Mobile Communication Networks and Digital Television Broadcasting Systems in the Same Frequency Bands: Advanced Co-Existence Scenarios

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Abstract. *The increasing demand for wireless multimedia services provided by modern communication systems with stable services is a key feature of advanced markets. On the other hand, these systems can many times operate in a neighboring or in the same frequency bands. Therefore, numerous unwanted co-existence scenarios can occur. The aim of this paper is to summarize our results which were achieved during exploration and measurement of the co-existences between still used and upcoming mobile networks (from GSM to LTE) and digital terrestrial television broadcasting (DVB) systems. For all of these measurements and their evaluation universal measurement testbed has been proposed and used. Results presented in this paper are a significant part of our activities in work package WP5 in the ENIAC JU project "Agile RF Transceivers and Front-Ends for Future Smart Multi-Standard Communications Applications (ARTEMOS)".*

Keywords

Co-existence of advanced wireless systems, GSM, HSPA/WCDMA, LTE, DVB-T/H/T2/-T2-Lite, ideal and fading channel conditions, SDR, BER, EVM.

1. Introduction

In our modern daily life there is a growing interest in different kind of multimedia services. Demands to provide these services (video image, audio and data) in superb quality (high data-rate) and with a constant level of Quality of Services (QoS) are rapidly increasing between users and markets. Moreover, the concept "transfers anything, at anytime, anywhere, to anyone, via any-path available" by means of any communication terminal must be also fulfilled. Consequently, a market is pulled by an increasingly connected world population asking for mobile access to the vast information resources through the internet and/or mobile, portable and fixed equipment [1].

These circumstances call for frequency-agile, multi-standard and multi-band terminals integrating the still used and upcoming mobile cellular standards and additional wireless communication standards for connectivity and positioning into more efficient radio architectures. In 2011 a new international project "Agile RF Transceivers and Front-Ends for Future Smart Multi-Standard Communications Applications (ARTEMOS)" [1] has been started which aims at developing architecture for implementing agile radio frequency (RF) transceiver capacities in future communication products.

One of the main purposes of this project is to develop new advanced RF technologies for smart equipments which can support many types of multimedia services, provided by different communication standards. In many countries around the globe, frequency spectrum that was previously reserved for still using wireless systems is being freed up for use under the upcoming ones. As a result, different kinds of wireless multimedia systems can operate in the same frequency bands. This phenomenon is called co-existence of communication systems. From the part of operators and broadcasters there is a great interest to explore impact of different co-existence scenarios on the performance of used wireless standards [2]. The technical and scientific work in the ARTEMOS project was subdivided in seven work packages (WPs) [1]. From these WP's the WP5 was partly focused on the exploring, measuring and evaluation of co-existences between advanced communications systems at different transmission scenarios. The main focus of this paper is to summarize and describe our achieved results in this work package.

The rest of this paper is organized as follows. The state-of-the-art in the field of co-existences between different communication standards is presented in Section 2. Section 3 contains a description of our proposed and realized universal testbed for co-existence measurement. A brief study of influence of co-existence interferences on QoS in High Speed Packet Access (HSPA) mobile networks is outlined in Section 4. In Section 5, influences of mobile interfering products on digital TV terrestrial broadcasting services, represented by GSM, LTE and DVB-T/H standards, are explored. In Section 6, the co-existences between upcoming advanced mobile TV and mobile networks, namely DVB-T2-Lite and LTE services, in ideal and non-ideal channel conditions are investigated. Study of possible co-existence between LTE using cognitive radio technology and DVB-T2 services broadcasted by SISO/MISO technology is outlined in Section 7. Finally, conclusions and future work plans are given in Section 8.

2. Related Works

In recent years the problem when using different wireless technologies in the same frequency band is that most of them are not compatible with each other [3]. In the case when adjacent or same frequency bands are allocated for these technologies, sharing is necessary [4]. As a result, undesirable interactions and mutual interferences can occur between them. The arising risks of co-existences negatively affect the quality of provided services of considered wireless systems. Therefore, measurement, monitoring and possible suppression of these co-existences is becoming one of the most important issues [5]. In literature many research works can be found which deals with this topic.

Attention is currently focused on two main areas. The first one defines co-existence and adjacent channel interferences between different wireless systems and networks of the same or similar kind [6]-[9]. In [10], co-existence interference of Long-Term Evolution (LTE) systems existing micro cell and/or pico cell in GHz band was investigated. Potential mutual interferences between wideband code division multiple access (WCDMA) user equipment (UE) during upload and one Global System for Mobile Communications (GSM) mobile station (MS) at downlink were explored in [11]. In [12] interferences from co-existence between two-tier orthogonal frequency division multiple access (OFDMA) networks, e.g. microwave access (WiMAX) and LTE was studied. Researchers in [13] analyzed the co-existence of a primary and secondary cognitive network when both of them use the IEEE 802.11 standard. Generally, the common result of these studies was that mutual interferences can decrease the quality and the throughput of still used 3G and new 4G mobile networks.

In the second area, the attention is focused on modeling, simulating and measuring of unwanted interferences from co-existing scenarios, occurring between different communication standards [14]. Dependence of the degree of digital TV (DTV) signal degradation on the bandwidth of another system – terrestrial truncated radio (TETRA), operating in adjacent channel, is explored in [15]. Kang et al. investigated and described the decreasing performance of Digital Video Broadcasting –Terrestrial/Handheld (DVB-T/H) system in a channel with co-channel interference and its possible suppression [16]. On the last World Radio Conference (WRC-2007) it was decided to allocate the $790 \div 862$ MHz frequency band to mobile services in Europe from 2015. Due to this, unwanted co-existence scenarios between still used and upcoming DTV (DVB-T/H/T2/T2-Lite) and mobile systems (GSM, UMTS, HSPA, LTE, LTE-A) can occur. First theoretical analysis of mutual co-channel interferences between these standards have been presented in [16]-[19]. In other works [20]-[23] destructive interferences from DVB-T to LTE services and vice versa has been proved.

As it can be seen from presented references the co-existence between different mobile networks and DVB systems is an actual topic that needs to be carefully analyzed. In this paper we explore and measure advanced co-existence scenarios between still used and upcoming (advanced) mobile and DTV services. We focus on the monitoring of physical layer parameters of mobile and DVB services which have not been deeply explored yet. All our results, summarized and discussed in this paper, have been in details published in [24]-[26] and [29].

3. General Measurement Method

In this section, a multifunction measurement testbed and its setup for measuring the interaction between mobile and DVB systems and vice versa is introduced.

A general block diagram for the measurement and analyzing of different kinds of co-existence scenarios between mobile networks and DVB broadcasting services is proposed in Fig. 1. Essentially, this configuration can be divided into two main parts. The first one includes signal sources. The second one is the measuring blocks, where the impact of co-existences on performances for a chosen type of multimedia systems can be analyzed.

The basic principle of the general measurement method is as follows. At the beginning, the types of input RF signals must be defined. These can be real received or synthetically generated signals. Real RF signals of DVB (DVB-T/H/T2/T2-Lite) services and 3G/4G networks (GSM, UMTS, LTE) are acquired by common receiving equipment (antennas, low noise amplifiers). Furthermore, multimedia services are generated synthetically by laboratory devices. In the end, the complete system configuration (DVB and/or mobile services) of the synthesized signal is set and modulated to a required RF carrier. These input signals (real and/or generated) are then combined and divided in the signal combiner/splitter unit and as a combination of the service signal under interest and jamming signal fed to the measuring devices.

Based on the proposed and above described block diagram, many types of co-existences (mutual interferences, interferences in the same or adjacent frequency channel) between different kinds of communication systems can be measured. Depending on the explored co-existence scenarios a specific laboratory arrangement with appropriate signal frequency unit (SFU), signal generators, and measurement devices can be realized. All measurement equipments, used in our research activities, are supported by the SIX research center [30].

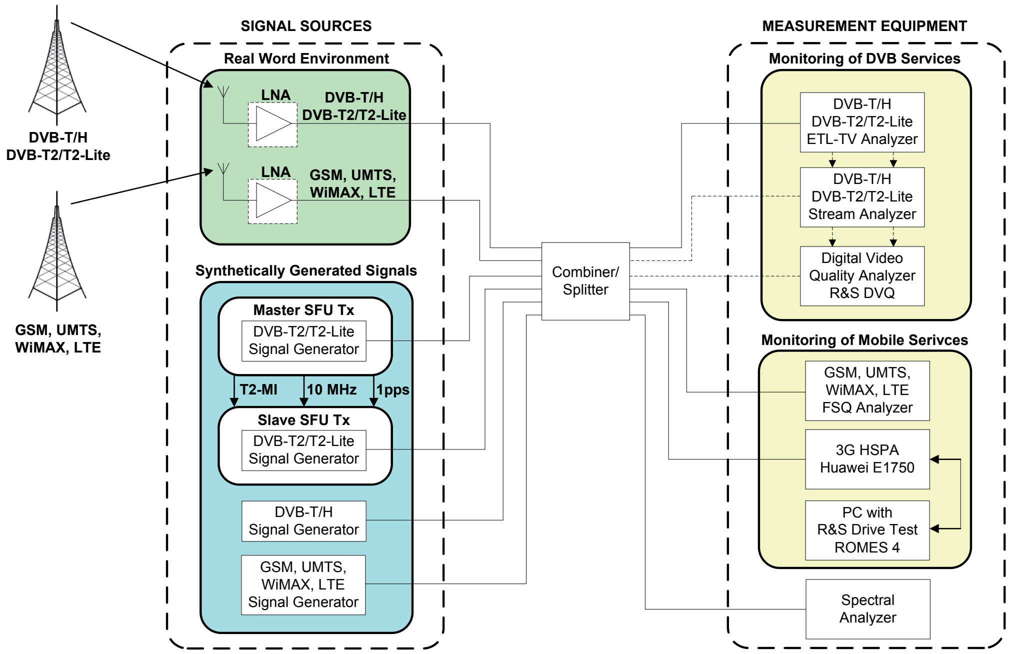

Fig. 1. General block diagram of a workplace for measuring interactions between wireless mobile networks and DVB services.

4. Overlaying Interfering Products Affecting 3G UMTS Networks

Nowadays, a number of user equipments (UE) and density of wireless mobile networks is rapidly increasing. Moreover, all kinds of these networks must provide multimedia services in excellent quality and with a constant level of QoS. The best option providing these services is in the ultra high frequency (UHF) spectrum, especially from 790 MHz to 862 MHz. On the other hand, many bands are allocated to more than one wireless service. Due to this, sharing of frequency spectrum between mobile and other wireless systems (e.g. DVB services) is inevitable. This would result in a high probability of different kinds of interferences between them [7], [18], [25].

As a result, mutual co-existences and unwanted interferences between wireless standards, e.g. GSM, Universal Mobile Communication Systems (UMTS), LTE, Wireless Fidelity (Wi-Fi) and other services can occur and can negatively affect the performance of these systems. Exploiting of the same position of Base Transceiver Stations (BTS) by multiple mobile services and even different operators causes various kinds of interferences, like co-channel, inter- and intra-channel, inter- and intra-system interferences [4], [11]. Furthermore, the interferences are also generated due to nonlinearities of amplifiers [24]-[26]. With a sufficient power the mixed signals could overlay inter or intra system channels and thus interfere useful signals of surrounding wireless services.

Based on these theoretical assumptions, our attention was focused on the challenges of the agile multi standard communication implementations in embedded platform or even in systems on a chip (SoC) which can support 3G/4G network services. In this section we examine the reliability of 3G network performance depending on an interfering signal. Interfering signals can come from many types of wireless communication systems (GSM, UMTS, LTE, Wi-Fi or DVB services) which overlap the useful channel. Our purpose is to explore the relation between unwanted interferences and the performance of a 3G network.

4.1 Description of Measurement

Our measurement setup is as follows. According to the described general block diagram (see Fig. 1) the antenna (Quad Band GSM/UMTS) receives radio signals of a 3G network. In the second input block ("Synthetically Generated Signal") an interfering signal is generated by R&S SMU 200A Arbitrary Generator. These two signals are combined in a power combiner. At the output a standard spectrum analyzer monitors the frequency spectrum of the combined signals. The PC equipped with R&S Drive Test ROMES4 is used for the monitoring and analyzing of HSPA network parameters. The radio connection is provided by 3G HSPA stick Huawei E1750 [27] via its external antenna connector. The UE is then connected via USB interface to this PC.

Our proposed measurement tests the vulnerability of the HSPA network to interferences. The waveform of the interfering (bandpass) signals is produced with the R&S SMU WinIQSIM2 Arbitrary Waveform Generator. Eight signals with different possible bandwidths, originated from GSM, UMTS, LTE and WiMAX systems were generated. In details, tested bandwidths were 0.2, 0.4, 0.8, 1.4, 2.8, 3.5, 4 and 5 MHz.

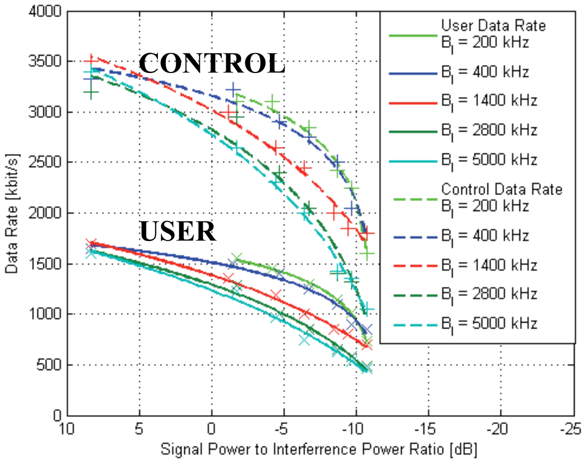

Fig. 2. Dependences of "User" and "Control" data rates on the signal to interference power ratio (PR) for different bandwidth of interfering signals.

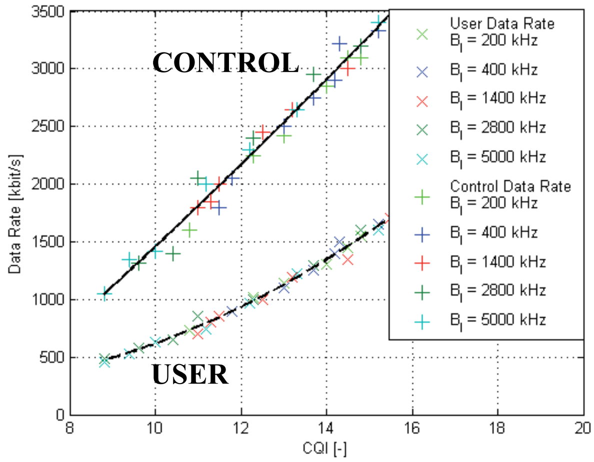

Fig. 3. User data rate (USR), Control information data rate (SCCH) on MAC layer in dependence of the CQI values for different bandwidth of interfering signals.

After the setting of all devices, data transfer was set up for both transfer paths (downlink and uplink) using FTP protocol. The linked UARFCN channel number was 10812, operating carrier frequencies 2162.4 MHz and 1972.4 MHz for downlink (DL) and uplink (UL), respectively. Next, the interfering signal, modulated on the carrier frequency of downlink channel, was added. During the measurement the level of the interfered channel was constant -61 dBm, only the level and bandwidth of the interfering signal were changing. The power level of the interfering signal is expressed as [25]:

$$PR = L_{SIG} - L_I \tag{1}$$

where PR [dB] is the signal power to interference power ratio, L_{SIG} [dBm] is the power of the linked HSPA channel and L_I [dBm] is the power of the interfering signal, all measured with a spectrum analyzer in 5 MHz channel.

4.2 Measurement Results

Measuring the performance of the 3G HSDPA DL transmission with co-existence interferences was carried out. Moreover, the QoS of the HSDPA network was monitored in the application ROMES4.

Dependences of *"User"* and *"Control"* data rates on the PR ratio are plotted in Fig. 2. When the PR ratios are positive (the power of the interfered signal is higher than the power of the interfering one), then the immunity of the linked HSDPA channel to the interfering noises is high. In this case the fluctuations of the observed data rates for interfering signals with lower bandwidth are negligible. Of course, at negative PR ratios the situation is opposite. Decreasing of both data rates (*User* and *Control*) is more remarkable and also depends on the bandwidth of the interfering signal. The difference between the user data rates between 200 kHz and 5000 kHz bandwidths of the interfering signal for the same ratio PR = -5 dB is almost 500 kb/s. More details and results can be found in [25].

Relation between the data rates and Channel Quality Indicator (CQI) is shown in Fig. 3. The obtained results are divided into two fields. The upper one (labeled as *Control*) shows the dependences of both the data rate on MAC layer and data rate of control information transmitted in Shared Control Channel (SCCH) on the CQI parameter at different bandwidths of interfering signals. The SCCH and MAC values were very similar, practically same. The under curve represents the same dependence, but in this case, the user data rate is monitored. From the results it can be seen that the user data rate and both MAC and SCCH data rates can be reduced more than three times till to disconnection.

5. Performance of DVB-T/H Services Affected by Interfering Products of GSM and LTE Mobile Networks

As it was mentioned above, on the last WRC-2007 it was decided to allocate the 790 ÷ 862 MHz frequency band to mobile services in several world regions [18], [21]. Due to this decision, the upper frequency band allocated for the DVB-T/H (Terrestrial/Handheld) system in Europe (606 ÷ 854 MHz) is co-allocated to mobile services. This should cause undesired mutual interferences between GSM and/or LTE and DVB-T/H services which are mainly used in Europe and in some other countries outside Europe.

From the viewpoint of the increasing demand for stable multimedia services the interference, as a product of co-existence between different wireless technologies, becomes a critical issue. Therefore, exact measurement and monitoring of co-existing wireless systems is necessary. In this section we will focus on exploring of the influence of GSM and LTE mobile network interfering products on DVB-T/H broadcasting services. Moreover, our attention is also devoted to the monitoring of affection of transmission parameter signaling (TPS) carriers, used in DVB-T/H system as reference information for the receiver [26], [28].

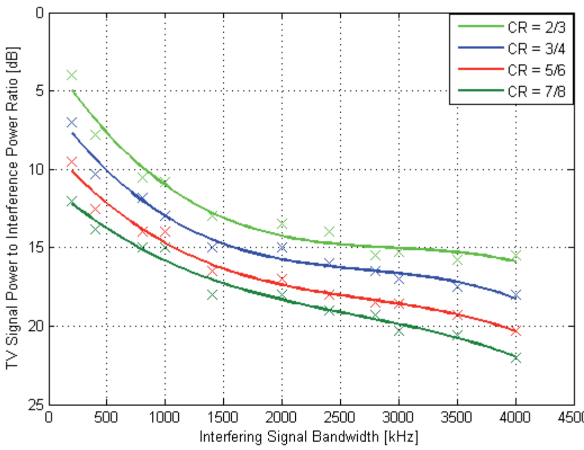

Fig. 4. Dependence of the TV signal power to interference power ratio on interfering signal bandwidth. The measurement was done for the FEC code rates (CR) which are the most widely used in DVB-T/H.

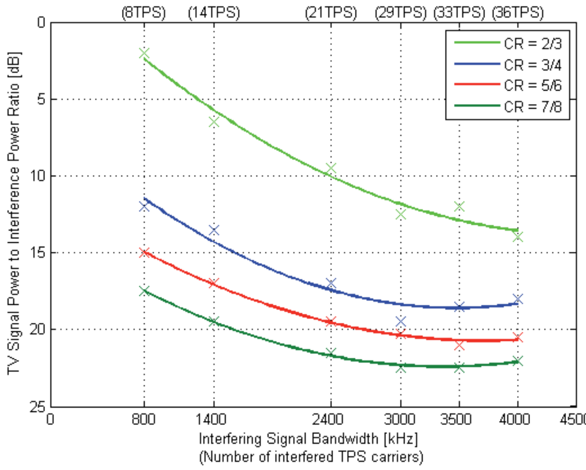

Fig. 5. Dependence of the TV signal power to interfering signal power ratio on the interfering signal bandwidth for dedicated TPS interfering signals. The measurement was done for the FEC code rates (CR) which are the most widely used in DVB-T/H.

5.1 Theoretical Background and Conception of the Measurement

DVB-T/H [28] is still used DVB European standard for broadcasting audio, video and data TV services using orthogonal frequency division multiplexing (OFDM) modulation. The OFDM transmitted signal is organized in frames and each of them includes 68 OFDM symbols, consisting of K subcarriers. Depending on the OFDM mode, K equals 1705 (2K), 3409 (4K) and 6817 (8K). All symbols in an OFDM frame contain data and reference information. Moreover, each OFDM frame contains special types of subcarriers. In these frames TPS carriers are used for transmitting system information from the transmitter to the receiver. More precisely, TPS carriers are used for the signaling of parameters related to the transmission scheme (code rate, OFDM mode, type of modulation, guard interval and frame number). Moreover, each TPS carrier is identified by as initialization, synchronization and redundancy bits and is related to one OFDM frame. It can be expected that, when these carriers are influenced by interfering products from mobile networks then a receiver (e.g. set-top-box) will have problems with synchronization and processing of the received TV signal. Therefore, the impact of the affected TPS carriers on the valid signal reception and synchronization is explored [26]. Moreover, the quality of the received and decompressed DVB-T content is analyzed, too.

Overall, our purpose is to explore how the level of overlaying GSM and LTE interfering products affects the quality of DVB-T/H services with various forward error correction (FEC) code rates. The conception of the measurement is very similar to the measurement presented in the previous section. The interfered DVB-T signal is generated in the SFU from R&S at the frequency of 778 MHz. It works in 8K OFDM mode using 64QAM modulation and with a bandwidth of 8 MHz. Interfering bandpass signals are produced in WinIQSIM2 software.

The narrowest and widest interfering signals have 200 kHz and 4 MHz bandwidth, respectively. They are positioned on the center of the DVB-T carrier frequency. For the “nosing” just the desired OFDM subcarriers (TPS) we use a generated signal with a bandwidth of approx. 1 kHz, which corresponds to the TPS subcarrier bandwidth, used in DVB-T/H 8K mode [28]. Furthermore, we concatenated exact number of carriers to overlay the TPS subcarrier frequencies. The equation can be found in [26]. We also aggregated such a number of interfering sub signals which corresponds to the specified channel bandwidth of interfering bandpass signals.

5.2 Obtained Results

The interfered (DVB-T/H) and interfering signals (GSM and/or LTE) are combined and the results are analyzed using the DVB-T/H measurement receiver, spectrum analyzer and digital video quality analyzer (see Fig. 1). Firstly, the dependence of the digital TV signal power to interfering signal power ratio [in dB] on the bandwidth [kHz] of interfering signal was explored. The results are related to the subjective video image criterion, based on structural similarity (SSIM) [31]. The limit for the sufficient subjective video quality was set as the value of SSIM, equal to 50%. The measuring technique consists in keeping the constant level of the DVB-T/H signal, while the level of the interfering signal was gradually increased to satisfy the minimum [26] of the DVB-T/H receiver input level (-76.9 dBm). The recommended level of TV signal is 50 dBμV (-58.8 dBm) and we set the level on the value 48 dμBV (-60.8 dBm). Obtained results are plotted in Fig. 4. The measurement was done for all the possible FEC code rates (CR), used in the DVB-T/H standard, except 1/2. With the increasing bandwidth of the interfering signal the performance of the DVB-T/H is decreasing. The worst results were obtained at code rate 7/8 (lowest error protection).

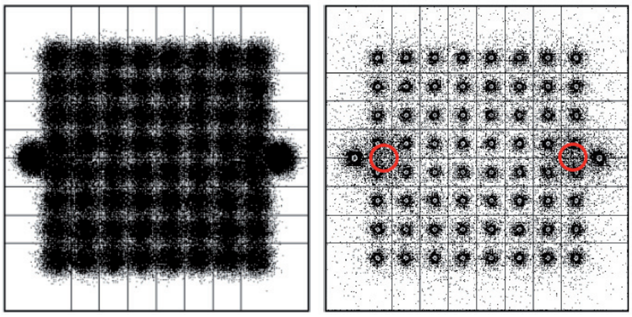

Fig. 6. Constellation diagram of 64QAM in the DVB-T/H system, when the DVB-T/H RF signal is highly affected by the GSM/LTE network (left). Picture on the right shows the interfered TPS carriers (denoted by red circles). The MERs are equal to 19 dB and 25 dB, respectively.

Secondly, the dependence of the digital TV signal power to interfering signal power ratio on the bandwidth of the interfering signal for dedicated TPS interfering signals was explored. The results are shown in Fig. 5. The level of the DVB-T/H signal was equal to -82 dBm. The number of interfered TPS carriers depends on the bandwidth of the interfering signal. It is clearly seen that this dependence has impact on the received TV signal quality. There is a significant difference between the highest (2/3) and lowest (7/8) FEC protection. Moreover, for code rates from 3/4 to 7/8, when the interfering signals have higher bandwidth than 2400 kHz, the obtained TV to interfering signal ratios were changed minimally. An example or illustration of the constellation diagram when the TPS carriers are noised is uncovered in Fig. 6.

6. Co-existences between DVB-T2-Lite and LTE Portable TV Oriented Systems in Ideal and Fading Channels

Demands for the multimedia services in superb quality for mobile and portable devices are on the very high level. Requirements of owners of smartphones for video content in a high quality are still increasing. Unfortunately, today's most widely used DVB standards for broadcasting of mobile TV services (DVB-T/H/SH) cannot fulfill requirements on the system flexibility, spectral efficiency and compatibility. In case of mobile systems there is a high effort to increase the capacity and speed of wireless data networks and ensure continuous and stable download and upload. Therefore, advanced 2nd Generation of DVB-T2 [32]-[34] and LTE [35], [36] standards have been developed.

The DVB-T2 standard, thanks to the advanced coding system, constellation rotation, extended OFDM modes, various guard intervals and flexible pilot patterns, extends the range of most parameters of the DVB-T/H/SH systems. Moreover, a special system profile within the DVB-T2 system is defined, marked as DVB-T2-Lite [32], to provide mobile and portable services to handheld receivers. The LTE, as defined by the 3rd Generation Partnership Project (3GPP), is a very flexible radio interface that offers a high scale of adjustable system parameters (e.g. increased spectrum flexibility, simplified architecture, improved support for mobility). However, both of these systems can work in the same frequency bands [2], [5]. In this section we explore the impact of co-existing LTE services on the broadcasted T2-Lite services.

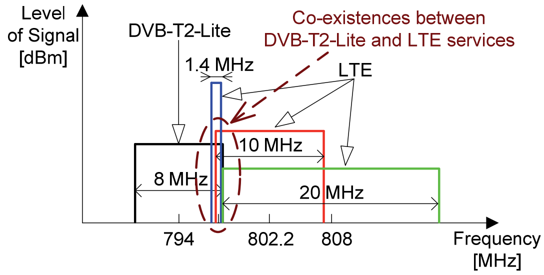

Fig. 7. Spectrum of analyzed co-existence scenarios between LTE (marked by blue, red and green colors) and DVB-T2-Lite (marked by black color) services.

6.1 Analyzed and Measured Co-existence Scenarios

Our attention is devoted to the co-channel scenarios, where T2-Lite and LTE services are operated in the same frequency band. The considered scenario is as follows. We have a common cell for DVB-T2-Lite and LTE services. The TV tower broadcasts DVB-T2-Lite services at a frequency of 794 MHz. In the same cell, a LTE base station transmitting a downlink signal, operates on 802.2 MHz. In the case, when the bandwidth of LTE signal is 10 MHz, it can interfere with the upper spectrum side of the T2-Lite signal. Therefore, LTE acts as an interferer on the mobile digital TV services. This could cause visible artifacts in the mobile TV reception and its complete failure. Decreasing of performance of the DVB-T2-Lite services depends on the level of the unwanted signal. Simple graphical presentation of the described co-existence scenario and other ones, explored in this section, is shown in Fig. 7.

Our purpose is to investigate the impact of the interfering LTE services (with different bandwidths and levels) on the DVB-T2-Lite ones and vice versa operating in the same frequency band. The principle of the measurement is as follows. The DVB-T2-Lite (interfered) signal is generated at a frequency of 794 MHz, works in 2K OFDM mode and uses 16QAM modulation. The LTE (interfering) services operate at frequencies from 791 MHz to 821 MHz and are generated as downlink signal in R&S SMU200A. The bandwidths of the LTE signals are 1.4, 10, and 20 MHz, respectively. Ten sub-frames were generated, where the used modulation types were used as follows: 3xQPSK; 3x64QAM and 4x16QAM. LTE transmits in the downlink, using frequency-division duplexing (FDD) mode [35]. More detailed system settings can be found in [29]. After sufficient generation of both services, they are combined and then the splitter is used for dividing this signal, which is measured with appropriate measuring devices [29].

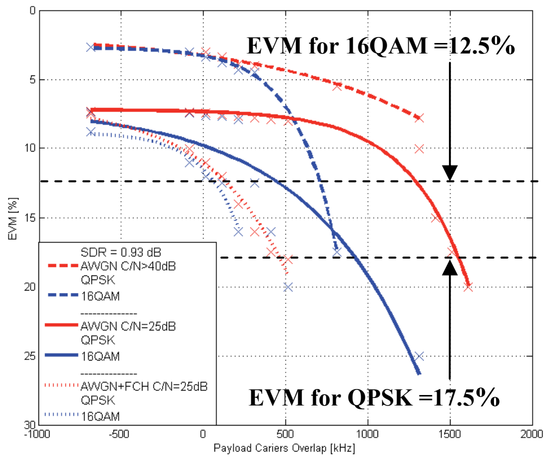

Fig. 8. EVM dependency, using QPSK and 16QAM modulations in the LTE system, on the level of frequency overlap between the DVB-T2-Lite and LTE services, working abreast in the same frequency band at ideal and portable (PI and EPA 5Hz) fading channel conditions.

6.2 Evaluation of Obtained Results

To evaluate the performance and QoS of the LTE system, error vector magnitude (EVM) was used [35]. EVM is a measure used to quantify the performance of a communication system. In LTE, it is a measurable vector in the In-Phase and Quadrature (IQ) constellation diagram between the ideal constellation point and the point, received by the receiver. Dependences of EVM of used modulations in the LTE system on the overlap of the payload carriers are shown in Fig. 8. Frequency overlap defines the level of channel overlaps between the co-existing DVB-T2-Lite and LTE channels in kHz. The obtained results are related to spectral density ratio (SDR) which is defined as the power ratio between LTE and DVB-T2-Lite per unit of the used bandwidth. Its calculation can be found in [29].

All the measurements were done with three channel environments. The first one is the Gaussian channel which is based on a direct signal path from the transmitter to the receiver. The second one is marked as Personal Indoor (PI) channel model and has been developed by the Wing-TV project for describing slowly moving (at a speed approx. 3 km/h) handheld indoor TV reception [37]. This channel model is based on measurements in the DVB-T/H single frequency network (SFN) and has paths from two different transmitter locations. The PI channel consists of 12 independent paths. The first path has Rice-Gauss and the remaining eleven ones have a Rayleigh-Gauss Doppler spectrum. Finally, in the LTE system, the EPA channel model is used to model the reference environment characterized by a low delay spread. The main parameters of this model are specified in [35]. The EPA channel consists of 7 independent paths. All the taps have a Rayleigh-Jakes Doppler spectrum. In addition to a multipath delay profile, the maximum Doppler frequency is specified for each multipath fading propagation condition. In our case it is 5 Hz.

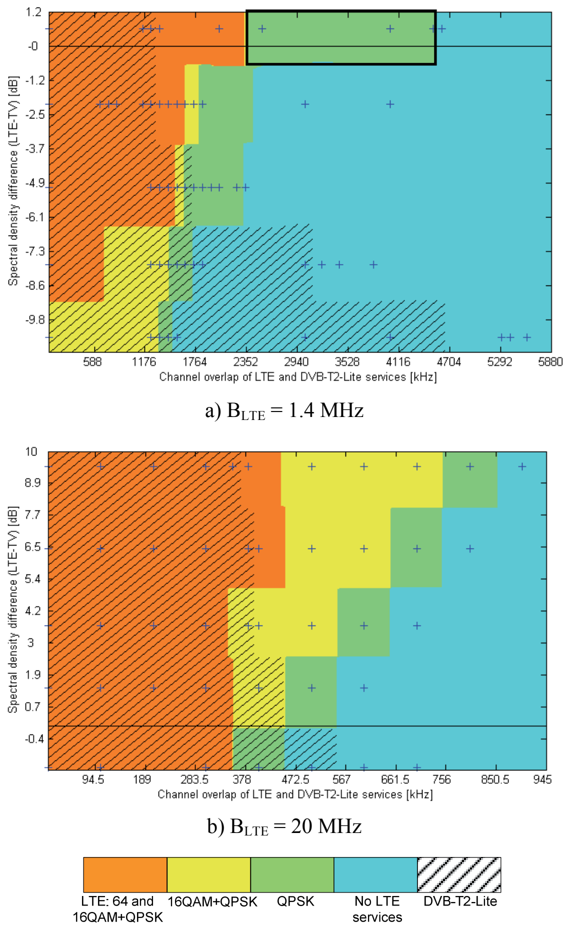

Fig. 9. Overall graphical presentation of performance of the co-existing DVB-T2-Lite and LTE services as a dependence of SDR on the level of the channel overlap at ideal channel conditions (C/N is higher than 40 dB).

The Gaussian (AWGN) channel was used as a reference and the carrier-to-noise (C/N) ratio is equal to 40 dB and 25 dB, respectively. The PI (DVB-T2-Lite) and EPA 5 HZ (LTE) fading channel models [35] were used as a second and third considered transmission environments, when C/N = 25 dB. These channel models describe slowly moving handheld reception of TV and mobile services. In the legend of Fig. 8 these channels are marked by the abbreviation “FCH”.

During co-existence scenarios, we explored the situations, when the power level of the LTE signal was less than, equal to or higher than that of the T2-Lite signal. The bandwidth of LTE signal (B_{LTE}) is 10 MHz. The SDR is equal to 0.93 dB (the spectral density of the T2-Lite level is lower than the level of LTE services). EVM limits [35], for which the transmitted LTE signal has still good performances, are marked by bold black dashed lines (see Fig. 8). The obtained results are significantly different when compared with results from the ideal channel environments. Thanks to higher delays and the Doppler spectrum features of considered fading channel models, the resistance of both communication systems to the noises during co-existence is much less. Data transmission of LTE services, using 16QAM modulation, in fading channels, falls at channel overlap equal to 112.5 kHz. This value at ideal (reference) channel conditions is higher than 600 kHz. The interesting result is that at the EPA 5 Hz channel model (at C/N = 25 dB) in the LTE system, sub-frames using 64QAM modulation are never fulfilled to the minimal limit of EVM. This is the reason why the EVM limit for 64QAM is not marked in Fig. 8.

The second part of our measurement was focused on the exploration of the dependence of the SDR ratio on the level of overall channel overlap of co-existing DVB-T2-Lite and LTE services. Results were obtained at ideal channel conditions for B_{LTE} = 1.4 and 20 MHz and are shown in Fig. 9 a) and b). Negative values of SDR parameter present the case, when the spectral density of the TV level is higher than the level of LTE services. In case of positive SDR values the situation is opposite. Possible situations are clearly explained in the legend of Fig. 9. For better explanation of these results, we describe a specific example from Fig. 9 a), when B_{LTE} = 1.4 MHz. We consider a field with green color (marked by black rectangular), where the channel overlap is from 2352 kHz to 4701 kHz and the spectral density differences are from -0.6 dB to 1.2 dB, respectively. As can be seen from the legend, in LTE system, only sub-frames using QPSK modulation will be received and demodulated correctly. Sub-frames using 16QAM and 64QAM modulations cannot be successfully processed. Furthermore, this field also indicates that at this place DVB-T2 services will not be available (no hatched fields).

7. Advanced Co-existence Scenario between LTE-CR and DVB-T2 SISO/MISO Services

Nowadays, the effort of broadcasters and mobile operators is to provide all kinds of multimedia services with high efficiency. DVB-T2/T2-Lite and LTE standards can fulfill these requirements. As was outlined in the previous section, they can operate in the same or an adjacent frequency spectrum [2]. Thanks to analog TV switch-off (ATVSO), there are additional TV white space spectrums (TVWS) which can be allocated for cognitive radio (CR). The CR technology has been proposed to resolve the increasing spectrum requirements and possible co-existing scenarios [38]. We consider that two users operate in the same location, marked as primary (PU) and secondary user (SU). The SU automatically detects and checks available channels in the frequency spectrum. When the PU wants to operate in the same channel as the SU, then the SU switches to another channel. Hence, mutual inferences can be suppressed and accuracy of efficient spectrum using is increasing. Therefore, it can be expected that in the future the LTE services will be transmitted/received based on CR technology, denoted as LTE-CR [39].

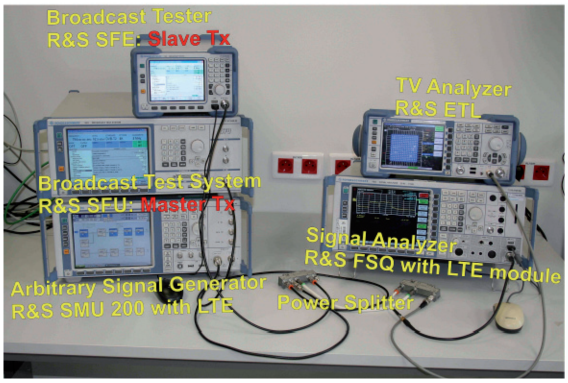

Fig. 10. Realized laboratory workplace for measuring the interaction between DVB-T2 (SISO and MISO configuration) and LTE-CR networks.

Similarly, better spectrum efficiency and transmission diversity could be achieved also in a case of DVB-T2. Besides a classical single input single output (SISO) technique, the DVB-T2 system enables to use a multiple input single output (MISO) transmission technique. Two transmitters can be used which transmit a slightly modified version of each pair of constellations, but in the reverse order in frequency [34]. This technique allows initial frequency domain coefficients to be processed by a modified Alamouti encoding [32], [33] which allows the DVB-T2 signal to be split between two groups of transmitters on the same frequency in such a way that the two groups will not interfere with each other. Therefore, the coverage and robustness of TV reception in SFN networks compared to SISO technique could be better.

Despite these significant innovations, possible interferences between considered systems can occur, mainly when the CR spectrum sensing mechanism is not able to detect any other signal levels (e.g. DVB) accurately. Therefore, our purpose is to explore possible co-existence scenarios between DVB-T2 and LTE-CR systems, operating in the same location and at neighboring frequencies.

7.1 Cognitive Radio Co-existence Scenario and Measurement Setup for Its Measuring

The considered scenario is as follows. Let be a common cell for DVB-T2 and LTE systems where both of them work without any problems. The user is receiving DVB-T2 services by a rooftop antenna (fixed reception scenario) at working frequencies of 786 MHz and 834 MHz. Other user has a smartphone for uploading of data (from a user to a base station). This wireless transmission is ensured by LTE-CR technology. The LTE system operates at frequencies from 832 MHz to 862 MHz. Thanks to the applied CR technology, co-existences and mutual interferences cannot occur. On the other hand, for the LTE-CR system we consider a situation when a number of allocated channels for its services is limited. Thus, its move on the next possible working frequency is difficult.

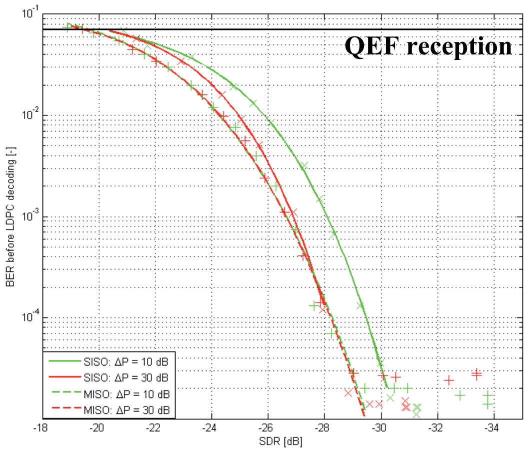

Fig. 11. Dependences of channel errors in DVB-T2 on the SDR ratio, when DVB-T2 and LTE services are co-existing. DVB-T2 services are broadcasted by SISO and/or MISO technique, when transmited powers of TV transmitters are different (power imbalance). The bandwidth of LTE signal is 10 MHz.

Near to the described cell, other cell exists and its configuration is very similar. The main difference is that in this cell the provided DVB-T2 services can be transmitted by SISO or MISO technique and they are broadcasted at 842 MHz. Reception of these services from the second cell by a TV user in the first cell (after the tune on its frequency) is without problems. On the other hand, LTE system in this cell is working at frequencies from 832 MHz to 862 MHz and if its bandwidth is equal to 1.4 and/or 10 MHz then there is a very high risk that the user of the smartphone can negatively affect remote TV reception of the TV user in the first cell. Tuning on the other channel will not happen, because the level of the received TV signal (remote reception) is less than that one of the LTE or there is no free working frequency. Hence, unwanted co-existence scenarios may occur.

Based on the general block diagram (see Fig. 1) for the measurement of the interaction of the described co-existence scenario, an appropriate laboratory workplace was realized (see Fig. 10). Two R&S SFU units are used. The first one is denoted as a master transmitter; the second one as a slave. Of course, the master transmitter will be the central unit of the created DVB-T2 MISO signal [40]. Configuration of SFU units is outlined in Fig. 1. From the point of MISO technique, an appropriate transport stream (TS) must be selected in the TS generator of the master SFU. Therefore, different streams for SISO and MISO scenarios were used. After the setting of all system parameters (code rate 2/3, 16K OFDM mode, 256QAM modulation, PP3 (SISO) and PP1 (MISO) pilot pattern structure, and 19/128 guard interval length), the generated TS was RF modulated. LTE signals were generated by R&S SMU200A using the same way, as it was described in the previous section. After that, both services are combined and then the splitter is used for dividing signals for analyzing.

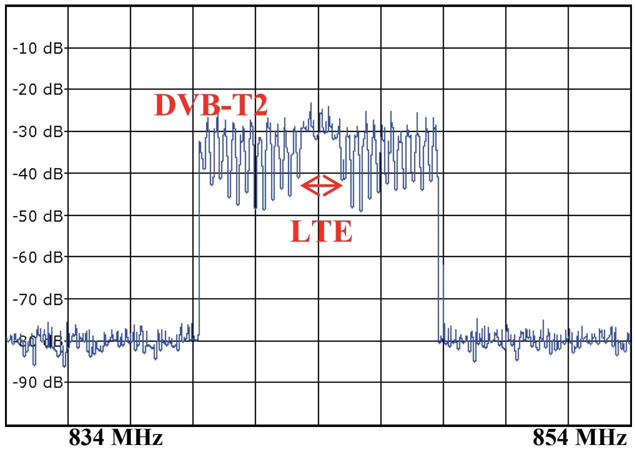

Fig. 12. RF spectrum of co-existing DVB-T2 (SISO technique) (TX1 = TX2 = 72 dBμV) and LTE-CR (70.8dBμV) services. The limit for an error-free reception in the DVB-T2 is not fulfilled. The B_{LTE} is equal to 1.4 MHz.

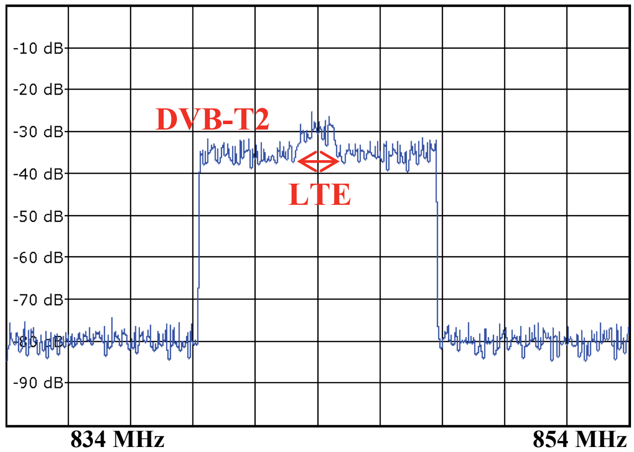

Fig. 13. RF spectrum of co-existing DVB-T2 (MISO technique; TX1 = 42 dBμV and TX2 = 72dBμV) and LTE-CR (70.8 dBμV) services. The limit for an error-free reception in the DVB-T2 is not fulfilled. The B_{LTE} is equal to 1.4 MHz.

7.2 Impact of Co-existence Scenario on the DVB-T2 SISO/MISO Performance

Dependences of bit error ratio (BER) before LDPC decoding (channel errors) in DVB-T2 on different SDR ratios (power ratio between DVB-T2 and LTE per unit of the used bandwidth) are plotted in Fig. 11. The results for both DVB-T2 transmission technique SISO and MISO are presented. All the measurements were done at ideal channel conditions (C/N = 40 dB). The border for the quasi-error-free (QEF) reception [33] is marked with a bold black line. Furthermore, in our measurement we worked with different power levels of DVB-T2 signals. It is clearly seen that the considered power level of DVB-T2 transmitters has an impact on their performances, broadcasted by SISO technique. When the power imbalance between the transmitters is 10 dB then occurring errors in the transmission channel at low SDR ratio (approx. -30 dB) are very low (approx. 2.0E-5).

The situation is reversed when DVB-T2 services are transmitted by the MISO technique. When the power imbalance is equal to 10 dB then the amount of occurring BER ratios in the transmission channel is less at higher SDR ratios. This is caused by the modified Alamouti technique. On the other hand, achieved results at higher power imbalances and at higher SDR ratios were only slightly better in comparison with SISO mode.

Finally, two snapshots of the RF spectrums of the DVB-T2 and LTE services, operating at the same carrier frequency are shown in Fig. 12 (SISO technique in DVB-T2) and Fig. 13 (MISO technique in DVB-T2). Both RF spectrums were obtained at C/N = 40 dB. The start and stop frequency is equal to 834 MHz and 854 MHz, respectively. At these measurements, units in the ordinate are related to the resolution bandwidth (RBW) of 10 kHz and video bandwidth (VBW) of 10 MHz. The resistance of the RF input of the R&S ETL TV analyzer is 75 Ω.

8. Conclusion and Future Works

In this paper, the advanced co-existence scenarios between mobile communication networks and digital television broadcasting systems in the same frequency bands were explored, measured and evaluated. For this purpose a universal multimode testbed with appropriate measurement devices was proposed and realized. We have investigated the impact of different co-existence scenarios between the still used (GSM, UMTS and DVB-T/H) and upcoming (LTE, LTE-CR and DVB-T2/T2-Lite) wireless standards. Detailed results, shortly discussed and summarized in this paper, have been preliminarily published in [24]-[26] and [29]. From the obtained results, it is clearly seen that the co-existence between considered wireless systems can significantly affect their performances. Therefore, its deeper study should be continued and appropriate methods for its suppression should be proposed.

In our future work we would like to focus on the development of semi-automatic simulation system for avoidance of co-existence problems. Potential intersystem interferences should be identified by a system under development utilizing metadata inputs. These data include maps of coverage, system transceivers' positions and their antennas' radiation patterns. System transceivers mean broadcast transmitters in case of DVB-T/H/T2 and access points (AP) in case of mobile networks (BTS, Node-B, etc.). For this purpose, we have done measurements on typical TV-UHF antennas (panel and Yagi antennas) to find out their parameters in their operation frequency bands as well as out of them. The measured data presented previously and also in this paper, will be used to system calibration and validation.

Nowadays, a new type of communication, the LTE-Advanced (LTE-A) network has been standardized by the 3GPP organization by Specification Groups TSG RAN WG1 and WG2. This communication approach is called device-to-device (D2D) and allows setting up a direct communication between UEs without participation of evolved Node B (eNB) in data transmissions. D2D allows to increase the throughput and spectral efficiency and also to decrease the interferences and power consumption [41]. To achieve these enhancements eNB could assign to the D2D session both uplink and/or downlink resources. Therefore, inter and intra system interferences could affect the setup of D2D session and/or influence the already ongoing sessions [42]. In order to explore effect of the interferences and behavior of the affected systems, further simulations, measurements, and experiments are required.

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