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Coexistence and interference analysis in TV white spaces

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ABSTRACT

The demand for wireless connectivity is increasing exponentially resulting in an unprecedented demand on the limited radio spectrum. Due to the current fixed spectrum licensing scheme, it is becoming increasingly arduous to find extra spectrum resulting in a paradigm shift towards efficient utilization of radio spectrum in order to address the spectrum scarcity. The transition from analogue to digital terrestrial television has freed-up some spectrum thereby creating unique opportunities for exploitation of locally underused portions of the TV bands referred to as TV white spaces (TVWS) and their exploitation offers an attractive way of making efficient use of radio spectrum as long as the secondary users do not interfere with the primary users. This is enabled by employing cognitive radio technology that allows for dynamic spectrum access. This paper investigates the aspect of interference in TV White spaces and the possibility of mutual coexistence between primary users and secondary users operating in TV White spaces. The impact of interfering signals is undertaken to show the probability of interference in both same channel and different adjacent channels scenarios. The interference analysis is carried out using the SEAMCAT simulation software. Simulation results show that in a power limited secondary network, vacation of cognitive users from active spectrum bands is crucial for ensuring coexistence. The various interference mitigation mechanisms employed by CR networks are also reviewed. In TV white spaces, mitigating interference is vital not only for primary user protection, but also for ensuring the quality of service of the secondary users.

1. Introduction

According to research done by the IEEE 802.22 Working Group (IEEE 802.22 WG) less than 14% of the spectrum is effectively utilized – 86% of the spectrum is not used or is scarcely used as shown in Fig. 1 (Mody, 2013).

In Kenya, a study was done to determine the usability of 700 MHz frequency band currently allocated for TV channels 52-69 (Arato and Kalecha, 2013). The study showed that the spectrum occupancy is only 5.26%. This shows that although most of the electromagnetic spectrum has already been allocated to the different users, its utilization is quite low. A new approach is thus required to utilize this free spectrum without antagonizing the already licensed users of the spectrum in order to cater for the expanding wireless systems competing for the finite spectrum resource.

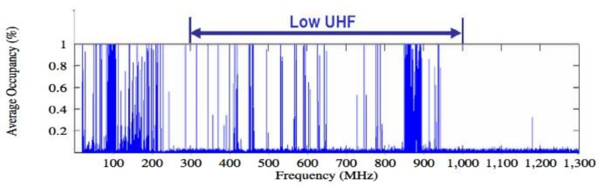

Fig. 1: Spectrum Occupancy Measurements (Mody, 2013)

The rest of this paper is organized as follows: Section 2 gives a brief description of TV White Space. Section 3 introduces the digital dividend resulting from the digital switchover. Section 4 describes the spectral coexistence scenario between the primary users and IEEE 802.22 WRAN system. Section 5 presents interference and the various types of interference between the primary and the secondary users. Section 6 describes the interference modelling and simulation. Section 7 gives a discussion of the results. Section 8 describes the interference

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avoidance and management schemes. Finally, Section 9 draws the conclusions.

2. TV white space

TV White Space refers to low-power, unlicensed operation of communications services in unused portions of RF spectrum that fall within frequencies allocated by regulators to television broadcasters and wireless microphones. A TV white space channel is thus an unoccupied or unused TV channel in the Very High Frequency (VHF) and Ultra High Frequency (UHF), i.e. there is no active TV broadcasting on the channel.

We have already seen that a large number of TV channels are not effectively utilized as discussed in section I. However, the use of available TV channels is constrained depending on the device type. Fixed and portable devices have varying requirements for utilization of TVWS including different separation distances from analog and digital TV protected contours. For example, fixed devices cannot use every available TV channel since they are not allowed to operate on first adjacent channels to a TV station while portable devices are allowed to operate on first adjacent channels subject to lower maximum transmit power constraints. This causes the number of available TV white space channels to reduce and also translates to different white space availability for fixed and portable devices. TV white space available for fixed devices is mostly available in sparsely populated areas, such as the semi-urban and rural areas, while the densely populated metropolitan areas have fewer available TVWS channels (Cacciapuoti and Caleffi, 2015).

The distribution of available TV white spaces in the UHF/VHF spectrum can thus be classified into urban, semi urban and rural settings. The amount of available TVWS spectrum thus depends on the device physical location setting, the height above average terrain of the transmitter (HAAT) and whether fixed or portable operation planned (Choi et al., 2012).

3. Digital dividend

The migration to digital platform of broadcasting has produced what is known as digital dividend. Digital dividend is the radio spectrum that is freed up in the process of digital television switchover. After television broadcasters switched from analog TV to digital-only platforms, part of the spectrum that was previously used for broadcasting was freed-up since digital television needs less spectrum than analog television. The main reason for this is that new digital video compression technology can transmit numerous digital sub-channels using the same amount of spectrum as the one used to broadcast one analogue TV channel. Another reason is because digital transmissions require much less of a guard band on either side, since they are not nearly as prone to RF interference from adjacent channels. This therefore eliminates the need to leave empty channels to protect stations from each other, hence allowing stations to be repacked into fewer smaller channels, leaving more contiguous spectrum to be allocated for other wireless services. Digital TV therefore reduces the bandwidth requirement of existing broadcast TV stations.

The amount of spectrum available after the digital switchover depends mainly on factors such as the geography and topography of each particular country, the degree of penetration of satellite and cable television services, spectrum usage in neighboring countries, the requirements for regional or minority television services and the digital television technology being applied to replace analogue services. The size of the digital dividend will therefore be different from region to region, and from country to country. Kenya uses DVB-T2 and MPEG – 4 Technologies for digital TV broadcasting.

The 800MHz frequency (actually consisting of spectrum in 790-862 MHz frequency bands) is referred to as digital dividend 1 (DD1) while the 700MHz frequency (actually consisting of spectrum in the 694-790 MHz frequency bands) is referred to as digital dividend 2 (DD2) (Kennedy et al., 2015). The digital dividend spectrum is located in the frequencies between 200 MHz and 1 GHz. These frequencies possess better signal propagation properties compared to those frequencies at, for example, 2.4 GHz.

The range of a radio depends on the wavelength where longer wavelengths (lower frequencies) travel longer distances for a given receiver sensitivity, antenna gains and power levels. Whereas a 2.4 GHz signal maybe transmitted up to several kilometers under ideal conditions, a signal in the UHF range from 470 MHz to 698 MHz can propagate to up to 100 kilometers. These lower frequencies enable the provision of widespread coverage and thus can help to achieve an ideal balance between transmission capacity and operational coverage. This means that less infrastructure would be required to provide wider network coverage, translating to cheaper prices for telecommunication services, especially in rural areas.

4. Spectral co-existence

Opportunistic Spectrum Access (OSA) enables wireless devices to identify and make use of spectrum that is unused at a particular location and/or at a particular time. Primary users (PU) are licensed incumbent users and have the exclusive rights in using certain frequency band for communications. Secondary users (SU) are allowed to use the frequency spectra momentarily but only if they do not interfere with the PU. The primary and the secondary users coexist together in the same wireless ecosystem. OSA allows sharing of existing spectrum licensed to primary users to allow the exploitation of unused and under-utilized spectrum by the secondary users.

IEEE 802.22 is a standard specifying wireless regional area network (WRAN) communication systems operating in TVWS. IEEE 802.22 technology enables the construction of wireless regional area networks that utilize UHF/VHF TV bands between 54 and 862MHz (TV channels 2 to 69) with a bandwidth of 6, 7 or 8MHz depending on the country while ensuring that no harmful interference is caused to the incumbent TV broadcasting and low-power licensed devices such as wireless microphones. The base station (BS) of an IEEE 802.22 cell manages the channel allocation amongst customer premises equipment (CPEs) and aims at coexistence with the PUs and the neighboring IEEE 802.22 cells (Foo, 2016) as shown in Fig. 2.

Primary users i.e. licensed TV broadcasters and wireless microphone users must certainly be protected against potential interference from the secondary users and, on the other hand, sufficient freedom must be given to secondary users to exploit the available spectrum while guaranteeing the quality of service of the secondary users.

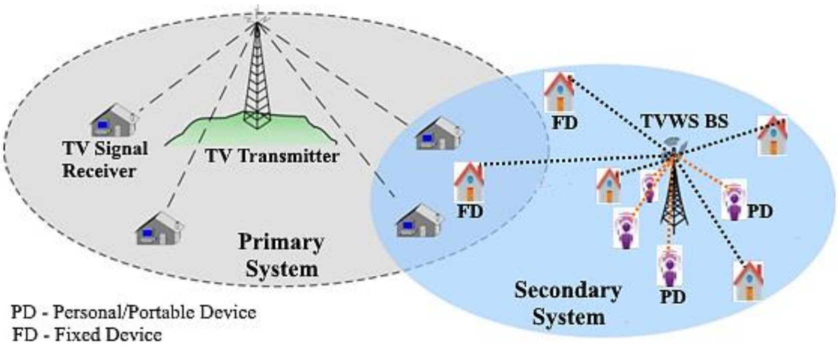


Fig. 2: Co-existence scenario between DVB-T2 broadcast system and IEEE 802.22 WRAN system

4.1. Protection of DVB-t receivers

A typical DTT broadcasting network comprises of high-rising TV towers mounted with high power transmitters. In order to minimize inter-symbol interference (ISI) the broadcasting channels are delivered over different frequency bands from each TV tower or in a group of TV towers that forms a single frequency network (SFN). This combination of large coverage area and fixed frequency planning offers a unique opportunity for secondary access in TV bands, as the primary usage can be easily identified and stored in a geo-location database. Spectrum sensing as a detection mechanism could be employed to complement the geolocation database for improved detection accuracy (Popescu et al., 2016a; Popescu et al., 2016b; Sendrei et al., 2015).

In the presence of cognitive radio, specifically of the white space devices in the UHF band, protection of Digital Terrestrial Television (DTT) receivers is required to ensure the quality of DVB-T reception is free from unwanted interference from WSD signals in the adjacent UHF bands. Since DVB-T has a set of standardized wave forms, the detection methods can take advantage of the embedded signal features in order to improve performance (Choi et al., 2012; Foo and Takada, 2016).

For the purpose of this paper, the transmission technology will be assumed to be OFDM since the OFDM family of technologies currently represents the most efficient and reliable transmission.

4.2. Protection of PMSE applications

Programme Making and Special Events (PMSE) refers to equipment that is used to support broadcasting, large outdoor concerts, outdoor news gathering and TV programmes, theatrical productions and special events, such as culture events, concerts, sport events, conferences and trade fairs where there is widespread use of wireless microphones.

PMSE shares the TV white spaces with broadcasters as they have low radiated power and their equipment has the ability to use spectrum that is interleaved with other existing services hence making efficient use of the spectrum. In order to protect PMSE, relevant Equivalent Isotropic Radiated Power (EIRP) restrictions need to be applied on WSDs operating in the geographic cells around the PMSE events. The protection approach is to limit the interference at the PMSE receiver such that the sensitivity of the equipment is not degraded beyond an acceptable margin (Waddell et al., 2012; Dionisio et al., 2012).

One approach is to base the WSD power levels upon a fixed threshold at the PMSE receiver to protect the PMSE event. One method (which affords higher protection to PMSE) is to determine the level of a WSD such that the sensitivity of the PMSE receiver were not degraded significantly, often referred to as an interferer to noise (I/N) approach. This can be expressed as (Eq. 1):

$$\delta = 10 \cdot \log 10(10^{(\gamma/_{10})} - 1) \tag{1}$$

where δ is the relative level of the WSD in dB and γ is the degradation in PMSE Rx sensitivity in dB.

To achieve this, the interference from WSD, weighted by the receiver ACS value should be in the range below the receiver's noise floor. Fig. 3 shows the degradation in receiver sensitivity as function of I/N (Waddell et al., 2012).

5. Interference

A measure for the occurrence of interference is when the victim receiver has a carrier to interference ratio (C/I) that is less than the minimum value allowed (Referred to as protection ratio).

However, for us to calculate the victim's C/I it is imperative to determine the victim's desired Received Signal Strength (dRSS) in addition to the interfering Received Signal Strength (iRSS). The location of the victim's wanted signal transmitter is established and a link budget calculated. If we know both the interfering signal strength and the wanted signal strength, then we can easily compute the victim's C/I.

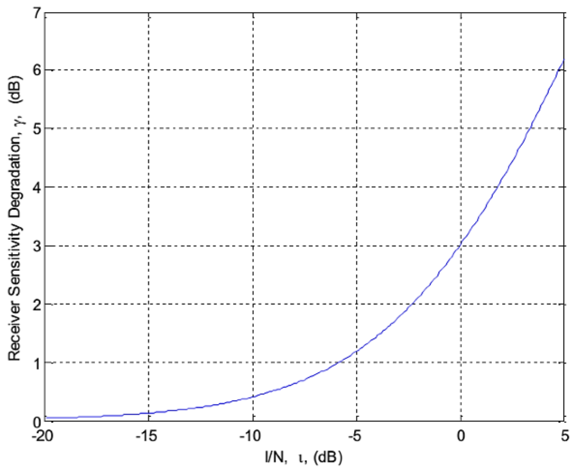


Fig. 3: Degradation in receiver sensitivity as function of I/N (Waddell et al., 2012)

Fig. 4 illustrates the various signal power levels used to determine the presence or absence of interference.

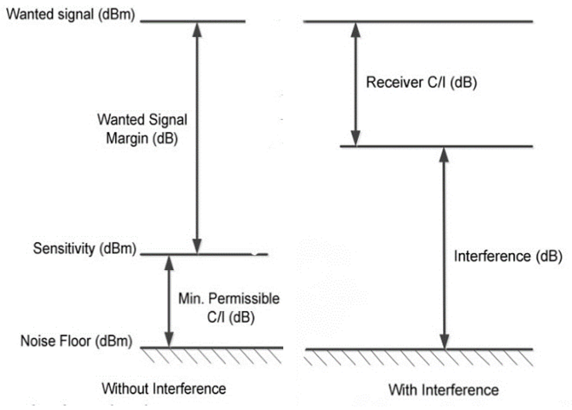
Fig. 4(a) represents a scenario where there is no interference and the victim is able to receive the wanted signal with some margin. In such a case the victim's C/I ratio can be obtained by the summation of the minimum permissible C/I and the wanted signal margin.

Fig. 4(b) shows what occurs when interference is present. The interference adds to the noise floor and the victim's C/I ratio is decreased. The new C/I ratio is obtained by the difference (in dBs) between the increased noise floor and the wanted signal strength. If interference is to be avoided, then this ratio must be greater than the minimum permissible C/I.

5.1. Interfering modes (unwanted and blocking)

The level of unwanted emissions consists of the spurious emissions and out-of-band emissions of the interfering transmitter falling within the victim's receiver bandwidth. The unwanted emission is also referred to as the Adjacent Channel Leakage Ratio (ACLR) and is illustrated as shown in Fig. 5 (ECO, 2016).

The blocking power of the receiver is the power detected from the interferer's transmissions resulting from selectivity imperfections of the victim's receiver i.e. total emission power of interfering transmitter (It) reduced by the blocking attenuation (selectivity) function of the victim receiver (Vr) as shown in Fig. 6.



(a) (b)

Fig. 4: Power levels used to determine presence/absence of interference

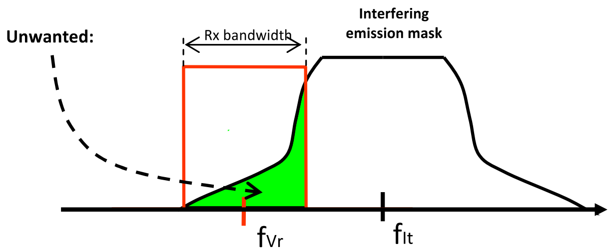


Fig. 5: Interference due to the unwanted emissions

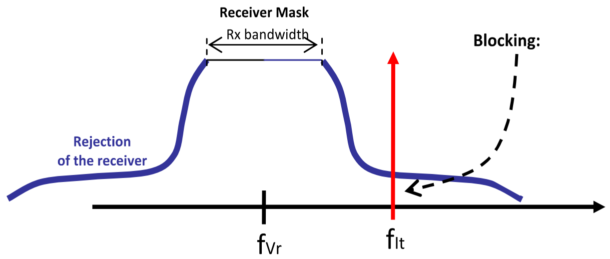


Fig. 6: Blocking of the victim receiver

The main interference mechanisms to be analyzed are both the unwanted emissions and receiver blocking shown in Fig. 7.

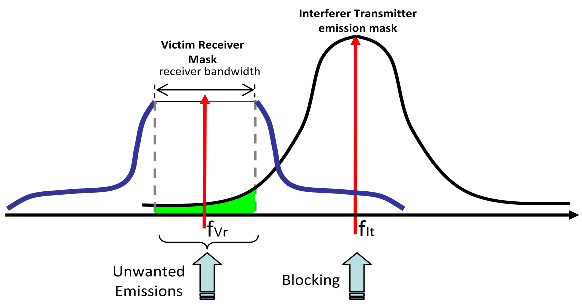


Fig. 7: Combined unwanted emissions and the receiver blocking mechanism (European Communications Office (ECO, 2016; Agrawal et al., 2016)

The main types of interference between primary users and secondary users are explained in the following sub-sections, i.e., 5.2, 5.3, and 5.4.

5.2. Co-channel Interference

Co-channel interference refers to interference from the transmitter of the secondary system to the receiver of a licensed primary system and usually occurs if the secondary system transmits in an occupied TV channel as illustrated in Fig. 8. This may be due to misdetection where the secondary user detects the primary user as absent due to fading and shadowing and attempts to transmit in the same frequency as the primary user. It can also occur if the spectrum-sensing period is long enough that the secondary user is not able to detect the reappearance of the primary user fast enough in a previously unoccupied channel that it continues to transmit instead of vacating the channel.

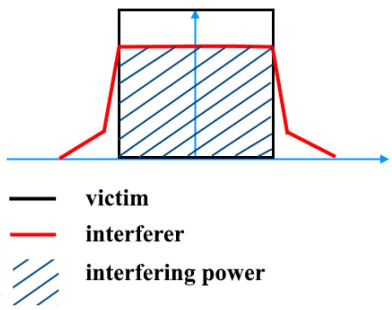


Fig. 8: Co-channel interference scenario

5.2.1. Co-channel Interference ratio

The signal-to-interference ratio (S/I or SIR), is the quotient between the average received modulated carrier power (S or C) and the received average co-channel interference power (I), i.e. cross-talk, from other transmitters other than the useful signal. It is also known as the carrier-to-interference ratio (C/I or CIR).

The CIR resembles the carrier-to-noise ratio (C/N or CNR), which is the signal-to-noise ratio (S/N or SNR) of a modulated signal before demodulation. A major distinction is that interfering radio transmitters contributing to Interference (I) may be controlled by radio resource management, while Noise (N) involves noise power from other sources, usually Additive White Gaussian Noise (AWGN).

5.2.2. Carrier-to-noise-and-interference ratio (CNIR)

The CIR ratio is usually studied in interference limited systems, i.e. where Interference(I) dominates over Noise(N), especially in broadcasting and cellular radio systems where frequency channels are frequently reused in order to achieve high levels of regional coverage. The C/N on the other hand is studied in mostly the noise limited systems. However, if both situations do occur, then the carrier-to-noise-and-interference ratio (CNIR or C/(N+I) is studied.

5.3. Adjacent channel interference

Adjacent channel interference occurs when the receiver of the licensed primary system is subject to interference in its channel from a secondary system operating in TVWS in an adjacent (neighbouring) channel. The cause of this is usually extraneous power originating from a signal in an adjacent channel mainly due to different power levels employed by the two systems and especially if the secondary system transmits at extremely high power levels beyond those stipulated by the ITU and the regulators. Since TV receivers are not designed to tolerate interference, most of the TV receivers' filters have poor adjacent channel selectivity.

Adjacent channel power ratio (ACPR) is the power ratio of the transmitter average power centered on the frequency of the assigned channel to the average power centered on the frequency of an adjacent channel (Vieira et al., 2010). The ACPR provides the amount of interference that a transmitter could cause to a receiver operating in the adjacent channel (Eq. 2).

$$\mathrm{ACPR} = 10\log_{10}\left(\sum_{k=1}^{k} 10^{\left(\frac{P_{SU}-L-ACPR_k}{10}\right)}\right) \quad (2)$$

where, K is the number of subbands of the SEM within an adjacent channel.
P_{SU} is the transmission power of the Secondary User,
L is the path loss between the SU and the PU,
$ACPR_k$ is the effective attenuation of the SEM in a given subband k.

Adjacent Channel Leakage Ratio (ACLR) is a measure of transmitter performance and is defined as the ratio of the transmitted power to the power measured in the adjacent radio frequency evaluated at the output of a receiver filter whereas Adjacent Channel Selectivity (ACS) is a measure of receiver performance and is defined as the ratio of the receiver filter attenuation on the allocated channel frequency to the receiver filter attenuation on the frequency in an adjacent channel.

Adjacent Channel Interference Ratio (ACIR) is a measure of overall system performance and is defined as the ratio of the total power transmitted from an interfering source to the total interference power affecting a victim receiver, due to both transmitter and receiver imperfections. These parameters have the following relationship (in linear domain) (Eqs. 2 and 3):

$$\frac{1}{ACIR} = \frac{1}{ACLR} + \frac{1}{ACS} \quad (3)$$

$$ACIR = \frac{PR(f_1 = f_W)}{PR(f_1 \neq f_W)} \quad (4)$$

5.4. Image channel interference

Some superheterodyne DVB-T receivers are susceptible to interference from transmissions nine 8 MHz spectrum channels above the intended spectrum channel. This is often referred to as the 'image channel' or the 'n+9 channel'. This means that, for a particular channel, if a transmitter site (for

DVB-T or any other service, including TVWS services) were deployed in the n+9 channel, there may be an area around the transmitter site where that DVB-T signal could not be received. Therefore, for some TV receivers, the interference received on channels around the N+9 channel could be equally damaging to the TV reception.

6. Interference modelling and simulation

SEAMCAT (Spectrum Engineering Advanced Monte Carlo Analysis Tool) is a statistical simulation software tool based on Monte-Carlo analysis (ECO, 2016). SEAMCAT is used for addressing compatibility studies between different radio technologies by assessing the potential interference between different radio communication systems. In this section we will consider various SEAMCAT aspects that are taken to account in modelling the interference between primary and secondary users. A typical scenario for monte carlo simulation is shown in Fig. 9.

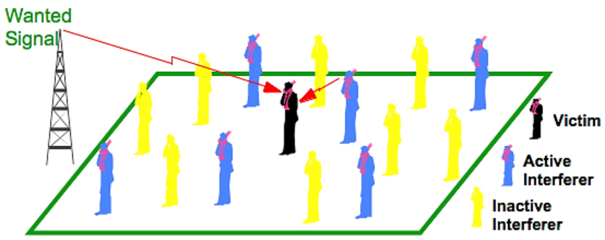


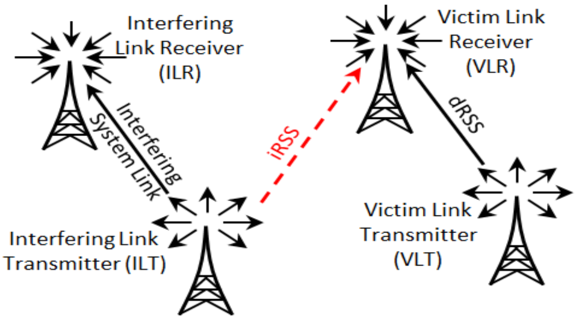
Fig. 9: A typical victim and interferer scenario for Monte Carlo Simulation

Usually, an urban environment has a high concentration of interferers than a rural environment.

In SEAMCAT, the interference scenario considers 3 different received signals. These signals are illustrated in Fig. 10 below and defined as follows:

- dRSS (desired Received Signal Strength) refers to the signal broadcasted to the Victim Receiver (Vr) by the Wanted Transmitter (Wt). This is the signal which will experience attenuation due to the interferer. In our case, the dRSS is a DTT (Digital Terrestrial Television) system.
- iRSS (interfering Received Signal Strength) refers to the signal received by the Victim Receiver (Vr) and broadcasted by the Interfering Transmitter (It). This is the signal which will impair the dRSS. In our case, the It is acting as a transmitting device.
- sRSS (sensing Received Signal Strength) refers to the signal that is broadcasted by the Wt and is sensed by the It. In our case, it acts as a transceiver, meaning that it is acting both as a transmitting device and a receiving device. (The energy is sensed though the bandwidth of the It device).

The sRSS (taking into account the unwanted mask of the DTT) at the channel m can be calculated as Eq. 5.



iRSS – Interfering Signal dRSS - Wanted signal

Fig. 10: Overview of interference scenario in SEAMCAT

$$RSS(f_m) = P_{Wt}(f_m) + G_{Wt\rightarrow It} + G_{It\rightarrow Wt} + L \qquad (5)$$

where:

P_{Wt}: is the transmit power in dBm from the Wt.

fm : is the frequency of the WSD.

$G_{Wt\rightarrow It}$: is the gain of the antenna in dBi of the Wt, in the Wt to It direction

$G_{It\rightarrow Wt}$: is the gain of the antenna in dBi of the It in the It to Wt direction

L: is the path loss in dB between the It and the Wt.

If the sRSS is below the Detection threshold then there is no interference but if the sRSS is greater the Detection threshold then there is interference that has occurred. Simulation parameters are summarized in Table 1.

Table 1: Simulation modelling parameters

Simulation Parameters	DVB-T/T2	Cognitive Radio
Channel Width	8 MHz	8MHz
Transmit Power	72.15 dBm	36.02 dBm
Receiver Bandwidth	7.71MHz	7.71MHz
Antenna Height Tx	100m	30m
Antenna Height Rx	10m	1.5m
Antenna Gain	6dBi	6dBi
Receiver Sensitivity	-98dBm	-98dBm
Receiver Noise Floor	-114dB	-114dBm
Propagation Model	Extended Hata	Extended Hata
Receiver Noise Figure	7dB	5dB
Modulation	64 QAM	64 QAM
Frequency Band	498 MHz	470~698 MHz

The spectrum from 470 MHz through channel 698 MHz is the most preferred as at these higher UHF frequencies, the antennas are shorter and much more manageable as compared to antennas for VHF frequencies 54 MHz through channel 216 MHz. The ratio of the wanted signal power to that due to the unwanted (co-channel or adjacent-channel) signal power at the point of failure of the receiver is referred to as the protection ratio of the receiver. The higher the protection ratio, the more prone the receiver is to interference. The adjacent channel protection ratio (in dB) is usually a negative number while co-channel protection ratio (in dB) is usually a positive number.

In most instances, a WSD transmission usually occupies most, but not all, of an 8 MHz TV channel. However, WSDs with wider and narrower bandwidths are also possible. A radio microphone transmitter generally occupies a bandwidth of 200 kHz. In deriving the protection ratio, the wanted

PMSE signal power is measured in 200 kHz and the unwanted WSD signal power is measured in 8 MHz.

In Holland et al. (2015) a review of the application of the extended Hata propagation model was carried out and fixed and mobile measurements showed that the extended hata model is appropriate to describe the path loss over in the UHF/VHF frequency bands.

A simulation study in (Popescu et al., 2014) has shown the effect of aggregate interference on the spectrum opportunity of TV white space. The measurement results obtained showed that Adjacent Channel Interference (ACI) is dominant inside the coverage area closer to the primary transmitter while Co-Channel Interference (CCI) is dominant closer to the victim receiver at the boundary region.

6.1. Separation distances for co-channel and adjacent channels

FCC has calculated separation distances for different Cognitive Radio transmitter heights by using C/I defined in Table 2. A CR device with a transmit power of 4 Watt have to be located between 6- 14.4 km away from the edge of the service area to be able to use the co-channel and between 0.1- 0.74 km to reuse the adjacent channel without causing any interference to possible TV receiver within the service area.

Table 2: Required separation distance defined by FCC (2008)

Antenna Height of TVWS Device	Required Separation Distance (in km) From Analog or Digital TV Protected Contour	
	Co-channel	Adjacent Channel
less than 3 meters	6.0 km	0.1 km
3 to less than 10 meters	8.0 km	0.1 km
10-30 meters	14.4 km	0.74 km

7. Results and discussion

Radio frequency signal-to-interference ratio (C/I) is the power ratio of the total power from the wanted signal to that of the combined interfering signals and noise, as detected at the receiver input. Radio frequency protection ratio (PR) is the minimum value of the signal-to-interference ratio required to obtain a specific reception quality, at the receiver input, under specified conditions. PR is usually specified as a function of the frequency offset between the interfering and the wanted signals over a wide frequency range.

In this paper we will consider the case where the victim link receiver (VLR) bandwidth and the interfering link transmitter (ILT) reference bandwidth have the same value (i.e. 8 MHz) hence no bandwidth correction factor is to be applied.

7.1. Simulation scenario 1

In this case we consider the effects of a secondary user transmitting at the same frequency as the primary user. The secondary user is transmitting at 498 MHz. There is a high probability of interference at 32% as shown in Table 3. Fig. 11 compares the dRSS and iRSS values of the secondary user and DVB-T signals. While Fig. 12 shows the interference probability function for varying secondary user power levels.

Table 3: Simulation parameters (Same Channel)

Simulation Results	
Parameter	Value
dRSS mean value	-43.75dBm
iRSS unwanted value	-72.46dBm
iRSS blocking value	-101.95dBm
C/I	19.0
Probability of interference	32.60%

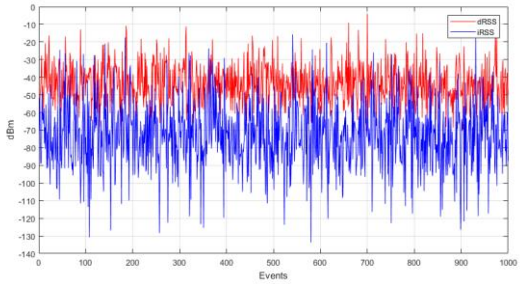


Fig. 11: dRSS and iRSS values

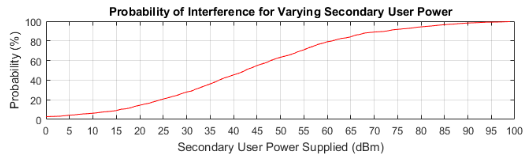


Fig. 12: Probability function of varying power of secondary user

7.2. Simulation scenario 2

In this case we consider the effects of a secondary user transmitting in an adjacent channel to the one in use by the primary user. There is a high probability of interference at 19.60% as shown in the Table 4. Fig. 13 compares the dRSS and iRSS values of the secondary user and DVB-T signals. While Fig. 14 shows the interference probability function for varying secondary user power levels.

Table 4: Simulation parameters (Adjacent channel)

Simulation Results	
Parameter	Value
dRSS mean value	-43.37dBm
iRSS unwanted value	-82.19dBm
iRSS blocking value	-102.74dBm
C/I	19.0
Probability of interference	19.60%

7.3. Simulation scenario 3

In this case we consider the effects of a secondary user transmitting in a second adjacent channel to the one in use by the primary user. There is a high probability of interference at 4.10% as shown in the Table 5. Fig. 15 compares the dRSS and iRSS values of the secondary user and DVB-T signals. While Fig.

16 shows the interference probability function for varying secondary user power levels.

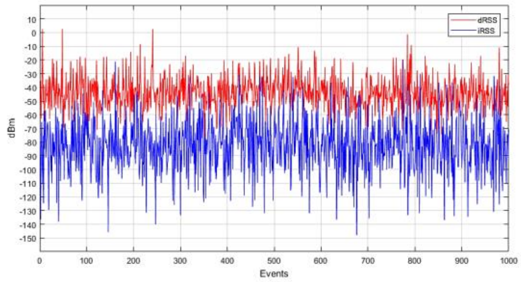


Fig. 13: dRSS and iRSS values

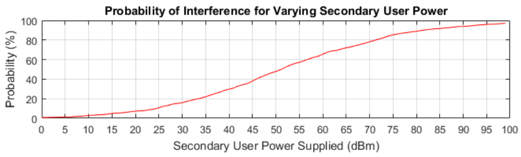


Fig. 14: Probability function of varying power of secondary user

Table 5: Simulation parameters (2nd Adjacent Channel)

Simulation Results

Parameter	Value
dRSS mean value	-44.51dBm
iRSS unwanted value	-109.56dBm
iRSS blocking value	-103.05dBm
C/I	19.0
Probability of interference	4.10%

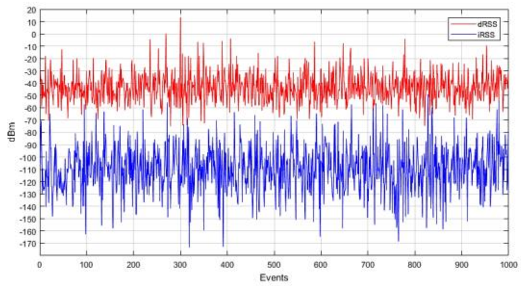


Fig. 15: dRSS and iRSS values

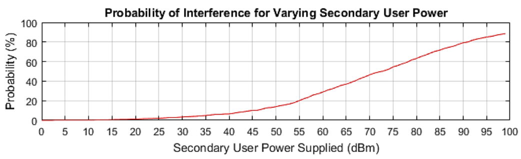


Fig. 16: Probability function of varying power of secondary user

One of the most challenging problems and concerns in using cognitive radio systems is interference, which occurs when the SU accesses the spectrum but fails to become aware of the presence of a transmitting primary user in the channel. The interference is thus highest when both the primary user and the secondary user are transmitting on the same channel as can be seen in scenario 1 where the probability of interference is 32.6% at 4W secondary power. Interference in the same channel may also occur when multiple secondary users select the same TV channel for transmission due to an uncoordinated selection process or limited availability or if the spectrum-sensing period is very long such that the secondary user is not able to detect the reappearance of the primary user fast enough in a previously unoccupied channel that it continues to transmit instead of vacating the channel.

It is therefore important for the secondary users to sense not just the primary users but also sense for other secondary users that might be transmitting at the same instance to avoid interference between the secondary users as they try to transmit at the same time. Secondary users transmitting at the adjacent channel to a currently occupied channel also causes interference though not nearly as high as in the same channel interference. This is as demonstrated in scenario 2. However, we find from Fig. 14 that the interference can be minimized if the secondary user transmits power is low enough. Mode II portable devices can easily transmit in the adjacent channels since they have low transmit power requirements as low as 40 mW (16.02dBm) compared to the high power fixed TVBDs that require a transmit power of 4W (36.20 dB).

Secondary users transmit power control is therefore a very important factor to consider as it is a major factor affecting the interference of primary users by the secondary users. The higher the transmit power supplied to the secondary user, the larger the coverage radius of the secondary cognitive user network, but also the higher the interference on the primary users as can be seen in Fig. 12, 14 and 16. Tradeoff is therefore required when setting up the secondary network to ensure maximum coverage radius at minimum interference to the primary users.

Interference avoidance techniques provide unique ways of minimizing and mitigating interference between the various systems exploiting spatial reuse opportunities.

8. Interference avoidance and management

The main fear arising from utilizing TVWS arises due to the possibility that it might cause harmful interference to the primary users by the secondary users. To counter this, various mechanisms can be employed for interference avoidance, interference control and interference mitigation. These include geo-location awareness, use of spectrum databases, sensing of available spectrum and cooperative sensing. Limiting the maximum allowed EIRP, and avoiding use of the first adjacent channel especially for fixed white space devices can also be employed to minimize interference on the primary users.

8.1. Geo-Location awareness and spectrum databases

Several mechanisms for interference avoidance are supported in TVBDs. The first interference avoidance mechanism is geo-location capability of TVBDs. This location awareness must be accurate to within 50 meters for both fixed TVBDs and Mode II portable devices and is coupled with access to a database containing information about licensed transmission in the various TV channels in the given location. In order to track and assign available TV white space channels, a geo-location database are required (Puri, 2012).

In order to remove the complexities of having multiple spectrum databases, then all spectrum databases have to be in sync with each other such that a PU device will only need to register with a single database. A SU that might want to utilize TV white space would have to register with a geo-location database first, through a control channel, by sending its current GPS coordinates, its ID, as well as other parameters. Once a SU has registered successfully with a geo-location database, the database will then provide information including a list of available radio channels and bandwidths that can be used by the device based on the device location and subject to the device type and the maximum allowable transmit power, to protect the PUs from harmful interference.

8.2. Cooperative Sensing

Local sensing at each individual SU is the starting point for spectrum sensing. However, local sensing is often not very accurate in detecting the presence of the PU signal, due to fading and shadowing.

This may lead to the secondary user incorrectly concluding that spectrum is unoccupied while it is actually occupied a situation known as hidden primary user problem. Hidden primary user problem might degrade the sensing performance by a single SU (Xin and Song, 2015). For example, if a SU is obstructed from the primary transmit signal, it might cause the unwanted interference to the PU due to a missed-detection of the PU's transmission as shown in Fig. 17.

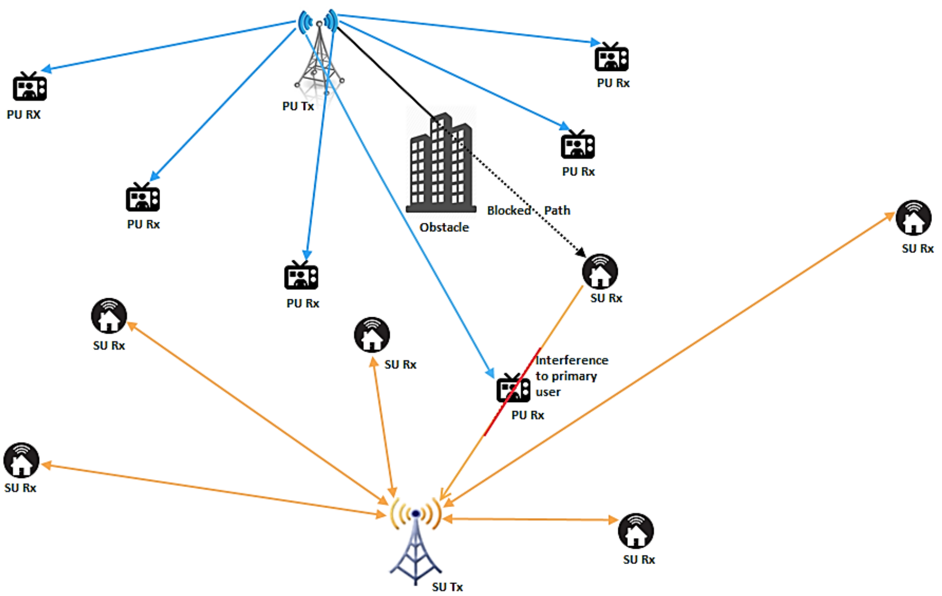


Fig. 17: Hidden user problem in non-cooperative sensing

By using a cooperative sensing system, it is possible to reduce the possibility of this happening because a greater number of receivers will be able to build up a much more accurate picture of the transmissions in the area by taking advantage of the spatial diversity of the different sensing nodes. Therefore, cooperative sensing can help improve the detection accuracy through cooperation among SUs on spectrum sensing (Sum et al., 2013; Sum et al., 2011).

8.3. Spectrum sensing

Another interference avoidance mechanism is spectrum sensing where a TVBD observes the various TV channels and then determines if any of these channels are currently occupied by any licensed PU transmissions. A SU detects a spectrum that is unused or spectrum hole (i.e. band, location, and time) and determines the method of accessing it (i.e. transmitting power and access duration) without interfering of a licensed user's transmission (Bhattacharya et al., 2011). This is very important in detecting other unlicensed users that may be operating in the TV white spaces and may not be recorded in the spectrum database. Such users include other SUs transmitting in the channel and wireless microphones operating in the TV band frequencies.

However, some factors such as temporal fading caused by multipath propagation are likely to be one of the major factors affecting the ability of WSDs to exclusively use sensing as the only viable technique to protect primary systems from interference.

8.4. Beacons

Beacons are signals which are used to indicate that particular channels are in use either by licensed primary services or are idle. The use of beacons can ease the complexities associated with TVBDs that use spectrum sensing, thereby increasing the likelihood of detection at lower threshold values. However, the interference protection provided to licensed users would come at a cost in spectrum capacity as well as the cost of purchasing and operating the beacons.

9. Conclusion

This paper has focused on the issue of interference generated by secondary users to primary user in TV white spaces. From the analysis done it has been shown that the design of a wireless cognitive system cannot be made without accounting for the effect of the aggregate interference they could generate. This is a very critical design aspect that should never be neglected in any cognitive radio design.

The dynamic spectrum nature of cognitive radios therefore requires special attention to the issue of interference. The technology of cognitive radio is founded on the assumptions that cognitive radio devices can detect the presence of the primary user's transmissions and that they will not cause significant degradation of the licensee's performance. If any of these assumptions does not hold true, then the concept of cognitive radio is no longer viable. Therefore, proactive monitoring and remedial tools are needed to predict and mitigate any potential interference that may be impacted on the performance of the primary users.

Based on the findings, it is very important to maintain the protection ratios for the incumbents (DTT and PMSE users), determine the maximum WSD power levels and channel separation from the incumbents as has been specified by the regulatory authorities. These protection ratios are very important in maintaining spectral coexistence between the different technologies exploiting TV white spaces while also minimizing the risk of harmful interference to primary users.

References

Agrawal S, Bhatia R, and Bhadoria MS (2016). Interference mapping for spectrum sensing in cognitive radio. International Journal of Innovations in Engineering and Technology, 6(4): 696-702.

Arato SS and Kalecha PO (2013). UHF (700 MHz) spectrum band occupancy measurements, analysis and considerations for deployment of long term evolution (LTE) deployment in Kenya. International Journal of Scientific and Engineering Research, 4(11): 572-580.

Bhattacharya PP, Khandelwal R, Gera R, and Agarwal A (2011). Smart radio spectrum management for cognitive radio. International Journal of Distributed and Parallel Systems (IJDPS), 2(4): 12-24.

Cacciapuoti AS and Caleffi M (2015). Interference analysis for secondary coexistence in TV white space. IEEE Communication Letters, 19(3): 383-386.

Choi JP, Chang HM, Choi HN, and Lee WC (2012). A study on interference analysis between DVB-T2 broadcasting service and TV white space device. In the 4th International Conference on Ubiquitous and Future Networks, IEEE, Phuket, Thailand: 234-235. https://doi.org/10.1109/ICUFN.2012.6261701

Dionisio R, Marques P, and Rodriguez J (2012). Interference study between wireless microphone systems and TV white space devices. In the IEEE International Conference on Communications, IEEE, Ottawa, Canada: 1874-1878. https://doi.org/10.1109/ICC.2012.6364101.

ECO (2016). SEAMCAT handbook (Vol. 2). European Communications Office, København, Denmark.

FCC (2008). Second report and order and memorandum opinion and order FCC 08-260 pg 65. Federal Communications Commission, Regulatory report, Washington, USA.

Foo YL (2016). Interference analysis of cognitive radio networks. International Journal of Communication Systems, 30(8). http://onlinelibrary.wiley.com/enhanced/exportCitation/doi/10.1002/dac.3176

Foo YL and Takada Ji (2016). Coexistence of DTV and TV white space systems. International Journal of Communication Systems, 30(9). https://doi.org/ 10.1002/dac.3222

Holland O, Bogucka H, and Medeisis A (2015). Validating the extended hata model for use in UHFs. In Holland O, Bogucka H, and Medeisis A (Eds.), Opportunistic Spectrum Sharing and White Space Access: 482-497. John Wiley and Sons, Hoboken, USA.

Kennedy R, George K, Vitalice O, and Okello-Odongo W (2015). TV white spaces in Africa: Trials and role in improving broadband access in Africa. In AFRICON, IEEE Africon, Ababa, Ethiopia: 1-5. https://doi.org/10.1109/AFRCON.2015.7331920

Mody DA (2013). IEEE 802.22 –Cognitive radio-based regional area and smart utility networks. ITU Regional Radio-communications Seminar for Arab Countries: Cognitive Radio and TVWS Workshop. Available online at: http://smartgrid.epri.com/doc/Mody_IEEE802_22_Cognitive_Radio_based_Smart_Utility_Networks_v2.pdf

Popescu V, Fadda M, and Murroni M (2016a). Performance analysis of IEEE 802.22 wireless regional area network in the presence of digital video broadcasting – second generation terrestrial broadcasting services. IET Communications, 10(8): 922-928.

Popescu V, Fadda M, Murroni M, and Giusto D (2016b). Coexistence Issues for IEEE 802.22 WRAN and DVB-T2 Networks. In the IEEE International Conference on Broadband Multimedia Systems and Broadcasting, Nara, Japan: 1-4. https://doi.org/10.1109/BMSB.2016.7521899

Popescu V, Fadda M, Murroni M, Morgade J, and Angueira P (2014). Co-channel and adjacent channel interference and protection issues for DVB-T2 and IEEE 802.22 WRAN operation. IEEE Transactions on Broadcasting, 60(4): 693-700.

Puri S (2012). Analysis of interference from secondary system in TV white space. M.Sc. Thesis, Radio Communication Systems Group, KTH Information and Communication Technology, Stockholm, Sweden.

Sendrei L, Felix M, Oravec J, and Marchevskys S (2015). Coexistence simulation of DVB-T/T2 AND LTE800 in seam cat. Acta Electrotechnica et Informatica, 15(3): 32-38.

Sum CS, Harada H, Kojima F, Lan Z, and Funada R (2011). Smart utility networks in TV white space. IEEE Communications Magazine, 49(7): 132-139.

Sum CS, Villardi GP, Rahman MA, Baykas T, Tran HN, Lan Z, and Pyo CW (2013). Cognitive communication in TV white spaces: An overview of regulations, standards, and technology. IEEE Communications Magazine, 51(7): 138-145.

Vieira RD, Souza EB, Cavalcante A, Pirhonen R, Kafle P, Malkov A, and Li Z (2010). Interference analysis of coexistence scenarios in TV white spaces. In the 7th International Telecommunications Conference of Nokia Technology

Institute. Manaus, Brazil. Available online at: http://www.cricte2004.eletrica.ufpr.br/anais/sbrt/SBrT28/71533.pdf

Waddell M, Lillywhite A, Reihl E, Brookes K, Ernst F, Fehr M, Copsy B (2012). Initial considerations for protection of PMSE. BBC Research and Development White Paper, WHP 224. Available online at: http://downloads.bbc.co.uk/rd/pubs/whp/whp-pdf-files/WHP224.pdf

Xin C and Song M (2015). Opportunistic spectrum access. In: Xin C and Song M (Eds.), Spectrum Sharing for Wireless Communications: 7-16. Springer, Berlin, Germany.