

Performance Analysis of IEEE 802.22 WRAN in the Presence of DVB-T2 Broadcasting Services

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Abstract: In Cognitive Radio (CR) networks unlicensed secondary users aim at transmitting in licensed bands while preserving primaries from harmful interference. CR communications have been especially studied in the white spaces of TV band (TVWS) which are defined as the TV free channels left unused in each territorial area by the reallocation of the TV services as direct consequence of the switchover plans. The first full CR standard, the IEEE 802.22 Wireless Regional Area Network (WRAN), has been developed to bring wireless broadband access to remote and rural areas where other wireless networks are not present due to low revenue impact or critical network deployment. IEEE 802.22 WRAN devices are designed to operate in the range of frequencies between 54MHz and 862MHz alongside Digital Terrestrial Television (DTT) operation. In this work a complete analysis to evaluate the performance of IEEE 802.22 WRAN devices coexisting with DVB-T2 adjacent channel transmission in the TV bands in a rural environment has been performed. The link budget analysis for IEEE 802.22 WRAN in different coexistence scenarios, such as fixed DTT reception with indoor/outdoor IEEE 802.22 WRAN reception shows that robustness of IEEE 802.22 WRAN is comparable to Long Term Evolution (LTE) which represents the state-of-the art of cellular networks in rural scenario.

1. Introduction

In recent years, there has been a significant increase of wireless applications being deployed, which placed significant amount of pressures on sharing the available spectrum especially in Very High Frequency (VHF) and Ultra High Frequency (UHF) bands. On the other hand, in the last years over 60 countries worldwide have adopted the new digital terrestrial television (DTT) standards for TV transmissions [1]. For DTT operation, in the USA, extended measurements performed by the Federal Communication Commission (FCC) showed that a large part of the TV radio spectrum, although allocated, was virtually unused [2]: approximately 10% of the 67 high-power TV channels were allocated. Even in Europe, the digital switchover has induced a review of the UHF spectrum usage [3], leaving free TV channels in each territorial area. In the UK modelling commissioned by the “Independent regulator and competition authority for the UK communications industries” (Ofcom) revealed that over 50% of locations in the United Kingdom have more than 150MHz available in the bands assigned to DTT [4]. The unused channels within the TV band are called “TV white spaces” (TVWS) [2]. However, since TVWS are not

occupied, but still licensed channels, formally assigned to TV broadcasting services, traditional static spectrum allocation policy do not formally allow using them for other services [3].

To exploit the TVWS, dynamic spectrum access solutions based on Cognitive Radio (CR) technology has been proposed [5]. A CR is a system employing technology that allows obtaining knowledge of its operational and geographical environment, established policies and its internal state, to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives [6]. The spectrum management rule of CRs is that all new users for the spectrum are secondary cognitive users (SUs) able to detect and avoid primary licensed users (PUs) by adjusting functional parameters, such as carrier frequency, transmission power, and modulation type. In TVWS, PUs are DTT services that can be revealed by considering the information included in geo-location databases, if available, which provide, for a certain location, the list of the free DTT channels and the allowable maximum radiated power for transmitting without harmful interference to DTT users [7]. In order to afford appropriate levels of protection to the DTT service, it is necessary for the database to specify the maximum permitted emission levels for a CR across all DTT channels and in all geographic locations where the DTT service is being used [8][9].

The World Radio Conference decided in 2012 that CRs are to be interpreted as a set of technologies and not as a radio communication service. For this reason, there is no need to change radio regulations, but just to ensure that CRs do not cause any interference or claim protection from authorized services operating in the same or in adjacent bands [10]. Once TVWS are identified, the national authority protects broadcasting services through several technical rules applying to the CRs and their operation in such white space spectrum [11]. Several studies on compatibility problems have been conducted [12-15] identifying the joint use of detection techniques [16] (i.e., spectrum sensing) and geo-location databases as a possible way to enable harmless communications in the TVWS [17].

Within the CR paradigm, the first full CR standard, the IEEE 802.22 Wireless Regional Area Network (WRAN) [18], has been developed to bring wireless broadband access to remote and rural areas where other wireless networks, such as 3G/4G cellular networks or WAN, are not present due to low revenue impact or critical network deployment. IEEE 802.22 WRAN is designed to operate in the VHF and UHF bands in the range of frequencies between 54MHz and 862MHz. These bands are considered as a ‘sweet spot’ for their advantages in propagating signals and hardware costs with respect to current LTE/LTE-A or WiMAX technologies using higher frequency bands. CR techniques, such as geo-location capability and spectrum sensing technology, are used in IEEE 802.22 WRAN to enhance operation [19].

The tolerance of DTT receivers to Adjacent Channel Interference (ACI) has been quantified in several studies for IEEE 802.22 WRAN [20-25] and also for 4G LTE [26-28]. Both IEEE 802.22 WRAN and LTE operate in adjacent channels with respect to DTT. The Electronic Communications Committee (ECC) presented a report to provide technical and operational requirements for secondary unlicensed devices operating in the 470 - 790MHz frequency band, in order to ensure the protection of the incumbent radio services [21][22]. As a matter of fact, the IEEE 802.22 WRAN standard was released considering coexistence issue with respect to first generation DTT technologies, such as DVB-T [29], ATSC [30], and focusing on the impact of IEEE 802.22 WRAN transmission on DTT services. *Popescu et al.* in [25] presented a complete study on the maximum tolerable interfering power level and bandwidth configuration of an 802.22 signal in the co- and adjacent channel of an active second generation DTT system, namely DVB-T2 [31], whereas protecting the primary broadcast system.

On the other hand, there is lack of studies for evaluating the impact of DTT services on IEEE 802.22 WRAN. Therefore, considering the results obtained in [25], this work analyses the performance of IEEE 802.22 Customer Premise Equipment (CPE) in the presence of DVB-T2 DTT transmissions. Specifically, the values obtained in [25] for the maximum Effective Isotropic Radiated Power (EIRP) for the IEEE 802.22 WRAN devices in the presence of DVB-T2 transmissions in adjacent channel were used as a reference to respect the protection level of a DVB-T2 receiver [32][33] ensuring that there is no interference caused by IEEE 802.22 WRAN to DVB-T2 services. Nevertheless, still under this hypothesis, it is possible that DVB-T2 interferes IEEE 802.22 WRAN. Hence, the present study focuses on the adjacent channel interference caused by DVB-T2 systems operating into the same coverage range of an 802.22 CPE. The transmission scenario focuses on mobile outdoor and indoor CPEs in a rural environment, based on the results of a measurement campaign performed by the same authors in Europe on rural, suburban, and urban sites, at different heights over the ground by using different analysis bandwidths [34] which provides a set of practical parameters upon which harmless unlicensed communication in the TVWS is feasible.

The IEEE 802.22 WRAN PHY layer has been modelled on the transmitter and receiver side to transmit real standard compliant signals and to receive evaluating the bit error rate (BER) in the presence of adjacent DVB-T2 interference after a Forward Error Correction (FEC) algorithm: a Viterbi decoding has been considered. We tested different configurations of the IEEE 802.22 WRAN considering all modulation types and different code rates provided by the standard. For the DVB-T2 signal, the typical settings for the multiple frequency (MFN) and single frequency (SFN) broadcasting networks have been considered. A first measurement series has been performed to evaluate the BER values of the various

transmission modes for IEEE 802.22 WRAN systems coexisting with a DVB-T2 system operating in the first adjacent channel. Then, the signal-to-interference ratio values (C/I) were evaluated as a function of the guard band in order to maintain a constant BER level for a 802.22 transmission. Finally, the link budget for the coexistence in the first adjacent channel was evaluated.

The main contribution of the paper is a complete performance analysis that can be used to evaluate the most appropriate operative configuration of IEEE 802.22 WRAN devices coexisting with DVB-T2 adjacent channel transmission in the TV bands in rural environment. A radio coverage analysis considering the presence of DTT transmitter, 802.22 base station (BS), and 802.22 CPE in a real scenario is presented. The novelty of the paper resides in considering the DVB-T2 broadcasting standard as an interferer, a configuration not yet analysed by the studies published until now [20-25]. The choice of this new DTT standard is motivated by the current gradual passage to DVB-T2 which is likely to become a widespread standard in near future.

The rest of the paper is organized as follows: section II briefly describes the IEEE 802.22 WRAN transmission/reception system. Section III describes the coexistence scenario. Section IV and V present the measurement set-up and methodology. Section VI describes the results illustrating the performance of 802.22 devices coexisting with DVB-T2 services in rural environment. Finally, section VII draws the conclusions.

2. IEEE 802.22 WRAN TX-RX System

The IEEE 802.22 WRAN standard specifies the air interface, including the cognitive MAC and PHY, of point-to-multipoint wireless regional area networks operating in the TVWS of the VHF/UHF TV broadcast bands between 54MHz and 862MHz [19].

In this work the IEEE 802.22 WRAN PHY layer has been modelled using LabView software on the transmitter and receiver side in order to transmit a real standard compliant signal and to receive it evaluating the BER after the Viterbi decoder.

2.1. Transmission Side

Data bits are produced by a binary source modelled by a binary generator block. The data is then coded using convolutional coding, with a native rate of 1/2 with a constraint length equal to 7. The other code rates are obtained by puncturing bits. Coded bits are interleaved with a turbo-based algorithm and then mapped to subcarriers after modulation. Later, pilot, guard, and downlink subcarriers are inserted.

Then, an OFDM symbol is generated applying an IFFT to subcarriers. Pilot and data subcarriers have the same power level.

Finally, a cyclic prefix is added at the beginning of each OFDM symbol. After all these operations, the data is ready to be delivered to the radio channel.

The maximum transmission power of a white space device (WSD) depends on the various local regulatory authorities that provide a list of available channels and the maximum EIRP allowable on these channels based on queries containing the geolocation of the WSD. The IEEE 802.22 WRAN standard specifies the transmitting spectrum mask requirements authorized by the various regulatory domains for the different regulatory classes. In order to meet the various RF masks, there may be a need to shape the transmission signal with either filtering in the frequency domain or windowing in the time domain. This is implementation dependent.

2.2. Receiver Side

Initially, the receiver performs the synchronization of the signal. The symbol timing from the complex input waveform is recovered correcting the timing offset. Also a frequency offset correction is implemented using a frequency offset correction algorithm. Then, the cyclic prefix is removed to each received OFDM symbol and the FFT block operates the OFDM demodulation. After removal of pilot and guard each symbol is demodulated.

Data are de-interleaved using a turbo-based de-interleaver scheme complementary to the algorithm on the transmission side. For the FEC a lazy Viterbi decoder algorithm was implemented: it is a maximum-likelihood convolutional code being much faster than the original Viterbi decoder [35]. Finally, an evaluation of the BER after the Viterbi decoder can be performed.

3. Coexistence Scenario

The wireless regional area networks for which the IEEE 802.22 WRAN standard has been developed are expected to operate in low population density areas in order to provide broadband access to data networks. A typical application can be the coverage of the rural area around a village in which there are few buildings, within a radius up to 20 km from the BS, depending on its EIRP and antenna height [36].

In this study, we consider the effects of DTT transmissions adjacent to 802.22 CPEs receiving in an indoor and outdoor rural environment. This scenario implies that the 802.22 BS do not interfere in any way with the DTT signals, as compliant to the standard and to the specific coverage regulations.

Based on the previous assumptions, the worst case scenario of the 802.22 communication is when the CPE is in Line-of-Sight (LoS) with the DTT antenna at a distance that maximizes the interference (i.e., case A of figure 1). For this case, a Rician model is used to simulate a multipath distribution for a strong LoS component along with the weaker components [37]. For the indoor case (i.e., case B of figure 1) a mean value for the penetration loss is considered [34].

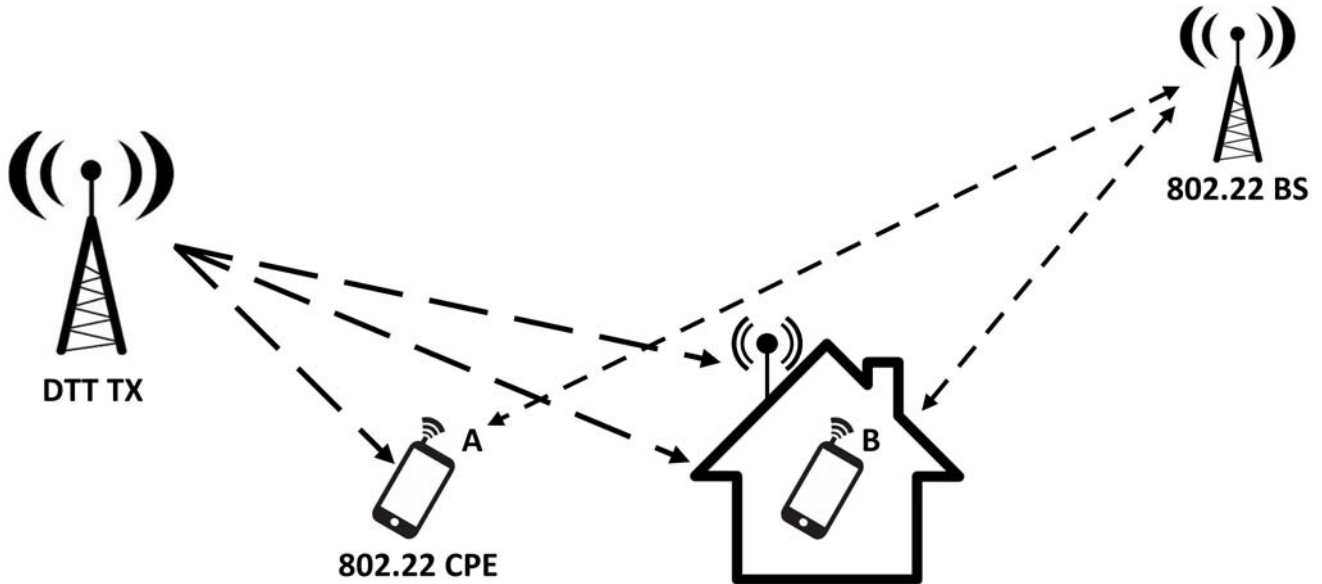


Fig. 1. Real scenarios for DVB-T2 coexistence with outdoor (A) and indoor (B) 802.22 CPEs in rural environment

4. Measurement Set-up

In order to assess the performance of an 802.22 system interfered by DVB-T2 transmissions operating in the adjacent channel, the BER has been monitored for different operation modes of the IEEE 802.22 WRAN standard.

The 8MHz DVB-T2 signal was generated using the Agilent Signal Studio for Digital Video software connected to an Agilent N5182A MXG RF Vector Signal Generator. Typical settings for the MFN and SFN broadcasting networks have been considered. The IEEE 802.22 WRAN PHY layer transmission scheme has been modelled in LabView, as described in section 2. The signal was RF modulated and transmitted using a NI N-2920 software defined radio (SDR) platform connected to a computer running the transmission LabView model. The IEEE 802.22 WRAN and DVB-T2 signals were combined using a directional coupler. The 802.22 signal was received by means of an USRP2 SDR platform connected to a computer running the reception LabView model, described in the previous section.

The Agilent EXA9010A Vector Signal Analyzer (VSA) was used to power measurements performed both for DVB-T2 and IEEE 802.22 WRAN signals. A simple schematic of the measurement system is shown in figure 2.

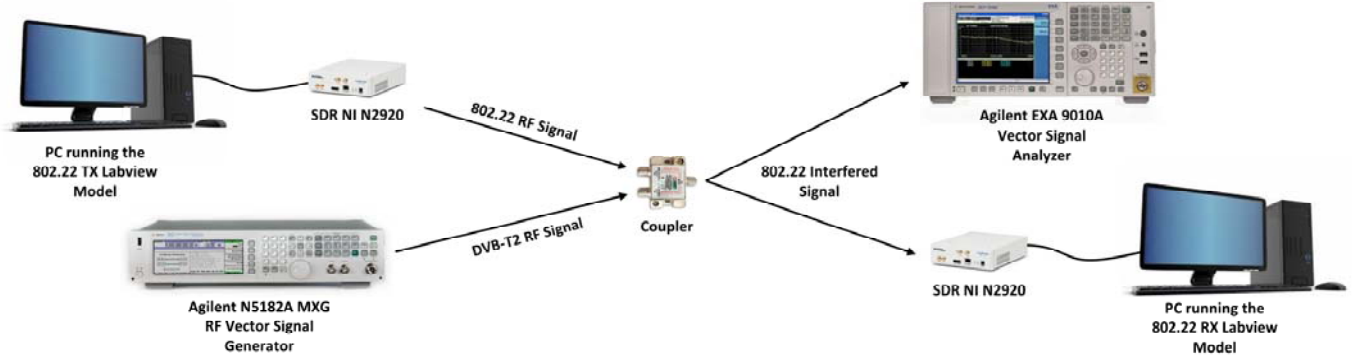


Fig. 2. Schematic of the measurement system

5. Measurement Methodology

The IEEE 802.22 WRAN standard has been designed to allow cognitive devices to coexist in the TV band without causing any disturbance to existing broadcasting services and low-power licensed devices. The receiver minimum sensitivity level is defined as the minimum power, measured at the antenna port, at which the BER performance is equal to 2×10^{-4} and varies from -90dBm to -94.5dBm depending on role and configuration [19]. Furthermore, the maximum transmitted EIRP level, considering the various regulatory domains for the different regulatory classes, for the CPE is 20 dBm (100mW) [19]. In [25] the protection of DVB-T2 broadcasting service interfered by IEEE 802.22 WRAN transmissions in the co- and adjacent channels has been evaluated. The measured protection ratio (PR) values were evaluated in order to assess the maximum transmission power levels, respecting the standard limit, of an 802.22 signal to respect the condition for the minimum PF level of a DVB-T2 receiver [32][33]. Therefore, in this work the PR values obtained in [25] were used to set the initial transmission power level of the 802.22 signal in order not to disturb a DVB-T2 receiver.

The following performance parameters have been measured:

- the BER of 802.22 signals as a function of C/I values considering DVB-T2 signal as interferer;
- the C/I values as a function of the guard band from the carrier of the DVB-T2 signal, in order to maintain a BER equal to 2×10^{-4} for 802.22 transmissions with different bit rates.

Initially, the BER values of the various transmission modes for IEEE 802.22 WRAN systems coexisting with a DVB-T2 system operating in the first adjacent channel were measured. The most representative operation modes for the MFN and SFN broadcasting networks, as shown in [38], were considered. Table 1 presents all the parameters that characterize the DVB-T2 and 802.22 signals.

Table 1 DTT and 802.22 Signal Parameters

DVB-T2			IEEE 802.22 WRAN			
Network Type	SFN	MFN	Modulation	QPSK	16-QAM	64-QAM
Modulation	64-QAM	256-QAM	Code Rate	1/2-2/3-3/4-5/6	1/2-2/3-3/4-	1/2-2/3-3/4-5/6
Code Rate	3/5	3/5	Data Rate [Mbps]	4.54 to 7.56	9.08 to 15.13	13.61 to 22.69
FFT	8K	8K	FFT	2048	2048	2048
Guard Interval	1/16	1/128	Bandwidth [MHz]	8	8	8
Pilot Pattern	PP4	PP7				
Bandwidth [MHz]	8	8				

Taking into account that the measurement set-up conditions are frequency invariant, channel 56 (754 MHz) was used for the measurements. The transmission frequency of the 802.22 signal was set to the central frequency of the first adjacent channel (i.e., channel 57 - 762MHz).

The following test procedure was used:

1. the transmission power level of the DVB-T2 signal (I) is set to -60 dBm and is fixed during all the performed measurements. This value ensures that the TV receiver is working at least 10 dB above the PF threshold;
2. the transmission power level of the IEEE 802.22 WRAN is initially set considering the PR value to respect the condition for the minimum PF level of a DVB-T2 receiver;
3. starting from the level set at point 2, the power level is decreased to evaluate the performance of the 802.22 receiver, in terms of resilience to the DVB-T2 signal;
4. the RMS power level of the 802.22 signal (C) is measured in the considered channel bandwidth using the Agilent VSA to calculate the corresponding C/I ratio;
5. the BER after the Viterbi decoding is evaluated;
6. steps 1 to 5 are repeated varying the 802.22 code rates;
7. steps 1 to 6 are repeated varying the 802.22 modulation types;
8. steps 1 to 7 are repeated varying the settings for the DVB-T2 broadcasting network.

Subsequently, considering three 802.22 configurations corresponding to different traffic loads, the C/I values were evaluated as a function of the guard band from 0 to 10 MHz from the carrier of the DVB-T2 signal, in order to maintain a BER equal to 2×10^{-4} for a 802.22 transmission. The C/I values obtained from the BER measurements were used to set the initial transmission power level of the 802.22 signal at which the BER performance is equal to 2×10^{-4} . Even in this case two typical settings for the MFN and SFN broadcasting networks were considered. The following test procedure was used:

1. the transmission power level of the 802.22 signal (C) is initially set considering the C/I value at which the BER performance is equal to 2×10^{-4} and is fixed during all the measurement (i.e., it changes depending on the 802.22 configuration);
2. the guard band is increased of 1MHz;
3. the transmission power level of the DVB-T2 signal (I) is initially set to -60 dBm;
4. starting from the level set at point 3, the power level of the DVB-T2 signal is increased to evaluate the performance of the IEEE 802.22 WRAN receiver, in terms of resilience to the presence of DVB-T2 signals;
5. the C/I ratio of the 802.22 signal interfered by a DVB-T2 signal is measured in the considered channel bandwidth when the BER performance of the 802.22 receiver is equal to 2×10^{-4} ;
6. steps 1 to 5 are repeated varying the guard band with step 1MHz up to 8MHz;
7. steps 1 to 6 are repeated varying the 802.22 configurations;
8. steps 1 to 7 are repeated varying the settings for the DVB-T2 broadcasting network.

6. Results

6.1 BER measurements

Figure 3 shows the results applying the Viterbi decoding to the received data of an 802.22 signal interfered by a DVB-T2 signal typical for a SFN network configuration, for QPSK, 16-QAM, and 64-QAM with different code rates in the 8MHz bandwidth. As can be seen, the robustness of the IEEE 802.22 WRAN system decreases with the modulation scheme, as well as with the code rate.

Higher modulation schemes with high data rates are less robust to DVB-T2 transmissions in the first adjacent channel without guard band: e.g., to achieve a BER equal to 2×10^{-4} for 16-QAM and 1/2 code rate, a C/I above 1dB is needed; for 64-QAM with 5/6 code rate the C/I is 17dB, showing a difference of 16dB for a higher modulation scheme and code rate.

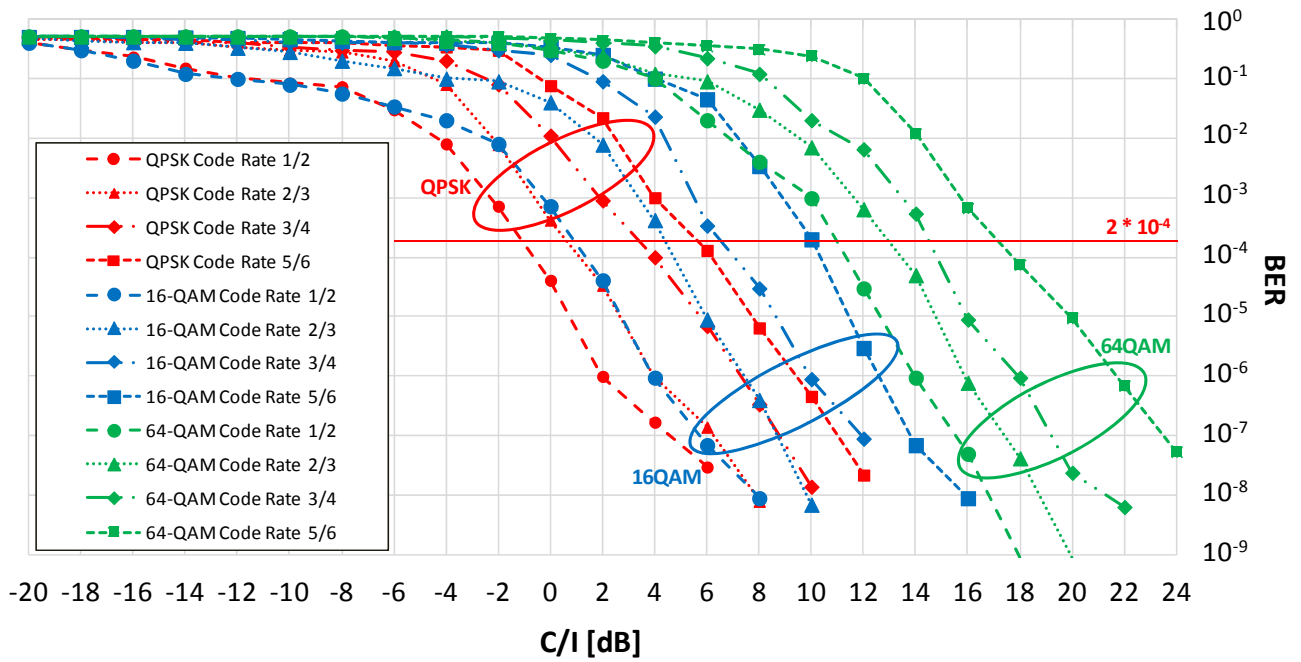


Fig. 3. BER evaluation for different configurations of 802.22 signals interfered by a DVB-T2 SFN signal

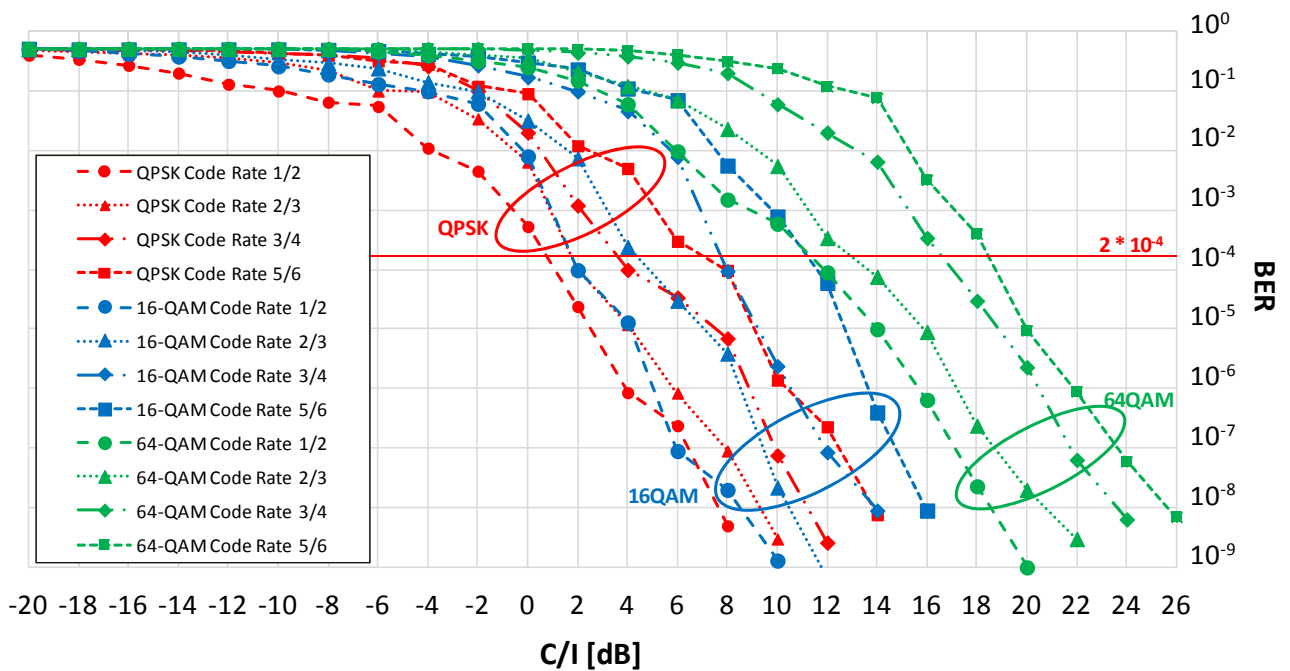


Fig. 4. BER evaluation for different configurations of 802.22 signals interfered by a DVB-T2 MFN signal

Figure 4 shows the BER evaluation after the Viterbi decoding for the received data of 802.22 signal interfered by a DVB-T2 signal typical for a MFN network configuration, for QPSK, 16-QAM, and 64-

QAM with different code rates in the 8MHz bandwidth. The results are similar to those obtained for the SFN case, leading to the same conclusion: higher modulation schemes with high data rates lead to a diminution of the 802.22 performance in the presence of a DTT interferer.

Comparing the curves obtained for the SFN case (i.e., figure 3) and for the MFN case (i.e., figure 4), it can be seen that the IEEE 802.22 WRAN standard is more susceptible to DVB-T2 interferences in a MFN configuration: e.g., to achieve a BER equal to 2×10^{-4} for a code rate equal to 5/6, in the SFN case a C/I above 10dB is needed, while in the MFN case a higher C/I is needed (i.e., about 2 dB higher).

6.2 Guard band and traffic load effect on the 802.22 signal

Figures 5 and 6 show the C/I evaluated as a function of the guard band from 0 to 10 MHz, in order to maintain a BER equal to 2×10^{-4} for a 802.22 transmission coexisting with a DVB-T2 signal typical for a SFN (i.e., figure 5) and MFN (i.e., figure 6) network configuration. For these measurements, three 802.22 configurations corresponding to different traffic loads have been considered. Only the right part of the adjacent spectrum has been considered in order to simplify the graphical representation. The lower, left part of the spectrum, presents a quasi identical behaviour.

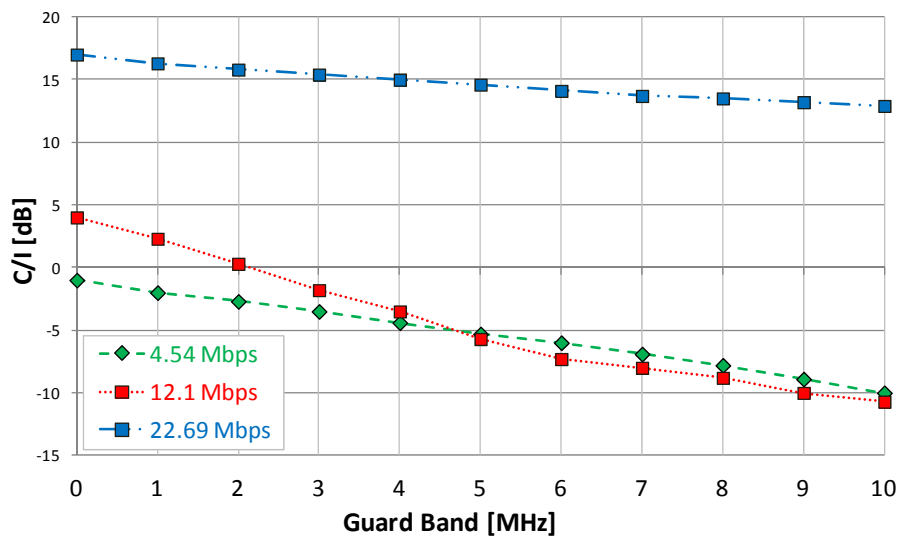


Fig.5. C/I as a function of the guard band in order to maintain a BER equal to 2×10^{-4} for a 802.22 transmission coexisting with a SFN DVB-T2 signal

As previously described, the worst case in the considered scenario is the outdoor scenario when the CPE is in LoS with the DTT antenna at a distance that maximizes the interference. The obtained results show how the higher the traffic load of the 802.22 configuration, the more it suffers from the presence of DTT signals. Higher traffic load signals, such as the 22.69 Mbps 64 QAM signal have a spectrum close to

white noise which is more disturbed by a similar shaped signal as it is the case of both the SFN and MFN DTT signals (64 QAM and 256 QAM respectively).

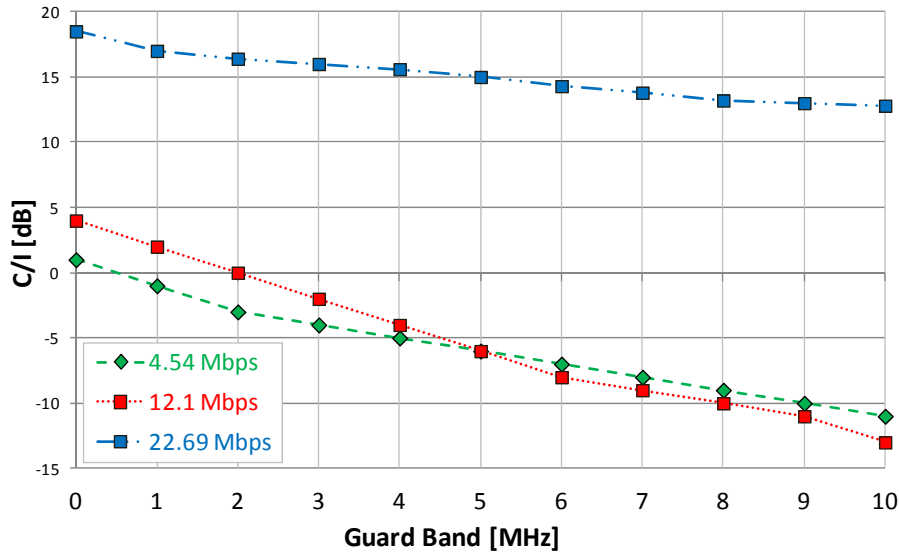


Fig. 6. C/I as a function of the guard band in order to maintain a BER equal to 2×10^{-4} for a 802.22 transmission coexisting with a MFN DVB-T2 signal

For the case of CPEs inside a building (i.e, figure 1, case B) the C/I can be extrapolated by subtracting a penetration loss of 6dB.

6.3 Coexistence analysis

In this section, based on the results of the previously presented measurements, the link budget for the coexistence in the first adjacent channel is performed. The 802.22 CPEs can be of two types: personal portable or stationary fixed, the latter being considered as the worst case scenario for the coexistence analysis. Furthermore, for the link calculations we used the least robust configuration for the CPE which is, according to the curves in figure 3 and 4, the 64-QAM with code rate 5/6.

Table 2 shows the link budget parameters for an outdoor 802.22 CPE with LoS between the CPE and the fixed DTT antenna.

The required PR for a 802.22 CPE to avoid interferences generated by DTT transmissions can be calculated from the minimum receiver sensitivity requirement P_{min} , by subtracting the DTT interference I and adding the receiver desensitisation value δ . This value is caused by the odd order intermodulation produced within a receiving chain, with a typical value of 1 dB [38].

Table 2 Link Budget Parameters

802.22	Fixed CPE	Portable CPE	BS	DVB-T2 reception	
Parameter	Value	Value	Value	Parameter	Value
Noise Figure	6 dB	6 dB	6 dB	Noise Figure	7 dB
Max TX Power	4 W	100 mW	4 W	Antenna Gain	9.15 dBi
Antenna Gain	11 dBi	11 dBi	6 dBi	Height	10 m
Height	10 m	2 m	250 m	Pattern	Dir
Pattern	Dir	Dir	Omni	Max RX signal (antenna input)	-35 dBm
Bandwidth	8 MHz	8 MHz	8 MHz		
Min RX Sensitivity (64-QAM)	-89.6 dBm	-89.6 dBm	-93 dBm		

The receiver minimum sensitivity level, P_{min} , is defined as the minimum power, measured at the antenna port, at which the BER performance is equal to the required limit (2×10^{-4}). The equation is given as follows:

$$P_{min} = N_{Ref} + NF + BW + SNR + RX_{Margin} + I_A \quad (1)$$

where N_{Ref} is the Reference Thermal Noise Density, NF is the noise figure (i.e., 6dB for the CPE), BW is the effective channel bandwidth calculated as $10 \times \log(8\text{MHz})$, SNR is the reference normalized signal-to-noise ratio for a BER performance of 2×10^{-4} where the values includes an 1.5dB decoder implementation margin for 64-QAM, RX_{Margin} is the receiver implementation margin (i.e., 2.1 dB for CPE) accounting for the coupling loss and pre-amplification filter loss, and I_A is the interference allowance (i.e., 1 dB for the CPE) to cover for the impact of local interference at the receiver. Taking into consideration the above values, a minimum receiver sensitivity for a 802.22 CPE is $P_{min} = -89.6 \text{ dBm}$

In real operational conditions, the maximum signal level P_{RXMax} of a DVB-T2 receiver can handle at its input is -35 dBm [33]. The signal level P_{CPEMax} at the antenna input of the CPE, necessary to overcome P_{RXMax} and simultaneously maintain the required BER, can be calculated using the worst case assumption from the curves presented in figures 3 and 4. As such, taking into consideration a PR of 18.5, P_{CPEMax} has a value of -53.5 dBm. To calculate the link budget based on these constraints, the following equation can be used:

$$P_{CPEMax} = G_{DIR-BS} + P_{BSMax} - FSL + G_{DIR-CPE} - G_{RX-CPE} \quad (2)$$

where G_{DIR-BS} and P_{BSMax} are the antenna gain and the maximum transmission power respectively for a 802.22 BS, $G_{DIR-CPE}$ is the gain of the CPE antenna including feeder loss, G_{RX-CPE} the antenna discrimination (i.e., 0.45dB) and FSL is the free space loss.

By considering the previously calculated value for P_{CPEMax} together with the other values from table 2, the FSL can be calculated, obtaining a value equal to 106.5 dB which leads to a coverage area of 6.8 km. This means that in the presence of a maximum value of the DTT signal, as it can happen for DTT receivers located close to the transmitter, the functionality of a 802.22 outdoor CPE is limited to a maximum distance of 6.8 km from the 802.22 BS. The maximum nominal coverage of a 802.22 BS is, according to the standard [38], 20 km. This distance can be achieved, even for the previously mentioned worst case scenario, by using a notch filter [39] with at least 9.5 dB of attenuation.

7. Conclusions

This work presents the result of measurements to evaluate the performance of IEEE 802.22 WRAN system operating into the same coverage range of DVB-T2 system. The scenario focuses on mobile outdoor and indoor 802.22 CPE in rural environment coexisting with fixed DTT transmitter. The worst case is when the CPE is in LoS with the DTT antenna at a distance that maximizes the interference.

Several configurations of the IEEE 802.22 WRAN with all modulation types and different code rates provided by the standard have been considered. For the DVB-T2 signal, the typical settings for MFN and SFN broadcasting networks have been considered. A first measurement series has been performed to evaluate the BER values of the various transmission modes for IEEE 802.22 WRAN systems coexisting with a DVB-T2 system operating in the first adjacent channel. Then, the C/I values were evaluated as a function of the guard band in order to maintain a constant BER level for a 802.22 transmission.

The results show that for both the SFN and MFN configurations, higher modulation schemes with high data rates lead to a diminution of the 802.22 performance in the presence of a DTT interferer. The results show also that the IEEE 802.22 WRAN standard is more susceptible to DVB-T2 interferences in a MFN configuration.

The C/I values evaluated as a function of the guard band, in order to maintain the minimum BER level for a 802.22 transmission coexisting with a DVB-T2 signal, show how the higher the traffic load of the 802.22 configuration, the more it suffers from the presence of DTT signals due to the spectrum shape close to the one of a white noise signal.

The performed link budget analysis for IEEE 802.22 WRAN for the worst-case coexistence scenario, (i.e., fixed DTT reception with outdoor IEEE 802.22 WRAN reception) showed that the 802.22 BS coverage is reduced to a third of its maximum radius (i.e., 20 km). Nevertheless, maximum coverage can be still obtained using a simple notch filter at the CPE with at least 9.5 dBm of attenuation. Such a mitigation technique can be found also in the coexistence scenarios between DVB-T and LTE [26-28]. Indeed, the use of LTE imposes a low-pass filter to the DTT users to maintain coverage, whereas IEEE 802.22 WRAN suggests the use of filter in its own devices, making the standard more flexible to implementations. Comparing the link budget and the PR results to the ones obtained by [26-28] for LTE, it is noticeable a comparable robustness of the IEEE 802.22 WRAN to the LTE standard which currently represents the state-of-the art of cellular networks.

A further study considering a real scenario where different channels in the TVWS are simultaneously accessed is under planning, so as to assess the results of the present work in real operating conditions, taking into account the aggregate adjacent channel interference.

8. Acknowledgments

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