself are significantly less in WS band. Another advantage is improved receiver sensitivity due to lower system bandwidth (5 MHz vs. 20 MHz). For example, considering free space loss and 5 MHz system bandwidth, it is obtained 12.1 dB lower loss than 2.4 GHz, 18.7 dB lower loss than 5 GHz and 6 dB gain in receiver sensitivity for 5 MHz compared to 20 MHz bandwidth. The above comparisons are for similar modulation and coding schemes (MCS), but data rates for WS variant are about 4 times lower for same MCS.

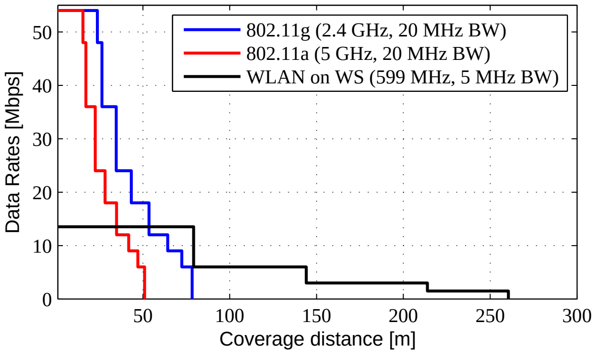

Fig. 1. WLAN link budget.

Figure 2 presents DTV receiver Signal-to-Interference-plus-Noise-Ratio (SINR) in a home scenario when there is an WLAN Access Point (WLAN AP), with bandwidth equal to 5 MHz, in the neighborhood operating in accordance with the power constraints ruled by FCC (i.e., EIRP of 36 dBm for fixed devices). The propagation model used in this case was ITU-R P.1546-3. The WLAN AP was kept at the first floor at the height of 3 meters and far away 20 meters from the DTV receiver in the horizontal plane. The DTV receiver was placed in the rooftop of the first floor (4 meters above the ground), second floor (8 meters above the ground) and third floor (12 meters above the ground). Three cases are considered in this analysis: WLAN system operating in the co-channel (channel 49), in the first-adjacent channel (channel 50) and in the second-adjacent channel (channel 51). Interference levels are estimated taking into account ACS and ACPL RF impairments for several distances between DTV transmitter and DTV receiver.

DTV receivers exhibit a very sharp noise-limited operation when it they are very close to the Grade B contour, i.e., the DTV receivers were designed to have a noise-limited performance threshold very close to the Grade B input signal level. According to [12], the required DTV receiver SINR at the protected contour (i.e., at 130 kilometers from DTV transmitter for this scenario) should be greater than 15 dB. Then, only in case where the DTV receiver is placed in the third floor and the WLAN system operates in the second adjacent channel meets this requirement.

It is important to mention that in this home scenario the FCC requirement for separation from digital TV protected contour is not met for co-channel and adjacent channel because the WLAN AP is far away from the DTV receiver only by few meters. FCC rules state that the required separation from digital TV protected contour must be 6 kilometers for co-channel operation and 0.1 kilometers for adjacent channel operation.

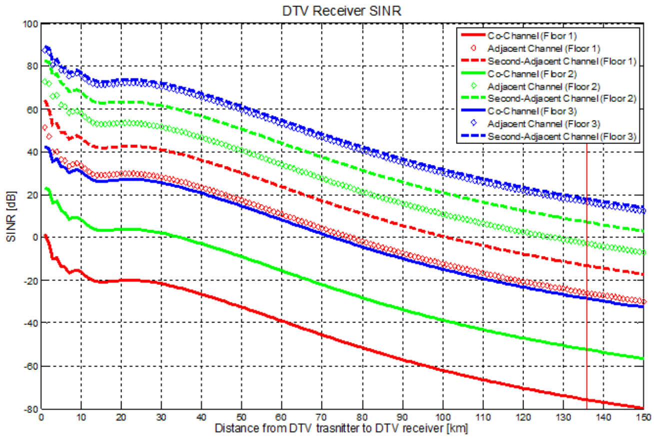

Fig. 2. SINR of the DTV receiver in home area.

For the purpose of evaluation of the outdoor system LTE specification details have been used as it is being deployed on the adjacent 700 MHz band. The interference from the DTV transmitter to LTE eNodeB in a town center environment is shown in Figure 3. Again, the propagation model used was ITU-R P.1546-3. The maximum interference level allowed for three values of desensitization are also presented. Interference on the first and second adjacent channels is mainly due to intermodulation distortion and it is very high inside the DTV protected contour (protected area) for distances lower than 50 kilometers. Besides, those interference levels are higher than the thresholds shown for the given values of desensitization. For distances greater than 50 kilometers, the interference in adjacent channel is dominated by transmission mask imperfections (ACPL). However, according to FCC rules, this channel could not be used if the unlicensed user is located inside the protected TV noise-limited contour. Regarding the maximum interference level allowed, the second adjacent channel can only be used for distances greater than 75 kilometers.

In town center scenario it is analyzed the situation where an indoor unlicensed WLAN access point interferes at outdoor unlicensed LTE user equipment. It was used the improved model for path loss prediction between terminals of low-height that was provided in [13]. Desensitization of LTE UE is shown in Figure 4. It is observed that there is harmful interference and the desensitization values on the first adjacent channel are not negligible. It was assumed an LTE UE equipped with 0-dB gain omnidirectional antenna. If the victim was assumed to be an LTE base station with a 14-dB gain antenna, then the desensitization would be even higher.

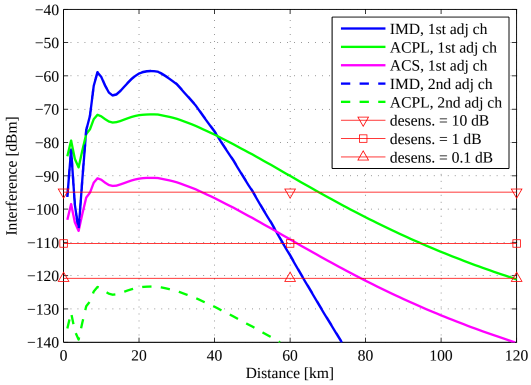

Fig. 3. Interference from DTV station on LTE base station.

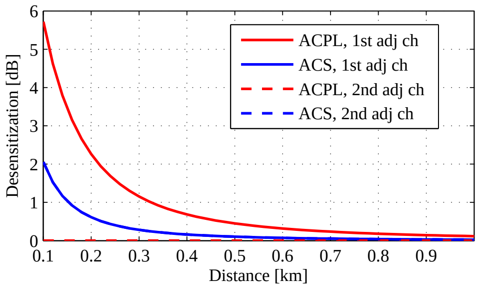

Fig. 4. Desensitization of LTE UE in the presence of a WLAN device.

In order to investigate the wide area scenario, it is assumed a DTV station at channel 49 and a DTV receiver at the protection contour, at 130 kilometers of the transmitter. At this distance, the DTV signal should not be blocked by interference generated by unlicensed device. It is also assumed that the antenna of the DTV receiver is pointed to the DTV transmitter receiver and its front-back ratio is 14 dB. Hence, the interference received from the unlicensed device will be attenuated by 14 dB because the unlicensed device is in the opposite side of the DTV transmitter. Regarding the unlicensed system, it is assumed LTE eNodeB with bandwidth equal to 5 MHz subject to the power constraints ruled by FCC. In Figure 5 is presented the SINR of the DTV receiver calculated as a function of the distance to the LTE eNodeB for the cases when the eNodeB is transmitting in the same channel, first and second adjacent channels, and the propagation model used was ITU-R P.1546-3.

When eNodeB transmits in the co-channel and fulfills FCC requirements (EIRP equal to 36 dBm) the DTV receiver would be subject to harmful interference only if the distance is below 7.2 km, since the SINR would assume values below the required ones. If the EIRP is increased to 39 dBm, the distance increases to 8.5 km. On the other hand, when LTE eNodeB transmits in the first or second adjacent channels it does not cause harmful interference to the DTV receiver even if transmit power is 3 dB above the maximum level allowed by FCC. Hence, these results show that the maximum transmission power of the unlicensed device can be increased without blocking DTV reception. Or, equivalently, the minimum distance ruled by FCC could be decreased. Currently, the minimum distance for the unlicensed device to transmit in the co-channel is 14.4 kilometers according to the FCC rules. These two changes in the maximum transmission power and in the minimum distance could be requested, unless if the interference in other scenarios is prohibitive.

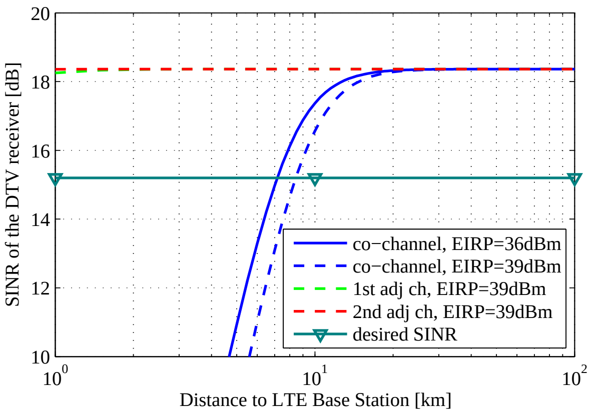

Fig. 5. SINR of the DTV receiver in wide area.

Finally, Figure 6 shows the impact of desensitization on LTE downlink link budget. For a given target rate, cell range decreases 17.8% when desensitization increases by 3 dB. It shows that the system may be subject high performance degradation when it coexists with potential interferers (DTV or other unlicensed systems) that cause desensitization levels equivalent to the ones shown in Figure 6.

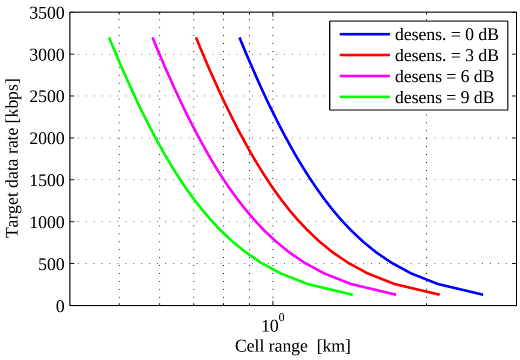

Fig. 6. LTE downlink link budget for several values of desensitization.

IV. CONCLUSIONS

The analysis of radio frequency issues plays an important role on the process of evaluation the benefits and challenges of candidate technologies which may operate in the TV white spaces spectrum. Out of band emissions and intermodulation products are examples of RF impairments that have be taken into account in the interference analysis. When the requirements of the devices are not fulfilled, receiver desensitization can reduce not only the cell coverage but also the cell spectral efficiency.

The deployment of WLAN systems in white space spectrum has been foreseen as a possible solution, specially because of greater coverage range when compared to other system candidates. Simple WLAN indoor coverage analyses showed that one may obtain a threefold and fourfold increase of the coverage range in white space spectrum compared to the ranges obtained in the original bands used by 802.11g and 802.11a systems, respectively. On the other hand, WLAN transmitting signal may degrade DTV signal reception if a minimum keep-out distance from the DTV receiver is not satisfied.

The spectrum sharing among other secondary users, such as other WLAN devices or even LTE- and WiMAX-like devices, in the TV band is not mature yet. Secondary users can easily cause interference due to obstructed coverage, inaccuracy in spectrum sensing, etc. Some calculations on town center scenario showed that the coexistence of two unlicensed systems in the same channel without any coexistence mechanism is totally forbidden. If the systems are deployed in the first or second adjacent channels, they have to be separated by a minimum distance in order to avoid mutual interference.

Other important aspect is that the rules imposed by FCC for unlicensed systems operating on available white spaces channels have large safety margins in some cases. Studies on wide area scenario revealed that the maximum transmission power of the unlicensed device could be increased without generating harmful interference to the DTV receiver and that a decrease of the minimum separation distance ruled by FCC could also be combined with such power increase. However, before the eventual requisition of these two changes, one must study the their colatheral effects on other scenarios.

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