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Interference Issues for VANETs Communications in the TVWS in Urban Environments

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***Abstract* — Within the scenario of the proliferation of smart vehicles, a novel tendency is to exploit the cooperation between vehicles to create vehicular ad-hoc networks (VANETs) using the IEEE 802.11p standard. IEEE 802.11p includes Dedicated Short Range Communications (DSRC) between high-speed vehicles and between the vehicles and the roadside infrastructure in the licensed Intelligent Transportation System (ITS) band at 5.9 GHz. At such frequencies fading problems caused by Doppler effect and/or multipath adversely affect propagation, especially in dense urban environment. To reduce such propagation impairments the use of lower frequencies has been proposed in literature, namely the TV White Spaces (TVWS) in the UHF band. TVWS is the part of the spectrum licensed to broadcasters which is not occupied at a given time in a given geographical area on a non-interfering /non-protected basis with regard to primary services. This work analyses coexistence issues between DVB-T2 broadcasting and IEEE 802.11p transmission in the TVWS. Aim of the study is twofold: to evaluate the protection of DVB-T2 broadcasting services interfered by IEEE 802.11p communications as well as the impact of adjacent DVB-T2 services on IEEE 802.11p communications in the TVWS. The main outcomes of the study are the maximum transmission power level and bandwidth configuration of an 802.11p signal in the adjacent channel (i.e., TVWS) of an active DVB-T2 system whereas protecting the broadcast service, and the error rate curves for each allowed mode of IEEE 802.11p in the TVWS to evaluate the performance of VANETs communications coexisting with DVB-T2 regular services in the licensed TV band.**

***Index Terms*— VANETs, IEEE 802.11p, DVB-T2, interference, TVWS.**

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I. INTRODUCTION

Vehicular ad-hoc networks (VANETs) are wireless networks with constantly changing network topology, due to the mobility of the nodes. In this context, a specific standard, the IEEE 802.11p for wireless access in vehicular environments (WAVE), has been designed [1]. IEEE 802.11p enables the 802.11 family (Wi-Fi) [2] to support intelligent transport systems (ITS) allowing the exchange of data between vehicles (V2V) and between vehicles and infrastructure (V2I) in the 5.9 GHz band [3]. Unfortunately, the use of such high frequencies raises fading problems such as the Doppler effect and/or multipath that adversely affect propagation, especially in dense urban environments. To solve this drawback, researchers proposed the use of lower frequency bands [4], considering also that, for frequencies below the GHz, the system would be more robust in real urban traffic conditions due to the less severe impact of fading effects. This frequency range is currently divided mainly between digital terrestrial TV (DTT) broadcast services and cellular mobile services. For the DTT services the frequencies are allocated by a geographical-based planning to ensure reduced interference between adjacent TV channels. This allocation process leaves free channels in each territorial area, the so-called "TV white spaces" (TVWS) [5], which could be used to implement opportunistic ad-hoc short-range and low-power communication systems [6], such as systems based on the IEEE 802.11p standard.

DTT broadcasting worldwide relies on several standards. Among these standards the digital video broadcasting – terrestrial (DVB-T) is widely deployed with over 60 countries that have adopted it. The second-generation DVB-T2 has been already introduced in Europe as an extension of DVB-T, based on the 2009 specifications of the European Telecommunication Standardizations Institute (ETSI) [7].

The tolerance of DVB-T/T2 receivers to adjacent channel interference (ACI) has been quantified [8], revealing that transmission on adjacent channels can cause harmful interference if the output power of the transmission exceeds the maximum received interference

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power tolerable by the receiver. 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 [9][10].

In this context, this work proposes a coexistence study between VANETs communications based on IEEE 802.11p standard adapted to operate in the TVWS and DTT services based on DVB-T2.

A first measurement series has been carried out to determine the protection levels for DVB-T2 receiver interfered by IEEE 802.11p communication operating in adjacent channel (i.e., TVWS) at varying the carrier frequency for different operation modes of the IEEE 802.11p standard [11]. In particular, the Protection Ratio (PR), that is the minimum value of the signal-to-interference ratio (C/I) required to obtain a specified reception quality under specified conditions at the receiver input [12] has been evaluated.

For these measurements, the reception quality has been quantified using a subjective evaluation criterion: the absence of a picture error for a certain period of time, called picture failure (PF). PF is commonly used as impairment criteria for broadcasting services to determine the signal-to-interference threshold C/I_{th} at which the interfering signal source has degraded the TV reception to an unacceptable quality. TV reception is considered unacceptable in presence of picture break-ups during 30 consecutive seconds of observation period. [13][14][15]. These measurements allowed identifying the maximum transmission power level and bandwidth configuration of a 802.11p device operating in the adjacent channels and within the coverage area of an active DVB-T2 system whereas protecting the DTT service.

A second measurement series completes the coexistence study by reversing the view point, which is analyzing the performance of 802.11p devices operating in TVWS under DTT emissions based on DVB-T2. In particular, the bit error rate (BER) curves in the presence of adjacent DVB-T2 interference have been evaluated for each allowed mode of the IEEE 802.11p standard. For these measurements, to cope with real VANETs communication scenarios characterized by rapidly varying conditions due to changing topology of the networks of moving vehicles, multipath fading and Doppler effects have been considered. In [16] three different statistical distributions have been compared (i.e., Rayleigh, Rician and Lognormal) so as to choose the one causing the highest BER, hence the worst channel conditions. It is shown that the Rayleigh distribution generates the highest BER, while Rician distribution gives BER values between the Rayleigh and log-normal at mobile speeds of 30, 60, and 90 km/h when measured at the same distance. By the light of the above study, in our experiments a Rayleigh channel model has been considered, thus considering the worst condition case. Experiments have been performed under the assumptions of slow and flat fading which can be easily verified for IEEE 802.11p transmission in the TVWS in urban scenarios where the vehicle speeds is limited to 50 km/h.

In this study, the IEEE 802.11p PHY layer has been modeled on the transmitter and receiver side to transmit standard compliant signals in the TVWS, in order to evaluate the BER of the received signal in the presence of adjacent DVB-T2 interference. We tested different configurations of the IEEE 802.11p considering different bit rates, modulation types, and channel bandwidths 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.

The study allowed determining the maximum transmission power level and bandwidth configuration of an 802.11p signal in the adjacent channel (i.e., TVWS) of an active DVB-T2 system whereas protecting the broadcast service, as well as the BER curves for each allowed mode of IEEE 802.11p in the TVWS, thus evaluating the performance of VANETs communications coexisting with DVB-T2 regular services in the licensed TV band.

The rest of the paper is organized as follows. Section II describes the IEEE 802.11p physical layer, while section III illustrates the measurement set-up. Section IV describes the measurement methodology. The obtained results are discussed in section V. Finally, section VI presents the conclusions and future work.

II. IEEE 802.11P PHY LAYER

The IEEE 802.11p standardization process originates from the allocation of the dedicated short range communications (DSRC) spectrum band in the United States and the effort to define the technology for usage in the DSRC band [17]. The IEEE 802.11p is only a part of a group of standards related to all layers of protocols for DSRC based operations [18]. The IEEE 802.11p standard [19] is a MAC and PHY level standard. For the purposes of the present study the PHY layer has been fully implemented. The PHY layer is conceived to make small changes to the already existing 802.11 PHY, in order to optimize it for its use in vehicular networks. The IEEE 802.11p operates at a frequency of 5.9 GHz. The PHY layer in IEEE 802.11p is the same as in IEEE 802.11a

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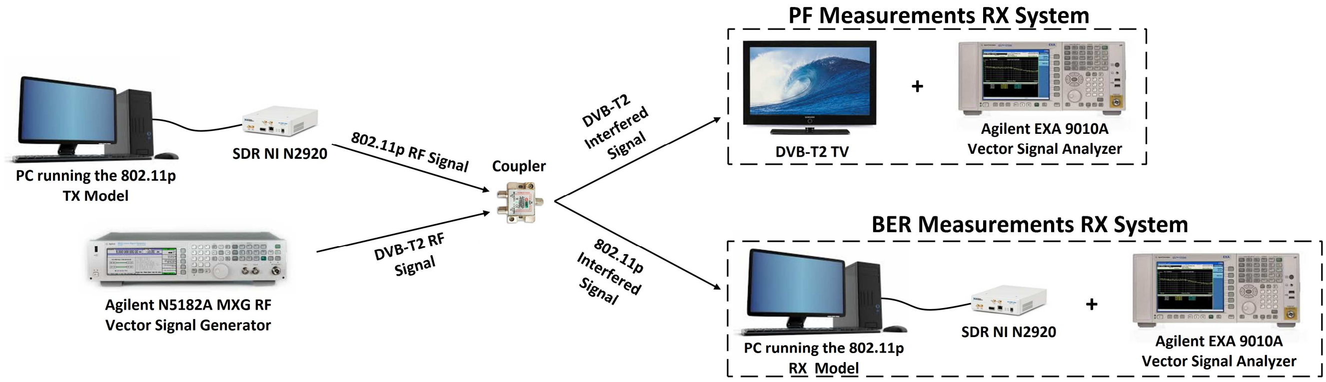

Fig. 1 Measurements Set-up.

except for the different sampling rate. It defines three different modes: 20 MHz, 10 MHz, and 5 MHz. The different modes can be achieved by using reduced clock/sampling rates. IEEE 802.11a usually uses the full-clocked mode with a 20MHz bandwidth. In comparison, IEEE 802.11p usually uses the half-clocked mode with a 10MHz bandwidth and the symbol length is doubled, making the signal more robust against fading.

The 20 MHz mode is optional. The 802.11p signal uses a carrier spacing reduced by half when compared to 802.11a.

In this work the IEEE 802.11p PHY layer has been modeled using Matlab/Simulink 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.

A. Transmission Side

The source bits are produced by a binary random generator block. The data is coded using convolutional coding, with a native rate of 1/2 with a constraint length equal to 7. The other code rates can be obtained by puncturing bits. Coded bits are then delivered to an interleaver. The interleaving scheme is defined by two permutations. The first permutation ensures that adjacent bits are modulated onto nonadjacent subcarriers and the second permutation ensures that the adjacent bits are mapped alternatively onto less and more significant bits of the constellation.

In the IEEE 802.11p standard four different types of modulation are used: BPSK, QPSK, 16QAM and 64QAM. The modulation type depends on the desired data rate, ranging from 1.5 to 27 Mbps. Data bits are mapped to subcarriers after modulation. The IEEE 802.11p uses OFDM modulation characterized by 64 sub-carriers (i.e., 1 sample per OFDM subcarrier), of which 48 used for the data, 12 void to reduce interference between adjacent channels and 4 pilot for the channel estimation. After insertion of pilot and guard, an IFFT is operated on them to create the OFDM symbol. A cyclic prefix is added at the beginning of each OFDM symbol. Finally the signal is converted from parallel to serial and prepared for transmission.

The 802.11p PHY layer signal is physically generated using the National Instruments USRP N-2920 Software Defined Radio (SDR) board connected to a PC running the implemented Matlab/Simulink software model.

The most important parameters characterizing the 802.11p signals transmitted during the measurements are shown in Table 1.

TABLE 1
MODULATION SCHEMES AND CODE RATES FOR 802.11P

Data Rates [Mbps]	Modulation Type	Coding Rate	BW [MHz]
1.5	BPSK	1/2	5
3	QPSK	3/4	5
9	16-QAM	2/3	5
13.5	64-QAM	3/4	5
3	BPSK	1/2	10
9	QPSK	3/4	10
18	16-QAM	3/4	10
27	64-QAM	3/4	10

B. Receiver Side

The synchronization of the signal assures that the symbol timing from the input complex waveform is recovered correcting the timing offset. Also, a frequency offset correction is implemented thanks to a frequency offset correction algorithm. Then, the cyclic prefix is removed to each received OFDM symbol and the OFDM

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demodulation is performed. After removal of pilot and guard, each symbol is demodulated.

Data are de-interleaved using a de-interleaver scheme complementary to the algorithm used at the transmission side. For the forward error correction (FEC) a lazy Viterbi decoder algorithm has been implemented: it is a maximum-likelihood convolutional code much faster than the original Viterbi decoder [20].

III. Measurement Set-up

The set-up for the measurements is shown in figure 1. The transmission side, a DVB-T2 signal and a IEEE 802.11p signal simultaneously transmitted and combined, is the same for the two measurement series. The DVB-T2 signal is generated using an Agilent N5182 Vector Signal Generator (VSG) and the Agilent Signal Studio Toolkit. Two typical settings for the MFN and SFN broadcasting networks were considered: 8K FFT size, 256QAM modulation, 1/128 guard interval, code rate 3/5, PP7 pilot pattern for MFN networks and 64QAM modulation, 1/16 guard interval, code rate 3/5 and PP4 Pilot Pattern for SFN networks. The 802.11p signal is RF modulated and transmitted using a NI N2920 SDR platform connected to a computer running the transmission Matlab/Simulink model described in section II. The 802.11p signals used for the measurements are of a pulsed nature, which allowed considering the intrinsic time variance for a typical vehicular transmission.

For the PR measurements, the combined RF signal is received both by a DVB-T2 receiver and by the Agilent EXA9010A Vector Signal Analyzer (VSA). The measurements on the power of the two signals (i.e., DVB-T2 and 802.11p) are crosschecked using as reference the VSA.

For the BER measurement series, the 802.11p interfered signal is received both by means of a NI N2920 SDR platform connected to a computer running the reception Matlab/Simulink model described in previous section, and by the Agilent VSA.

IV. Measurement Methodology

A. PR Measurements Series

Transmission on adjacent channels can cause harmful interference if the output power of the transmission exceeds the maximum received interference power tolerable by the DTT receiver. The parameter to evaluate this influence is the PR that quantifies the threshold value of the signal-to-interference ratio C/I_{th} required to obtain a specified reception quality under stated conditions at the receiver input [11]. For these measurements, the reception quality was quantified using a subjective evaluation criteria: the absence of PF [13][14][15], during a minimum observation time of 30seconds [14]. In order to evaluate the performance of a DVB-T2 system interfered by 802.11p transmission, PF has been monitored for different bit rates and bandwidths of the IEEE 802.11p standard.

Preliminary measurements have been performed, showing that the set-up conditions are frequency invariant within the UHF band, therefore, without losing generality, the TV channel 44 (i.e., $f_c = 658$ MHz, $B_c = 8$ MHz) has been considered in this study to report the results. The interfering 802.11p signal is transmitted on every adjacent channel starting from the first adjacent channel up to the ninth adjacent channel of the DTT signal on each side of channel 44. In this frequency range, the maximum transmission power levels of a 802.11p signal has been obtained in order to respect the condition for absence of PF for a DVB-T2 receiver. The following test procedure is used to measure the C/I_{th} for all adjacent channels:

1. The sensibility of the tested DVB-T2 receiver is measured with the Agilent VSA finding an average power level of -73 dBm. Thus, the DVB-T2 signal power level C was set to -73 dBm. This can be considered the worst operative case. The DVB-T2 signal power level is measured using the Agilent VSA with effective bandwidth of 7.61 MHz.
2. The 802.11p interfering signal is initially set to a power level of -20 dB below the sensibility of the tested receiver. This power level (i.e., -93 dBm) has been measured with the Agilent VSA.
3. The signal power level of the 802.11p interference is then adjusted at the output of the SDR board. The objective is to find the power level of the 802.11p signal above which the received and decoded TV signal starts to degrade (i.e., PF point).
4. The power level of the interferer is measured in the channel bandwidth of the receiver.
5. The C/I_{th} is calculated from steps 2 to 4.
6. Steps 2 to 5 are repeated for each of the channels from $N - 9$ to $N + 9$.
7. Steps 2 to 6 are repeated for a 802.11p signal characterized by a 10 MHz and a 5 MHz bandwidth, considering all the bit rate values as in the IEEE 802.11p standard.
8. Steps 1 to 7 are repeated for two different configurations (MFN and SFN) of the DVB-T2 signal.

B. BER Measurements Series

In BER measurement series again channel 44 is considered. The transmission frequency of the 802.11p

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signal is set to the central frequency of the first adjacent channel (i.e., $f_c = 666$ MHz). To characterize the Rayleigh fading channel model, the speed of the IEEE 802.11p transmitter and receiver is supposed to be constant during all the measurements: 50 km/h speed has been chosen so as to reproduce the worst channel conditions in VANETs communications in urban environment. Slow and Flat fading assumptions have been verified for every mode of IEEE 802.11p. The distance between IEEE 802.11p transmitter and receiver has been considered constant with a mean value equal to 5 meters, which is a mean distance between two flanked vehicles. The position of the DVB-T2 interferer is fixed.

The following test procedure is used to measure the BER for different bit rates and bandwidths of the IEEE 802.11p systems interfered by a DVB-T2 system operating in the adjacent channels:

1. The transmission power level of the DVB-T2 signal (I) is set to - 60 dBm and is fixed during all the measurement. This value ensures that the TV receiver is working at least 10 dB above the interference free PF threshold;
2. The transmission power level of the 802.11p signal is initially set considering the PR value to respect the condition for the minimum PF level of a DVB-T2 receiver, as calculated in the first measurement series (i.e., in section IV.A);
3. Starting from the level set at point 2, the power level is decreased to evaluate the performance of the IEEE 802.11p receiver, in terms of resilience to the DVB-T2 interference;
4. The RMS power level of the 802.11p signal (C) is measured in the considered channel bandwidth using the Agilent VSA to calculate the corresponding signal to interference C/I ratio;
5. The BER after the Viterbi decoding is evaluated;
6. Steps 2 to 5 are repeated for a 802.11p signal characterized by a 10 MHz and a 5 MHz bandwidth, considering all the bit rate values as specified in the IEEE 802.11p standard.
7. Steps 1 to 6 are repeated for two different configurations (MFN, SFN) of the DVB-T2 signal.

V. Results

In this section the results obtained from the PR and BER measurements are shown.

A. PR Measurements Results

Figures 2 and 3 respectively show the results for different bit rates of a 10 MHz and 5 MHz 802.11p signal interfering a DVB-T2 signal typical for a MFN network configuration.

Figures 4 and 5 respectively show the results for different bit rates of a 10 MHz and 5 MHz 802.11p signal interfering a DVB-T2 signal typical for a SFN network configuration. For the sake of clarity only a subset of the measured curves have been reported, corresponding to equally distributed bit rates in the range allowed by the 10 MHz and 5 MHz modes.

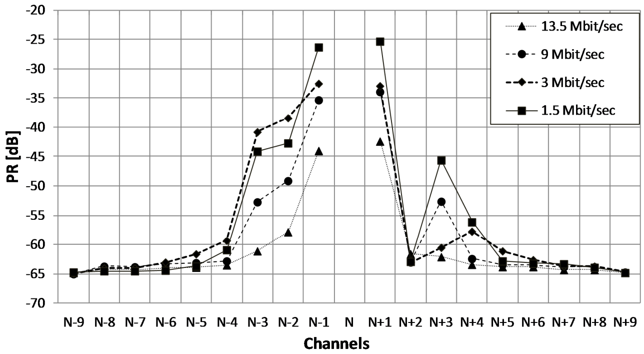

Fig.2 MFN DVB-T2 into 5 MHz 802.11p protection ratio.

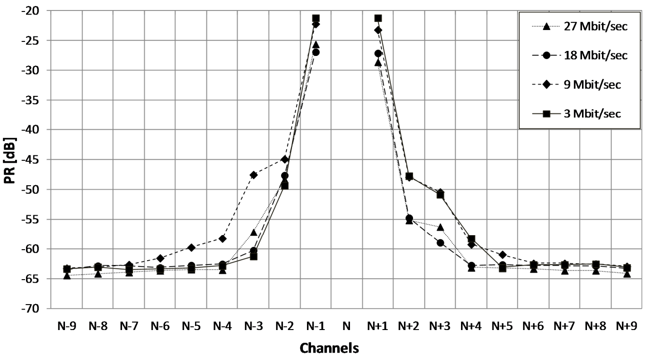

Fig.3 MFN DVB-T2 into 10 MHz 802.11p protection ratio.

By comparing the obtained results it can be noticed that the interference level changes with the bandwidth of the interfering signal. As expected, 5 MHz signals disturb less for all values of bit rate compared to 10 MHz signals both for the MFN and the SFN configuration. A 5 MHz bandwidth signal uses a subcarrier spacing of 78.128kHz while the 10 MHz bandwidth signal has subcarrier spaced at 156.25 kHz thus, producing less interference. Furthermore, it can be noticed that high interference is caused by signals with low bit rates. This criticality can be explained considering the spectral efficiency which is the ratio between the transmission rate offered to the user by a communication system and the bandwidth used for such communication [21]. A system with a higher spectral efficiency shows a more compact spectrum with an average lower power. This effect can be seen comparing two signals only differing for the bit rate, the first one

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having a low bit rate (for example 3 Mbit/s) and the second one characterized by a higher bit-rate (27 Mbit/s). The signal with lower bit rate has an average power level of -65 dB which is superior to that of the signal with a higher bit-rate, which is equal to -80 dB, both values measured with the Agilent VSA for the same transmission schemes. This difference accounts for higher PR for lower bit rates.

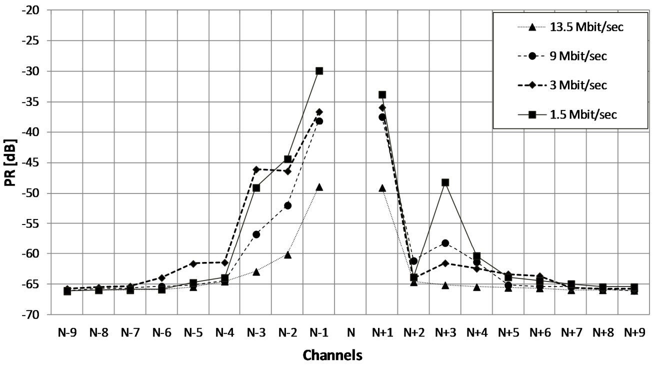

Fig.4 SFN DVB-T2 into 5 MHz 802.11p protection ratio.

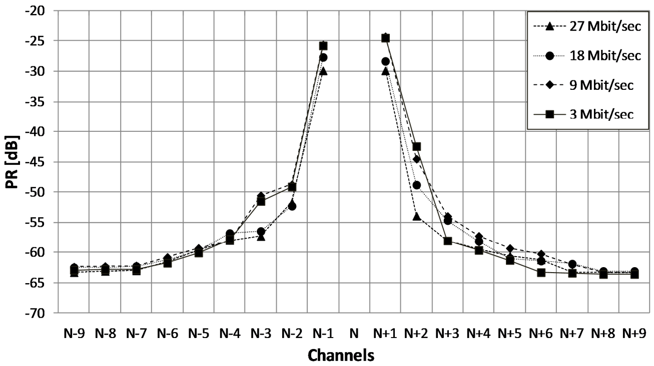

Fig.5 SFN DVB-T2 into 10 MHz 802.11p protection ratio.

Figures 2 and 4 illustrate that an 802.11p signal with 5 MHz bandwidth interferes a DVB-T2 signal over the adjacent channels especially for lower transmission bit rates and in particular in correspondence of the third adjacent channel $(N+3)$ where this effect is more pronounced. The problem does not occur for higher bit rates for both SFNs and MFNs.

Laboratory measurements on DTT receiver protection ratio values required to ensure adequate reception in the presence of interference from devices transmitting in the TVWS have been carried out for different DTT tuners (i.e., silicon and CAN tuners) in [22][23]. Some of these DTT tuners show a similar undesired effect, depending on the quality of the receivers.

Finally, comparing the curves obtained for the two considered DVB-T2 configurations for MSN and SFN, lower PR values have been obtained for 64QAM type (i.e., SFNs). The curves measured for the 256QAM modulation (i.e., MFNs) type differ up to 5 dB, showing a lower robustness (i.e., higher PR) of the MFNs. These results confirm the outcome of a previous work [24] that provides guidelines to optimize cognitive networks in the TVWS by choosing the parameters that best fit their needs in case of coexistence with DVB-T2 service operation.

B. BER Measurements Results

Figure 6 shows the BER results applying the Viterbi decoder to the received data of an 802.11p signal interfered by a DVB-T2 signal typical for a MFN network configuration, with different bit rates and bandwidths.

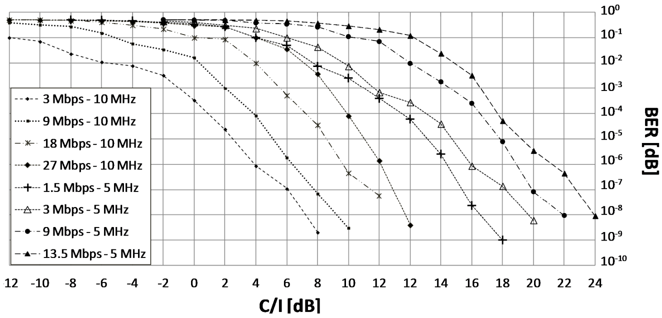

Fig.6 BER evaluation after Viterbi decoder for a 10 MHz and 5 MHz 802.11p signal interfered by a DVB-T2 MFN signal.

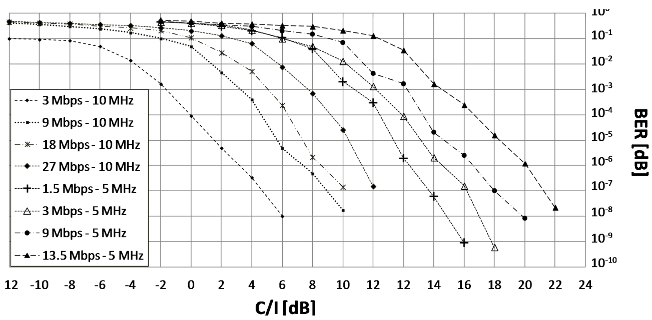

Fig.7 BER evaluation after Viterbi decoder for a 10 MHz and 5 MHz 802.11p signal interfered by a DVB-T2 SFN signal.

The 5MHz signals show higher BER levels compared with the 10MHz signals. This effect is due to the overlapping effect between the 10MHz 802.11p signal and the 8 MHz DVB-T2 signal, which adversely affects the quality of the received signal. Furthermore, the robustness increases with the bit rates. Higher modulation schemes with higher data rates are more robust to DVB-T2 interferences.

Figure 7 shows the BER results applying the Viterbi decoder to the received data of an 802.11p signal interfered by a DVB-T2 signal typical for a SFN network configuration, with different bit rates and bandwidths.

The results are similar to those obtained for the MFN case, leading to the same conclusion: 5MHz signals with higher bit rates are more robust to DVB-T2 interferences.

Comparing the curves obtained for the MFN case (figure 6) and for the SFN case (figure 7), it can be seen that the IEEE 802.11p standard is more susceptible to DVB-T2 interferences in a SFN configuration.

VI. Conclusions

This work presents a coexistence study between DVB-T2 broadcasting services and IEEE 802.11p transmissions in the UHF TV channels in urban evironments. A first measurement series allowed assessing the maximum transmission power level of an IEEE 802.11p signal while assuring the integrity of the DTT services for the typical MFN and SFN operation modes of a real DVB-T2 broadcasting network. To assure the protection of the DTT systems the reception quality was quantified assuming the absence of a picture failure during a minimum observation time of 30 seconds.

The results obtained for the investigated DVB-T2 transmission modes suggest that the effect of the 802.11p adjacent interference changes with its configuration. For the tested DVB-T2 receiver the worst operative case has been considered. The 802.11p interfering signal was initially set to a power level of -20 dB below the sensibility of the tested receiver and then adjusted at the output of the SDR board to achieve the required degradation (PF point) of the received and decoded TV signal. The bandwidth and the bit rate were the two monitored parameters.

A 5MHz bandwidth signal disturbs less for all values of bit rate compared to a 10 MHz bandwidth signal both for the MFN and the SFN networks configuration. For a 10 MHz bandwidth signal the most critical cases are for low bit rates. This can be explained considering that the spectral efficiency is high efficiency when using all the bandwidth, leading to a more compact spectrum with increasing bit-rate and a consequent decrease of the disturbance caused to the broadcasting signal.

Comparing the curves obtained for the two considered configurations, it could be noticed that lower protection ratio values have been obtained for 64QAM type. The 5 MHz case shows an undesired effect in correspondence of the third adjacent channel, even more pronounced for low bit rate values, depending on the quality of the receiver.

A second measurement series analyzed the performance of 802.11p devices in the presence of DVB-T2 broadcasting services. The BER of an 802.11p device after a Viterbi decoder has been evaluated in the presence of adjacent DVB-T2 interference. The results show a similar trend for both the SFN and MFN configurations, leading to the conclusion that higher modulation schemes with high data rates are more robust to DVB-T2 interferences. Moreover, the 5 MHz signals show higher BER levels compared with the 10 MHz signals, due to the overlapping effect observed in the 10 MHz case that adversely affects the quality of the received signal.

A further study considering real scenarios characterized by different environment conditions is under planning, so as to assess the results of the present work in real operating conditions.

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