BRNO UNIVERSITY OF TECHNOLOGY
VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ

FACULTY OF ELECTRICAL ENGINEERING AND COMMUNICATION
DEPARTMENT OF RADIO ELECTRONICS

FAKULTA ELEKTRONIKY A KOMUNIKAČNÍCH TECHNOLOGIÍ
ÚSTAV RADIOELEKTRONIKY

COEXISTENCE BETWEEN ADVANCED WIRELESS COMMUNICATION SYSTEMS IN SHARED RADIO FREQUENCY BANDS

HABILITATION THESIS
HABILITAČNÍ PRÁCE

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ABSTRACT

This habilitation thesis describes research activities in the field of coexistence between advanced wireless communication systems. A basic description of the considered communication systems, namely first and second generation Digital Video Broadcasting-Terrestrial (DVB-T and DVB-T2), Long Term Evolution (LTE) and Wireless Local Area Network (WLAN), is presented in the first part. This part also contains an overview of possible coexistence scenarios for these communication systems in a common radio frequency (RF) band. The second part of this habilitation thesis summarizes the applicant's research activities in the last 5 years (2013-2017) focusing on the coexistence of wireless communication systems. The thesis consists of 10 selected and previously published original scientific and research papers. The applicant is the main author of seven papers. Selected paper reprints are included in exact layout of full paper versions at the end of the thesis. Finally, the third part of the thesis contains a brief overview of the applicant's pedagogical and research activities, including a brief presentation of supervised bachelor and masters works.

KEYWORDS

wireless communication systems, digital television, mobile broadband access, DVB-T/H, DVB-T2/T2-Lite, LTE, WLAN, IEEE 802.11, RF spectrum, coexistence, interference, simulation, RF measurement, BER, MER, EVM, QEF

ABSTRAKT

Tato habilitační práce popisuje výzkumné aktivity v oblasti koexistence pokročilých bezdrátových komunikačních systémů. Základní popis uvažovaných komunikačních systémů, jmenovitě první a druhá generace digitálního terestrického vysílání (DVB-T a DVB-T2), Long Term Evolution (LTE) a bezdrátová lokální síť WLAN (využívající technologii IEEE 802.11), je prezentován v první části práce. Tato část habilitační práce také obsahuje stručný přehled možných koexistenčních scénářů mezi komunikačními systémy, provozovanými ve společném radiofrekvenčním (RF) pásmu. Druhá část práce shrnuje výzkumné aktivity uchazeče za posledních 5 let se zaměřením na oblast koexistence bezdrátových komunikačních systémů. Práce se skládá z 10 vybraných vědeckých prací uchazeče, které byly publikovány v období 2013-2017. Reprinty těchto článků jsou součásti této práce ve formě příloh. Poslední třetí část této habilitační práce obsahuje stručný přehled pedagogických a výzkumných aktivit uchazeče a to včetně krátké prezentaci vedených bakalářských a diplomových prací.

KLÍČOVÁ SLOVA

bezdrátové komunikační systémy, digitální televize, mobilní širokopásmové připojení, DVB-T/H, DVB-T2/T2-Lite, LTE, WLAN, IEEE 802.11, RF spektrum, koexistence, interference, simulace, RF měření, BER, MER, EVM, QEF

DECLARATION

I declare that I have written the Habilitation Thesis titled "Coexistence between Advanced Wireless Communication Systems in Shared Radio Frequency Bands" independently, under the guidance of the advisor and using exclusively the technical references and other sources of information cited in the thesis and listed in the comprehensive bibliography at the end of the thesis.

As the author I furthermore declare that, with respect to the creation of this Habilitation Thesis, I have not infringed any copyright or violated anyone's personal and/or ownership rights. In this context, I am fully aware of the consequences of breaking Regulation § 11 of the Copyright Act No. 121/2000 Coll. of the Czech Republic, as amended, and of any breach of rights related to intellectual property or introduced within amendments to relevant Acts such as the Intellectual Property Act or the Criminal Code, Act No. 40/2009 Coll., Section 2, Head VI, Part 4.

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Brno, February 1st, 2018 ....

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PREFACE

Habilitation thesis **"Coexistence between Advanced Wireless Communication Systems in Shared Radio Frequency Bands"** deals with defining, exploring and evaluating of coexistence scenarios between wireless communication systems operated in shared radio frequency bands.

This thesis is divided onto two main parts: research and pedagogical. The first part focuses on the definition, simulation, measurement and evaluation of coexistence scenarios between digital terrestrial television and mobile broadband systems and between mobile broadband and wireless communication systems in ultra high frequency bands. The thesis altogether consists of 10 selected papers (5 papers in SCI-E journals with impact factor, 1 journal paper indexed by Scopus and 4 papers presented at respected international conferences) written by the applicant (author or co-author). All works presented in these papers were done at the Department of Radio Electronics (DREL), Brno University of Technology (BUT) in the last 5 years (2013-2017). Some of the papers have been partially done in cooperation with respected colleagues and skillful students. The first part of this habilitation thesis is written with an accompanying commentary of achieved results.

The second part of this thesis deals with the pedagogical and scientific activities of the applicant. Courses where the applicant is actively participating as well as selected works of students, where the applicant aided as a supervisor, are briefly described. Finally, this part is enclosed with the presentation of national and international projects in which the applicant has actively participated in the last 5 years (2013-2017). Results presented in the first part of the thesis were achieved within the frame of these projects.

1 INTRODUCTION

In the last decade, the demand for multimedia services in various quality (standard and high) has been rapidly increasing. People are using many types of different multimedia devices, e.g. notebooks, tablets, smart phones and smart TVs. Depending on the type of wireless communication system, supported by the user's equipment, many ways exist to provide different multimedia services (image, audio and data content) offering different user experience. Requirements on such services in superb quality are common among users. The data rates required to carry high quality multimedia services are becoming still higher. For the providers of these services, the limited usage of radio frequency (RF) spectrum is one of the biggest challenges. Hence, there is a great effort to optimize existing wireless infrastructures and select suitable RF bands. Otherwise, the increasing density of different wireless communication systems in use escalate the risk of so called coexistence scenarios. The term "coexistence" in the theory of wireless communication presents a situation when different communication systems operate in shared RF bands. Coexistence of wireless communication systems can cause significant degradation in their performances.

Undesirable interactions between similar or different kinds of wireless communication systems, operating in adjacent or shared frequency bands, are not a new phenomenon. Nevertheless, this topic became more actual after 2007, when during the last World Radio Conferences (WRCs) the International Telecommunication Union (ITU) decided to harmonize the 700 MHz and 800 MHz bands for Long Term Evolution (LTE) telecommunication technology. Later, the European Union (EU) decided to harmonize the "800 MHz band" in favor of the LTE services, starting from January 2013. Previously, 700 MHz and 800 MHz bands were allocated for terrestrial Digital Video Broadcasting (DVB-T) and its successor (DVB-T2). Consequently, DVB-T/T2 and LTE services can occupy either the same or adjacent RF spectrum. Thereby, unwanted coexistence scenarios between DVB-T/T2 and LTE systems can occur.

The LTE system can also be used in the Industrial, Scientific and Medical (ISM) bands, especially at 2.4 GHz and 5 GHz, to increase user data throughput. This solution is very attractive mainly from the view point of upcoming next generation wireless broadband networks. On the other hand, these bands are utilized by Wireless Local Area Networks (WLANs) based on different Institute of Electrical and Electronics Engineers (IEEE) technologies marked as IEEE 802.11. Such a scenario can cause coexistence between LTE and WLAN systems. Consequently, defining, modeling, measuring and monitoring of various coexistence scenarios and suppressing of interferences from such coexistence scenarios are hot topics [1]-[10].

This habilitation thesis deals with defining, measuring and evaluating of coexistence scenarios between DVB-T/T2 and LTE systems and between LTE and WLAN systems in shared RF bands. Furthermore, it contains a brief presentation of the pedagogical and scientific activities of the applicant. From this point of view, the habilitation thesis is organized as follows.

A brief description of the DVB-T/T2, LTE and WLAN systems is given in the Section 2. Section 3 focuses on the description of possible coexistence scenarios between DVB-T/T2, LTE and WLAN systems. This section also contains the motivation of this habilitation thesis. An accompanying commentary of achieved results is presented in Section 4. Section 5 describes the applicant's pedagogical and scientific activities. Section 6 contains a short discussion of the selected practical results achieved within the frame of national and international projects.

This thesis consists a total of 10 selected papers written by the applicant (author or coauthor). More precisely, there are 5 papers in SCI-E journals with impact factor, 1 journal paper indexed by Scopus and 4 papers presented at respected international conferences. All presented works were done at the Department of Radio Electronics (DREL), Brno University of Technology (BUT) in the last 5 years (2013-2017). Some of the papers have been partially done in close cooperation with respected colleagues and skillful students. All 10 papers can be found in the appendix under the name **Enclosed Copies of Papers**, which closes this habilitation thesis.

2 WIRELESS COMMUNICATION SYSTEMS

This section gives a brief description of the wireless communication systems which are considered in this habilitation thesis. The main objective parameters used to completely evaluate their performance on the physical layer (PHY) level are also defined and described.

2.1 DVB-T/H

The Digital Video Broadcasting-Terrestrial (DVB-T) [11] system is a European-based DVB standard, proposed and developed for the broadcast and transmission of digital terrestrial television (DTT) services. It was published in 1997 as the European Telecommunications Standards Institute (ETSI) standard under the designation EN 300 744 [12]. This document specifies the framing structure, channel coding and modulation for DTT. DVB-T adopted an effective Forward Error Correction (FEC) scheme, using the Reed Solomon and convolutional encoding/decoding, and Orthogonal Frequency Division Multiplexing (OFDM) signal processing chain. It uses a large number of subcarriers (mode 2K and 8K) and delivers a robust signal that has the ability to deal with various transmission channel conditions (mobile, fixed). As an inner modulation, QPKS, 16QAM and 64QAM modulations can be used. Three channel bandwidths are defined for DVB-T, specifically: 8 MHz (typical in Europe), 7 MHz and 6 MHz. All the mentioned technical characteristics of DVB-T ensure its good flexibility which simplifies the design of the DVB-T network to meet with requirements of the network operators (e.g. robustness and capacity). The use of OFDM modulation with an appropriate guard interval (GI) length allows DVB-T to provide a tool for regulators and operators in the form of the Single Frequency Network (SFN). It is a network where a defined number of transmitters operate on the same RF frequency. SFN can cover a country or can be used to enhance indoor coverage using a simple gap-filler [14].

The DVB-T standard is closely connected with the standard DVB-Handheld (DVB-H) [13], formally adopted in 2004, which extends the possibilities of the DVB-T system with some backwards compatibility. It was designed to use the DVB-T system to deliver multimedia services to mobile devices (mobile TV). Thereby, it creates a bridge between the classic broadcast systems and the world of cellular radio networks. DVB-H obtained all the benefits of the DVB-T and adds new mobile-oriented features focusing on Internet Protocol (IP) data transport, adaptive per-service error protection, better mobility support (4K OFDM mode), and power saving capabilities (time slicing). More details can be found in [11], [13] and [15].

2.2 DVB-T2

The 2^{nd} generation terrestrial DVB standard (DVB-T2), published in 2008 [16] and updated in 2011 [17], as the successor of DVB-T, is nowadays the world's most advanced DTT system. Its emergence was mainly motivated by higher spectral efficiency and higher flexibility. The innovations and advanced techniques in signal processing make DVB-T2 at least 50% more efficient than DVB-T/H.

The differences between DVB-T and DVB-T2 standards for DTT are significant. DVB-T2 uses an advanced FEC scheme, specifically the connection of low-density parity-check (LDPC) and Bose-Chaudhuri-Hocquenghem (BCH) codes that can ensure higher error protection. The previously used modulations (QPSK, 16QAM, 64QAM) have been extended by 256QAM resulting in capacity gain of 25-30% [18]. Moreover, a new feature called rotated constellation was also introduced, providing additional robustness for low constellation sizes. The OFDM modes are extended from 8K to 32K which result in more reception scenarios (mobile, portable and fixed) of the DVB-T2 TV signal. Furthermore, new lengths of GI were defined (1/128, 19/256 and 19/128) to give higher flexibility at the planning of SFNs [19], [20]. DVB-T2 has eight different scattered pilot patterns (PPs) which in connection to OFDM sizes and GI lengths give high flexibility to propose appropriate system configurations for different transmission scenarios. It is important to mention that the classic single-input single-output (SISO) transmission mode was extended by the multiple-input single-output (MISO) mode using a modified form of Alamouti encoding. Alamouti encoding ensures that two transmitting antennas do not radiate the same broadcasted TV signal (no correlation between them). The diversity technique improves coverage in SFNs [11].

DVB-T2 has an additional profile called DVB-T2-Lite (or simply T2-Lite) [21], which was added to the DVB-T2 system specification in 2012 and it is considered as the successor of DVB-H. This subset within DVB-T2 is very perspective for mobile and portable TV broadcasting as it is designed to support low-capacity applications for advanced handheld receivers. It is based on the same core of technology as the DVB-T2 standard but uses only a limited number of available modes (e.g. limited usage of 256QAM, short length LDPC code, restricted combination of OFDM sizes, GI lengths, and PP patterns). By avoiding the modes, which require the most computational power and memory, the necessary complexity of T2-Lite-only receivers is reduced. DVB-T2-Lite, compared to the first-generation DVB-H, can support TV content delivery with higher flexibility. More details can be found in [16].

In Europe, DVB-T/T2 systems can operate in Ultra High Frequency (UHF) band from 470 MHz up to 790 MHz.

2.2.1 DVB-T/H/T2/T2-Lite - Measurement Parameters

For evaluating DVB-T/T2 signal performance on its PHY level, various objective parameters can be used [11]. Bit and Modulation Error Ratio (BER and MER) and signal level are one of the most important. BER is the primary parameter which describes the quality of the digital transmission link. In the case of DVB-T/T2 standards, BER is measured before and after FEC decoding. For DVB-T/H and DVB-T2, it is also called BER before and after Viterbi decoding and BER before and after LDPC decoding, respectively. For the assessment of a correctly received TV signal, the condition for quasi-error-free (QEF) reception can be used [11]. In general, the threshold for QEF reception is represented by BER leading to no more than one perceivable error event in the decoded video per hour. Such a threshold for DVB-T/H and DVB-T2 standards is defined differently. The limit for QEF reception in the DVB-T/H standard is defined as BER equal to 2.10^{-4} after Viterbi decoding [12], while in DVB-T2 this value is equal to 1.10^{-7} after LDPC decoding [17]. This difference is caused by different kinds of FEC encoding and decoding schemes used in DVB-T and DVB-T2 systems.

The MER [11] parameter is an aggregate quantity which includes all possible individual errors and thus completely describes the performance of the transmission link. In general, the values of MER are expressed in dB units. A higher value of MER means less unwanted noises in transmission. In general, BER and MER values are obviously measured as a dependence on carrier-to-noise ratio (C/N).

The LDPC FEC scheme, applied in DVB-T2/T2-Lite, uses an iterative algorithm to decode an FEC frame. Consequently, the performance of LDPC decoding can be improved by increasing the number of decoding processes [16], [17]. Due to this, the condition for QEF reception can be achieved at lower C/N ratios, compared to DVB-T. On the other hand, it is important to mention that a higher number of decoding iterations has a larger impact on the power consumption of the receiver and unwanted decoding latency is also possible. Hence, the monitoring of LDPC decoding iterations number is important. More details can be found in [11].

2.3 LTE

The Long Term Evolution (LTE) standard [22], [23] was introduced in the Third Generation Partnership Project (3GPP) Release 8 in 2008. It is a very flexible telecommunication standard that offers a high scale of adjustable system parameters, like flexible channel bandwidths, frequency band, duplexing, modulation and advanced audio coding.

The LTE system is based on successful predecessor mobile technologies, namely Global System for Mobile Communications (GSM) and Universal Mobile Telecommunications System (UMTS). Besides core network improvements, depending on the user equipment (UE) category (with up to 4×4 antennas using 20 MHz of RF spectrum), it enables to achieve high peak downlink (DL)/uplink (UL) bitrates ($\approx$ 300/75 Mbit/s). It utilizes the RF spectrum more efficiently than previous systems thanks to various system bandwidths (1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz and 20 MHz). In the LTE system, 3 inner modulation options can be used: QPKS, 16QAM and 64QAM modulations. For the DL and UL, Orthogonal Frequency Division Multiple Access (OFDMA) and Single-Carrier Frequency Division Multiple Access (SC-FDMA) concepts were adopted, respectively. Furthermore, besides the classic SISO transmission technique, it also supports multiple-input multiple-output (MIMO) techniques. The LTE architecture involves specific type of cells called femtocells. These short ranges, mainly indoor cells, improve coverage in desired areas, especially buildings. Among the most important features of LTE is definitely its support for both frequency and time division duplexing (FDD and TDD) techniques as well as half-duplex FDD with the same wireless access technology.

LTE can exploit the same UHF frequency bands which are already available for existing 2G/3G networks (e.g., bands: 800, 900, 1800, and 2600 MHz). Moreover, additional ranges in the ISM bands (at 2.4 GHz and 5 GHz) and the 700 MHz band are also allocated for LTE usage.

2.3.1 LTE - Measurement Parameters

To evaluate the performance of LTE on its PHY level, the Error Vector Magnitude (EVM), channel quality indicator (CQI), signal-to-noise ratio (SNR), and signal level parameters are used. EVM is a measure used to quantify the performance of an LTE communication link. It is the root mean square (RMS) value of the distance in the In-phase and Quadrature (IQ) constellation diagram between the ideal constellation point and the point received by the receiver. For each modulation used in LTE, there is a defined EVM limit, for which the transmitted signal has an acceptable quality. This limit is equal to 17.5% for QPSK, 12.5% for 16QAM and 8.0% for 64QAM [22]. The CQI parameter is the information that the UE sends to the Evolved Node B (eNodeB) about the quality of the communication channel. Its value, also called indexes, can be between 1 and 15. The CQI index defines the corresponding modulation type and code rate, including channel coding efficiency. A high value of CQI indicates better communication channel conditions. Actual SNR values play a key role for the expected CQI value.

2.4 WLAN

A wireless local area network (WLAN) [24] is practically a wireless computer network that enables to link devices using wireless communication technologies in different environments (e.g. home, office). A dominant part of WLAN networks are based on the IEEE 802.11 technologies [25] and are marketed under the Wireless Fidelity (Wi-Fi) brand name. Among its advantages are mobility, flexibility, high data rates and low cost. Wi-Fi services are provided in 2.4 GHz and 5 GHz ISM bands.

IEEE 802.11 is a set of PHY and media access control (MAC) specifications to define communication for WLAN/Wi-Fi networks. During the last decade, several IEEE 802.11 technologies have been developed to fulfill demand on increasing data traffic [26]. In this habilitation thesis, only IEEE 802.11n technology is briefly presented because this technology was considered in works [9] and [10]. More details about IEEE 802.11 standards can be found in [25].

IEEE 802.11n can be considered as a milestone in the evolution of IEEE 802.11 technologies. It improved the previous IEEE 802.11 specifications by the MIMO technique. Such a solution allows to increase the data throughput (up to 600 Mbit/s) not only in 2.4 GHz but also in the 5 GHz band [26]. It is possible to use either 20 MHz or 40 MHz channel bandwidth. Furthermore, it allows to use four spatial streams (it provides a significant improvement in the data rate) and additionally, it allows a number of different data streams to be carried over the same channel. 802.11n provides backward compatibility for devices working with previous IEEE 802.11 standards [25].

2.4.1 WLAN - Measurement Parameters

In WLAN systems, measurement of the received signal strength (RSS) is essential. Its value reflects the power of the received RF signal and directly affects the performance of received Wi-Fi services. It is measured in dBm units. Consequently, the higher the RSS number, the stronger the received signal [27]. Other objective parameters for evaluating the performances of WLAN are data throughput and BER, in some cases EVM or MER.

3 COEXISTENCE OF WIRELESS COMMUNICATION SYSTEMS

This section gives an overview of the possible coexistence scenarios which can occur between DVB-T/T2 and LTE systems and between LTE and WLAN systems. Common RF bands of wireless communication systems, considered in this thesis, are defined. Finally, different kinds of coexistence scenarios are defined and explained.

3.1 DVB-T/T2 and LTE

Advanced wireless communication systems can provide users with any type of multimedia. From the viewpoint of wireless service providers, efficient usage of limited resources in the RF spectrum is one of the biggest challenges. Hence, the increasing density of wireless networks and the increasing volume of UE terminals in use escalate the risk of unwanted coexistence scenarios between different kinds of wireless communication systems, sharing common RF bands. Nowadays, DVB-T/T2 and LTE systems are deployed to provide multimedia services in common UHF bands, mainly in Europe.

During the last WRC conferences it was decided that the upper parts of UHF bands, specifically 700 MHz and 800 MHz, shall be released for mobile broadband communications, provided by LTE technology. These parts of UHF bands were previously allocated for DVB-T/T2 systems to provide DTT services. Thanks to this decision, DVB-T/T2 and LTE systems can occupy either the same or adjacent frequency spectrum. As a result, unwanted coexistence scenarios between DVB-T/T2 and LTE can occur [28]. Graphical representation of such scenarios is shown in Fig. 3.1. Depending on the carrier frequency (also called as working frequency) and channel bandwidth of coexisting systems [29], in general, four different coexistence scenarios can occur: non-overlapping at a defined size of guard band (GB), non-overlapping without GB, partial overlapping, and full overlapping of RF spectrum [30]. All these scenarios in clearer form are graphically illustrated in Fig. 3.2.

The non-overlapping coexistence scenario with a GB band (see ① in Fig. 3.2) means that the adjacent RF spectrum of DVB-T/T2 and LTE RF signals do not touch each other. The GB band is an unused part of the radio spectrum between RF bands, for the purpose of preventing possible interferences, caused from the coexistence of RF signals [29]. The non-overlapping scenario with GB=0 MHz (see ② in Fig. 3.2) represents a situation when DVB-T/T2 and LTE systems can coexist in an adjacent channel with zero additional bandwidth. It means that there is no GB between the RF channels.

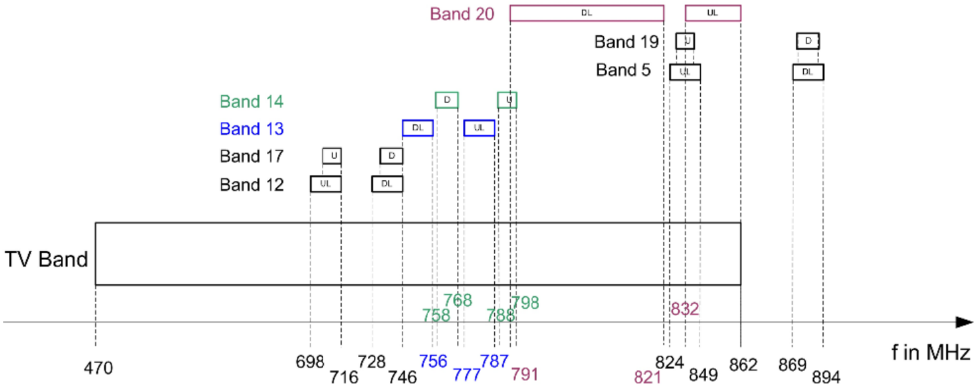

Fig. 3.1: Coexistence scenarios between DVB-T/T2 and LTE in the UHF band [28].

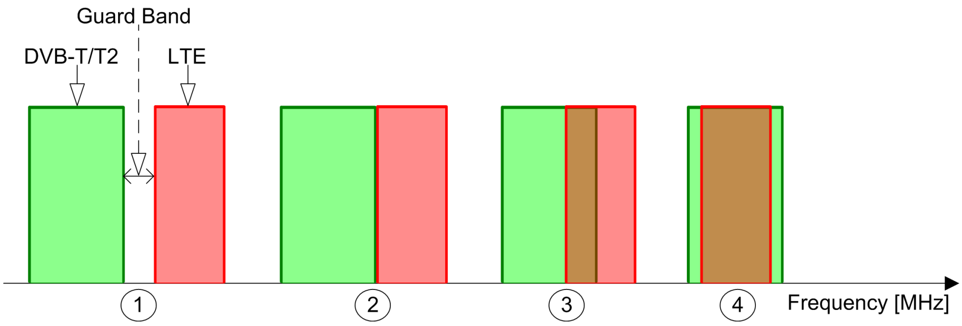

Fig. 3.2: Graphical illustration of possible coexistence scenarios between DVB-T/T2 and LTE systems: ① non-overlapping with GB>0 MHz, ② non-overlapping with GB=0 MHz, ③ partial overlapping, and ④ full overlapping RF spectrum.

Both of these scenarios can be also called adjacent channel coexistence. The partial overlapping coexistence scenario (see ③ in Fig. 3.2) can occur when the RF channel of the interferer system (e.g. LTE) partially overlaps with the RF channel of the victim system (e.g. DVB-T/T2). As for the last one, the full overlapping coexistence scenario (see ④ in Fig. 3.2), also called co-channel coexistence, it means that one RF signal is completely overlapped with another RF signal [5].

3.2 LTE and WLAN

The demand for higher mobile data rates and the growing number of mobile users brings forth the question of how to improve or extend the performance of existing 3G/4G cellular networks, mainly in small cells. The licensed spectrum is the best choice for operators thanks to predictable behavior ensuring Quality of Service (QoS), mobility, and system control. Unfortunately, the amount of available licensed spectrum is limited [10].

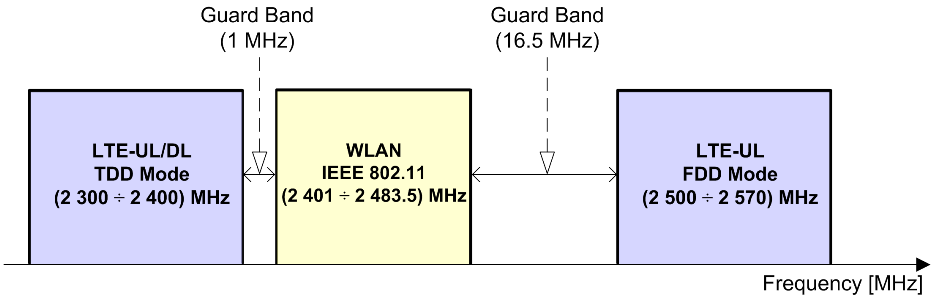

Fig. 3.3: Assumed utilization of the 2.4 GHz ISM band by the LTE system.

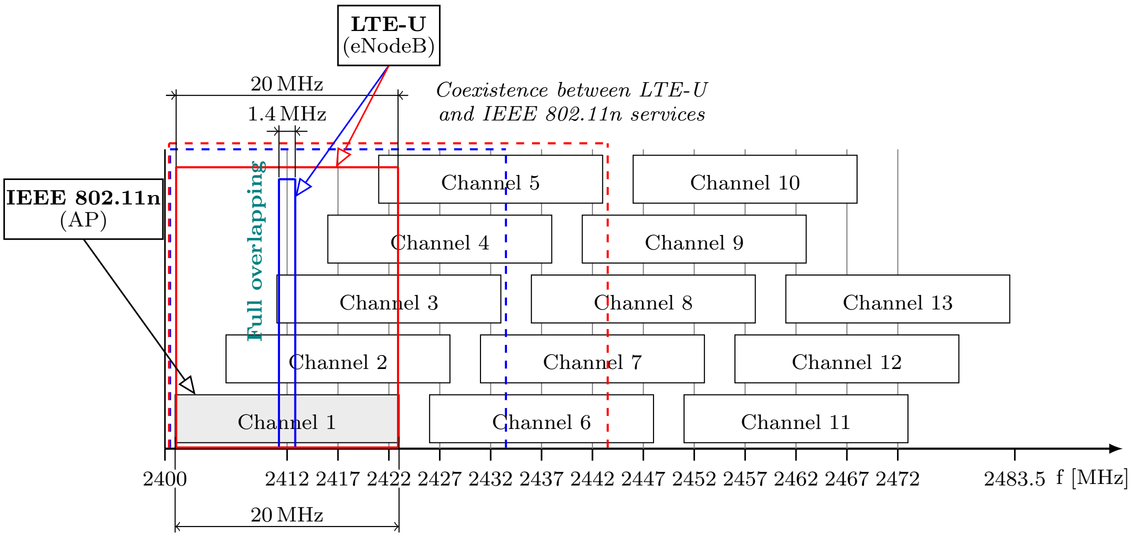

Fig. 3.4: Graphical representation of the LTE-Unlicensed (1.4 MHz and 20 MHz system bandwidth marked by blue and red color, respectively) and WLAN services in ISM 2.4 GHz band - full overlapping coexistence scenarios [10].

To fulfill the users' requirement "access anywhere and at anytime" a high density of mobile and wireless networks with effective usage is needed. LTE and WLAN networks can fulfill this requirement and moreover, they can complement each other. To be more precise, mobile networks can provide telecommunication services with high coverage, whereas WLAN networks could be a more effective and comfortable solution for indoor scenarios [31]. It is assumed that LTE and different kinds of Wi-Fi technologies will be utilized together in the upcoming fifth generation (5G) mobile networks [23]. Hence, LTE services can be provided in the ISM bands [32], primary allocated for WLAN. This concept is also called LTE-Unlicensed (LTE-U). This situation is captured in Fig. 3.3. It is clearly seen that between LTE and WLAN systems adjacent coexistence scenarios can occur.

Furthermore, thanks to higher density of wireless networks, co-channel coexistence scenarios are possible too. Such situations are shown in Fig. 3.4.

Undesirable interactions between similar or different kinds of wireless communication systems, operating in adjacent or shared frequency bands, are not a new phenomenon. On the other hand, the definition of coexistence scenarios between them, their modeling, measurement, and possible suppression of their impact on wireless system performances are a hot topic.

The main goals of this thesis, according to accompanying commentary on the achieved results in 10 selected papers, are as follows:

1) to define coexistence scenarios between DVB-T/T2 and LTE systems and between LTE and WLAN systems;
2) to explore the impact of coexistence scenarios on the robustness of DVB-T/T2 and LTE systems by appropriate measurement methods;
3) to evaluate the influence of unwanted interferences from coexistence scenarios on the performances of DVB-T/T2 and LTE systems.

4 ACCOMPANYING COMMENTARY ON THE ACHIEVED RESULTS

This section briefly summarizes research activities of the applicant in the last five years (2013-2017) at DREL, BUT. It consists of two main parts. The first part deals with the discussion of the achieved results from exploring the coexistence between DVB-T/T2 and LTE broadband networks. The second, shorter part, summarizes the results from the analysis of the co-channel coexistence between LTE and WLAN systems. Full length papers can be found in the appendix of this habilitation thesis.

4.1 Coexistence between DVB-T/T2 and LTE

The use of wireless and mobile networks has expanded into the daily life of people and a life without services, provided by these networks, is unimaginable. Demands to provide these services (video image, audio and data) in superb quality (high data-rate) and with an excellent level of 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 also be fulfilled. Thereby, different wireless communication systems are utilized to provide different kinds of wireless services in a wide range of RF band. As a result, different kinds of coexistence scenarios can occur. The influence of interferences from such coexistence scenarios must be explored, measured and evaluated by an appropriate measurement setup.

With the aim to measure the interaction between different wireless networks and between mobile broadband and DVB-T/T2 networks, in [1] a multifunction measurement testbed and its setup was introduced. Essentially, the proposed testbed configuration consists of three main units: RF signal source, signal combiner/splitter and measurement equipment. In the RF signal source unit the types of input RF signals are defined. It is possible to work with either real RF signals (received from real transmitters) or with RF signals generated by professional devices under laboratory conditions. Real RF signals of DTT services (DVB-T/H/T2/T2-Lite) and 3G/4G networks (GSM, UMTS, LTE) are acquired by common receiving equipment (antennas, low noise amplifiers). Laboratory devices such as a single frequency unit (SFU) and arbitrary signal generator from Rohde&Schwarz (R&S) can generate a complete RF signal. Such devices also contain functional blocks to emulate different kinds of multipah signal propagation (fading channel models). After setting up the complete system configuration, the DTT, mobile or wireless services with a defined signal level and carrier frequency are generated and RF modulated.

In the next signal combiner/splitter unit, the RF signals are combined and divided as a combination of the service signal under interest and jamming signal. Finally, the robustness of the service signal under interest is monitored, measured and evaluated with appropriate measuring devices. This part can contain, e.g., ETL TV analyzer, digital video quality analyzer (DVQ), signal analyzer FSQ with an LTE module and spectrum analyzer. The proposed measurement testbed enables to measure and evaluate various coexistence scenarios (described in Chapter 2) between different wireless communication systems. Its functionality has been also verified and demonstrated in [1].

The above described measurement testbed was used in [2] to explore partial overlapping coexistence scenarios between DVB-T2-Lite and LTE systems under laboratory conditions. A general coexistence scenario was assumed, where an LTE base station (eNodeB), transmitting a DL signal, acts as an interferer on the mobile TV receiver and vice versa. Both mobile broadband and TV services are provided in a common cell and received by a user in an indoor office. To emulate such a transmission environment, pedestrian indoor (PI) and extended pedestrian A (EPA) fading channel models for DVB-T2-Lite and LTE signal propagation are considered respectively, whereas channel with Additive White Gaussian Noise (AWGN) is considered as a reference [11]. Firstly, the performance of LTE was investigated based on EVM versus spectral density ratio (SDR) curves. SDR is defined as the power ratio between LTE and DVB-T2-Lite RF signals per unit of the used bandwidth [1], [2]. Results revealed that the robustness of LTE against interferences depending on the type of modulation, used channel bandwidth, and transmission conditions. QPSK and 64QAM modulations have the highest and lowest resistance against interferences, respectively. Secondly, the robustness of the DVB-T2-Lite signal was explored. In the case of partial RF signal overlapping, DVB-T2-Lite performance is highly affected by the power of the LTE signal and its channel bandwidth. Results show that an LTE signal with the smallest bandwidth (1.4 MHz) cause the lowest performance degradation of DVB-T2-Lite at explored coexistence scenarios.

To reveal real performances of wireless communication systems, it is possible only in real environments considering real case scenarios. With the aim of examining the influence of coexistence issues on DVB-T2-Lite and LTE systems at real transmission conditions, a complex measurement setup was used and an extensive measurement campaign was realized in [3]. Partial overlapping RF spectrum coexistence scenarios of DVB-T2-Lite and LTE systems in the shared RF band under outdoor-to-indoor and indoor reception conditions were explored. The overlap of coexisting RF channels was varied from 0.8 MHz to 3 MHz at the bandwidth of LTE signal 10 MHz or 20 MHz and T2-Lite channel bandwidth equaling 8 MHz, respectively.

An outdoor-to-indoor, also called as portable indoor, transmission scenario was assumed, where a DVB-T2-Lite TV signal is received in a building. In the same building, LTE femtocells are deployed and Home eNodeB (HeNB) provides mobile connectivity (indoor-to-indoor scenario). The whole measurement campaign was implemented on the 7^{th} floor in the building of BUT, FEEC, DREL, including several indoor offices. Approximate dimensions of the floor are 50×25 m. It is important to mention that for the emulation of LTE femtocell HeNB (LTE indoor coverage), a PC with the Fedora Linux operating system and Universal Software Radio Peripheral (USRP) N210 from Ettus, equipped with an SBX daughter card, were used. The receiving UE was Huawei e398-u15 (LTE UE Cat. 3), connected via a Universal Serial Bus (USB) port to a laptop equipped with the R&S drive test software ROMES4. For receiving LTE services, the TechniSat Digiflex TT1 mobile antenna was used ($G \leq 2$ dBi). The T2-Lite services were generated in R&S SFU and amplified by a custom-built RF power amplifier (based on hybrid module Mitsubishi RA20H8087M). It also ensured a power imbalance between the T2-Lite and LTE RF signals. The transmitter was located on the terrace (outside) and a multi-element Yagi antenna (G_{max} = 15.4 dBi) was used. The received TV signal was measured with the Sefram 7866HD-T2 analyzer and the same antenna setup was used as for LTE downlink. Firstly, propagation of LTE and T2-Lite RF signals was measured separately (reference results). Secondly, both T2-Lite and LTE services were provided together at the same time. The measurement was carried out in defined points on the floor and inside the offices. To evaluate the quality of the received and decoded TV services, the QEF reception conditions were monitored, whereas for the LTE signal the RSS, CQI and EVM parameters (see Chapter 2) were measured. According to the evaluated results, it was shown that the impact of DVB-T2-Lite system on the LTE system performance and vice versa in a shared RF band highly depends on the level of their RF channels overlapping and on the power imbalance between RF signals. Next, it was observed that the outdoor-to-indoor penetration of the T2-Lite signal is highly critical on indoor-to-indoor reception of LTE services when the power imbalance between the RF levels is high. In these cases, the T2-system acts as a co-channel interferer to indoor LTE femtocell and vice versa. Next, measurement outputs lead to the conclusion that portable indoor TV reception is more vulnerable to interferences than fixed outdoor TV reception. Finally, the overall analysis of the obtained results from real case scenarios confirmed outputs from previous laboratory measurements [1], [2].

Co-channel coexistence is a special type of scenario when two RF channels completely overlap each other. It can occur when DVB-T/T2 and LTE services are provided at the same RF frequency in the same area and the receiver of DTT services is located at the edge of cell coverage for LTE eNodeB.

The influence of interferences from such scenarios on the DVB-T video picture quality was measured and evaluated in [4]. In this work, a commercial DVB-T receiver was used and in addition, the previously used measurement testbed [2] had been extended with a digital video quality (DVQ) analyzer from R&S. It enables to assess the video picture quality according to the real-time measurement method. The digital video quality level-weighted (DVQL-W) test value was used for real-time monitoring of video picture quality degradation. For the picture quality analysis, the Single Stimulus Continual Quality Evaluation (SSCQE) [11] method was adopted. It uses a simple 100-point continuous scale in the range from 0 to 100, where intervals "100-80"; "80-60"; "60-40"; "40-20"; "20-0" mark "Excellent"; "Good"; "Fair", "Poor" and "Bad" picture video quality, respectively. Values from this range were obtained for 1.4 MHz, 3 MHz and 10 MHz LTE channel bandwidths at different levels of the interfering LTE RF signal. The SSCQE values indicated a gradual decrease of DVB-T video signal quality with increasing the level of the LTE RF signal and LTE channel bandwidth. At lower interfering signal levels, independently on the LTE channel bandwidth, the video picture quality was "Excellent" or "Good". However, at higher LTE RF signal levels the video picture quality was quickly decreased to thresholds "Fair", "Poor" and even "Bad". Such quick degradation was observed especially for an LTE RF signal with a bandwidth of 1.4 MHz.

Exploring the influence of LTE-UL RF signal on the real DVB-T RF signal at different coexistence scenarios was the main purpose of the work [5]. Specifically, three different coexistence scenarios were assumed: non-overlapping with GB=0 MHz, partial, and full overlapping RF spectrum. Once again, an LTE RF signal with bandwidths of 1.4 MHz, 3 MHz and 5 MHz acts as an interferer. The DVB-T RF signal, broadcasted from a TV tower, was received by a rooftop antenna and via an attenuator (with a 0 dB attenuation) connected to a set-top-box (STB). To emulate the LTE uplink signal, an arbitrary signal generator (SMU200) was used from R&S. The robustness of interfered DVB-T RF signals, measured by BER (before and after FEC decoding) and MER values, was analyzed as dependence on the SDR parameter [2]. Outputs of this measurement extend previous results as follows. The signal level and channel bandwidth of LTE-UL are the main factors which influence the robustness of DVB-T against interferences at non-overlapping scenarios with GB=0 MHz. Such a robustness increases with decreasing LTE-UL channel bandwidth. In the case of the partial overlapping RF spectrum (here, half of the DVB-T RF channel is overlapped by the LTE-UL RF channel) the level of the influence of the LTE-UL on the DVB-T until SDR=0 dB (same spectral density of the TV and mobile signal levels) did not depend on the considered LTE-UL RF bandwidths. At the full overlapping RF spectrum scenarios, the narrowband interfering LTE-UL has lower impact on DVB-T performance than the same level broadband interference.

Advanced simulation tools are essential to explore and understand the behavior of wireless communication for different system settings. A necessary tool to evaluate how the perspective techniques perform in a selected transmission scenario is a suitable simulation model. Such consideration inspired the work [6], where an appropriate MATLAB-based coexistence simulation model was proposed and realized to investigate co-channel coexistence scenarios between DVB-T/T2 and LT-DL on the PHY level. For this purpose, the DVB-T/T2 [19] and LTE-DL [33] link-level MATLAB simulators, realized previously at DREL, were used. The used LTE simulation model was based on the LTE downlink simulator [34], developed at TU Vienna. The coexistence of DVB-T/T2 and LTE-DL is emulated as follows. At the beginning, the DVB-T/T2 IQ-signal is generated in the Tx PHY model. It is followed by the generation of an LTE-DL IQ-signal according to considered channel bandwidths (1.4 MHz, 5 MHz and 10 MHz). In the next step, spectral levels of DVB-T/T2 (constant) and LTE-DL (various) signals are calculated related to assumed channel bandwidths. For the purpose of quantifying interferences, the spectral level ratio (SLR) was used, which is defined as the ratio of the spectral level of the LTE and DVB-T/T2 signals. Next, the previously generated LTE IQ-signal is multiplied by the actual SLR value. Finally, the signals of DVB-T/T2 and LTE are simply added. Ideal channel conditions are considered for both systems, so the only source of impairment is the inter-system interference. The impaired DVB-T/T2 signal is processed in the Rx PHY model and BER (before FEC), MER and the amount of repeated LDPC decoding (only for DVB-T2) values for evaluating the performance of DVB-T/T2 are calculated. A flowchart of the proposed model for analyzing the coexistence between DVB-T/T2 and LTE and its description in detail can be found in [6]. It is important to note that the proposed coexistence model enables to emulate only co-channel coexistence scenarios. The correctness of the proposed co-channel simulation model was proved by laboratory measurements. Simulation and measurement results, which were related for DVB-T/T2 mobile transmission scenarios, extended the previous state-of-the-art knowledge with two new results. In DVB-T2 systems, the decodability of received broadcast TV signals at co-channel coexistence gradually decreases with higher SLR ratio. Different bandwidths of the LTE signal affect the DVB-T2 FEC decoder performance (from the point of needed iteration number/amount of repeated LDPC decoding) at the same SLR ratio differently. It means that higher M-QAM order modulations needed a higher number of iterations. The requirements for QEF reception in DVB-T and DVB-T2 systems at the considered co-channel coexistence scenarios after FEC decoding are comparable.

The performance of wireless communication systems highly depends on the transmission conditions in the transmission environment. From this point of view, for the DVB-T2 system mobile, portable and fixed transmission scenarios can be defined.

Coexistence between DVB-T2-Lite and LTE-DL in mobile TV fading channels was studied in the paper [7]. In this work, partial overlapping RF spectrum scenarios were considered. Features of mobile TV environment (e.g. multipath propagation, movement of receiver) were emulated by Vehicular Urban (VU30) and Motorway Rural (MR100) advanced fading channel models [35]. Both channel models are based on real measurement data in a real environment (urban and rural area). The movement of the receiver in VU30 and MR100 channel model is considered around 30 km/h and 100 km/h, respectively. The laboratory measurement workplace had been prepared according to previous experience. The SFU unit from R&S was used to generate a complete DVB-T2-Lite RF signal. It also contains a module to emulate different fading channel conditions, respectively. The AWGN channel was considered for reference measurements. The LTE-DL RF signal with different power levels was produced in an arbitrary signal generator R&S SMU200A. BER before and after LDPC decoding and MER values of the interfered T2-Lite signal were measured. The analyzed results confirmed previous theory assumptions, specifically that conditions in the channel environment also have an impact on the T2-Lite performance interfered by LTE-DL. Deep fadings in the T2-Lite RF spectrum cause lower robustness against lower LTE-DL RF signal level and RF spectrum overlap. On the other hand, robustness of the T2-Lite systems in both VU30 and MR100 channel models was very similar. Such a phenomenon is caused by similar features of considered channel models (e.g. Doppler spectrum) [35].

As mentioned in Chapter 2, the DVB-T2/T2-Lite system enables to use the MISO transmission technique. The usage of modified Alamouti encoding and two transmitting antennas, which do not radiate the same transmitted signal (no correlation between them), can increase the signal robustness through transmit diversity [11]. In addition, the MISO mode can improve the coverage of the TV reception in SFN networks [36], [37]. The study in [8] focused on the co-channel coexistence scenarios between DVB-T2 and LTE-UL systems, when DVB-T2 uses both SISO and MISO transmission techniques. To measure the performances of the interfered DVB-T2 system using SISO/MISO modes, the previously used measurement testbed had been extended and the measurement setup was improved. To emulate an DVB-T2 MISO SFN network in laboratory conditions, two SFU units from R&S were used, where the first one is marked as a master (central unit) and the second one is marked as a slave transmitter. By using the internal T2-modulator interface (T2-MI) generator, the master SFU unit can provide a 10 MHz reference clock as well as other synchronization signals (T2-MI & 1pps) required for the slave SFU unit. In the master SFU unit, appropriate video transport streams (TSs) were generated for SISO and MISO transmission modes, respectively. To be more precise, two different streams were used, one each for the SISO and MISO modes.

After that, in MISO mode, the TV input signal in the slave transmitter was set as an external signal ("received" from the master SFU). From the point of correct synchronization and same system configurations (in both master and slave devices) this was very important. Otherwise, highly destructive spectral interferences can occur [11]. The remaining parts of the measurement setup (e.g. generation of an LTE-UL RF signal with bandwidths of 1.4 MHz and 10 MHz) are the same as in previous measurements. It must be noted that the robustness of the DVB-T2 SISO/MISO system has been explored for different power imbalances of DVB-T2 signals (DVB-T2 RF signals from the master ($T\mathrm{X}_1$) and slave unit ($T\mathrm{X}_2$), respectively). Here, it is marked as $\Delta\mathrm{P}_{TV}$. The evaluation of the obtained results can be divided into three parts. In the first part, the established DVB-T2 objective parameters (BER before/after FEC decoding and MER) on the SDR ratio were analyzed. In the next part, the overall performance of the DVB-T2 TV signal distributed using the SISO and MISO techniques, coexisting with the LTE-UL signal, was investigated by analysis of variance (ANOVA). Finally, compatibility of the DVB-T2 and LTE-UL systems in the same coverage area were studied. Here, a method to calculate the required minimal protection distance (no interference) between the UE equipment and DVB-T2 Tx was derived. From the obtained results in the explored coexistence scenarios, the following conclusions were derived. The DVB-T2 MISO gain against interferences from the LTE-UL system at power imbalances higher than $\Delta\mathrm{P}_{TV} = 10\,\mathrm{dB}$ gradually decreases. In the considered coexistence scenarios, the performance of DVB-T2 for SISO and MISO transmission techniques at $\Delta\mathrm{P}_{TV} \geq 10$ dB is almost the same. This finding was also proved by one-way ANOVA [8]. Different bandwidths of LTE-UL RF signal affect the DVB-T2 RF signal (broadcasted by SISO and MISO techniques) in a different way. From this point of view, the DVB-T2 MISO signal has the highest robustness against interferences, but only for $\Delta\mathrm{P}_{TV} \in <0,10>$ dB.

This subsection, according to the main goals of this habilitation thesis (see Chapter 2), defined, described and analyzed possible coexistence scenarios between DVB-T/H/T2/T2-Lite and LTE-DL/UL systems. For measurement and evaluation purposes, a universal measurement testbed was realized. More details with a discussion of all achieved results in detail can be found in the enclosed copies of related papers [1]-[8].

4.2 Coexistence between LTE and WLAN

The volume of data transmitted in wireless systems has been growing over recent years. This is mainly due to the increased usage of various multimedia services in advanced user devices. Perspective approaches and advanced wireless communication systems with flexible parameters are essential for providing effective and reliable services in different scenarios and various qualities. Among these aims, it is also important to carefully choose the RF bands that communication systems using to provide their services. To extend the borders of LTE technology, the companies Qualcomm [38] and Huawei [39] provided innovation and transfer LTE technology to ISM unlicensed bands. This innovation has been planned as a complementary or supporting data pipeline in small cells where demands on user data are higher. Both mentioned companies have utilized the 2.4 GHz and 5 GHz ISM bands for LTE and take advantage of its signal propagation possibilities. The mentioned frequency bands are used especially for WLAN. Thanks to this, the possibility of unwanted interactions of these technologies in shared RF bands is high [32]. Hence, possible performance degradation of these communication systems should be measured and evaluated in an appropriate way.

A universal laboratory measurement setup for evaluating possible co-channel coexistence between LTE-DL and WLAN on their PHY level was presented in [9]. In this work, a WLAN system using IEEE 802.11n technology was assumed. Possible co-channel coexistence between LTE and WLAN can occur, when broadband mobile and Wi-Fi services are provided in the same area and the UE of LTE is located at the edge of cell coverage for a Wi-Fi access point (AP). The proposed laboratory measurement setup and methodology is slightly different from the previously presented solutions proposed for DVB-T/T2 versus LTE [1]-[8]. In the measurement, a two-channel signal generator R&S SMU200A was used to create LTE-DL and Wi-Fi (according to the IEEE 802.11n Tx block) signals with bandwidths 1.4 MHz and 20 MHz, respectively. The working frequency of both signals was set to 2.412 GHz. After combining both RF signals, performance degradation of LTE-DL was measured by the R&S FSW26 signal analyzer. The R&S FSW26 signal analyzer supports measuring of raw BER depending on the allocation of resource elements using an allocation summary feature. Raw BER can be measured for all LTE-DL control channels in DL direction and it is an evaluation parameter of the measurement. LTE control channels are used for signaling and transferring system information from eNodeB to individual UE equipment (e.g. user equipment power level settings, type of precoding) [40]. The whole measurement was automatized, because R&S devices are connected via a USB interface to a PC equipped with MATLAB software and parameters of both systems are set by a custom written application.

This application also allows to evaluate and save the measured results continuously (e.g. EVM values from the allocation summary). BER results, as a function of the carrier-to-interference-plus-noise ratio (CINR), were measured for three LTE-DL control channels, namely Physical Control Format Indicator Channel (PCFICH), Physical Downlink Control Channel (PDCCH), and Physical Hybrid ARQ Control Channel (PHICH) [40]. The reference level of BER in all cases was 1×10^{-3}, according to [40]. The obtained results showed that the PHICH control channel has the highest resistance to interference, whereas PCFICH needs the highest CINR ratio to achieve the reference BER level. The proposed measurement methodology and related results have been verified by theoretical (simulation) results. Results from simulations and measurements corresponded in the range from 0.9 dB to 3.5 dB.

As was mentioned previously, simulation-based coexistence models are essential to explore the behavior of coexisting wireless communication systems with various configurations. In the work [10], an appropriate software-based approach to emulate and evaluate co-channel coexistence between LTE-DL and WLAN (IEEE 802.11n) on link-level in ISM bands was proposed. For this purpose, the LTE downlink link level simulator, developed at TU Vienna [34], was adopted as the basic simulation tool. It was extended by adding physical downlink control channel models (PCFICH, PDCCH, PHICH and PDSCH). For emulation of the interfering Wi-Fi signal, a universal WLAN link-level simulator supporting IEEE 802.11n technology was proposed and realized. The simulator was adjusted for simulations of inter-system coexistence. Motivated by processing time constraints, the simulator was implemented in baseband only. The whole process starts with generating LTE-DL and Wi-Fi IEEE 802.11n signals (a complex envelope) in baseband. Next, the power of LTE and Wi-Fi signal at the transmitter output is defined, respectively. LTE channel bandwidths of 1.4 MHz and 20 MHz are considered, and Wi-Fi with a bandwidth of 20 MHz. Finally, the signals of LTE-DL and Wi-Fi in the time domain are simply added. The simulation model assumes only AWGN channel conditions. Consequently, signal-to-interference ratio (SIR), defined after FFT operation in the LTE Rx block, is used to describe the level of interferences for LTE system. Overall, the proposed simulator enables to evaluate the following dependencies on SIR: block error rate (BLER) for PDSCH, PDSCH user data throughput, BER for PCFICH, and BER for PHICH. These results can be obtained for various Channel Quality Indicator (CQI) values. The CQI index [40] defines the corresponding modulation type and code rate, including channel coding efficiency. The analysis of the obtained results from the considered co-channel coexistence scenarios lead to the following general conclusions. LTE transmission is robust and resistant against interference from Wi-Fi services (IEEE 802.11n) in shared RF bands. User data transmitted via LTE PDSCH are well protected for the link with lower CQI index (from 1 to 11).

PDSCH link with CQI=12 operates properly for SIR greater than 15 dB. Using the PDSCH link with CQI higher than 12 is not suitable for LTE vs. Wi-Fi co-channel coexistence scenarios. Scalable bandwidth in LTE has inconsiderable impact on the PDCCH physical control channel performance (convolutional channel coding with code rate 1/3).

This subsection, according to the main goals of this thesis (see Chapter 2), defined and described possible co-channel coexistence scenarios between LTE-DL and WLAN systems. For measurement and evaluation purposes, a universal measurement testbed and MATLAB-based simulator were realized. More details with a discussion of all achieved results in detail can be found in the enclosed copies of related papers [9], [10].

5 APPLICANT'S PROFILE

In this section the applicant's profile is presented. The section is divided to three parts. The first and second parts focus on the applicant's pedagogical activities and supervised bachelor and masters works, respectively. The applicant's scientific activities are briefly presented in the third part.

5.1 Pedagogical Activities

The applicant's pedagogical activities started in 2009 covering several areas of wireless communication systems and signal processing. In 2009, as a Ph.D. student, he partly led laboratory exercises in the bachelor course *Fundamentals of TV Technology* (*BZTV*, winter semester). The laboratory exercises in this course covered the fundamentals of TV signal measurement.

Between 2010 and 2013, he partly led laboratory exercises in the master course *Digital Television and Radio Systems* (*MDTV*, winter semester). From 2014, he has lead it fully. Laboratory exercises in this course cover a wide range of measurement of digital TV services, broadcasted by DVB-S/S2, DVB-T/T2 and DVB-C standards. Moreover, attention is also devoted to digital video quality analysis and monitoring of MPEG-2 transport streams. The applicant in his Ph.D. years prepared a set of new laboratory exercises for this course within the frame of the project from the Council of Higher Education Institutions (*FRVŠ*) entitled *Education Workplace for Mobile Digital TV and* 2^{nd} *Generation DVB Systems (1303/2011/G1).* Within the frame of this project, new laboratory exercises, containing software tools and instructions, were proposed and realized to explore the performance of digital mobile TV standards (DVB-H/SH) and 2^{nd} generation DVB standards (DVB-S2/C2/T2). Thanks to financial support of this project, students obtained knowledge about the features of DVB-H/SH/S2/C2/T2 standards and their functional blocks which can directly influence the overall robustness of DVB-H/SH/S2/C2/T2 signals. Next, the applicant also participated in other FRVŠ projects, namely *Innovation of Laboratory Exercises in the Course Digital Television and Radio Systems (1283/2011/F1/a)* and *Innovation and Extension of Practical Education in the Course Video and Multimedia Technology (2370/2012/F1/a).* Financial support of these projects allowed modernization and extension of practical education in the above mentioned courses.

Since 2013, the applicant has been partly leading laboratory exercises in the bachelor course *Low-Frequency and Audio Electronics* (*BNFE*). Laboratory exercises in this course focus on the measurement of analog and digital low-frequency and audio signals, and on the parameters of amplifiers (e.g. class D and T).

5.1.1 Supervised Bachelor and Masters Works

The applicant aids as supervisor for bachelor and master theses in the fields of digital video broadcasting, image and video processing and wireless communications. From 2010 to 2017, he led altogether 11 successfully defended theses (6 bachelor theses and 5 master theses). These works from the viewpoint of their content can be divided to 3 topics: simulation and measurement based performance analysis of DVB standards, image video quality evaluation, and measurement of coexistence between wireless communication systems.

MATLAB-based simulation models[1, 2] to study performances of DVB-H/SH standards on PHY level were created. Next, other MATLAB-based models[3, 4] of DVB-T2/C2 standards with a GUI interface were developed for the purpose of exploring flexibility of these standards for different transmission scenarios. In one student work[5] a simple laboratory measurement workplace to explore the performance of the DVB-T2 standard under fixed transmission scenarios was proposed and realized. Outputs of these works directly supported the applicant's research activities.

A MATLAB-based application[6] was created for evaluating variously distorted images by different objective metrics. Later, this application was extended to evaluate short video sequences encoded by different encoding standards. An appropriate software application[7] was realized for subjective quality evaluation of short video sequences in different qualities. Furthermore, within this work a new laboratory exercise was prepared for the master course *Video and Multimedia Technology.*

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[1] HRACH, P. *Simulation of the RF Transmission Channel for the DVB-H and DVB-SH.* Brno University of Technology, Faculty of Electrical Engineering and Communication, 2011. 43 pages. Master's Thesis (in Czech) supervisor: Ing. Ladislav Polak

[2] ARVAI, L. *Simulation of the DVB-H and DVB-SH Transmission.* Brno University of Technology, Faculty of Electrical Engineering and Communication, 2011. 52 pages. Master's Thesis (in Czech) supervisor: Ing. Ladislav Polak

[3] STROUHAL, A. *Simulation of the RF Transmission Channel for the DVB-T2.* Brno University of Technology, Faculty of Electrical Engineering and Communication, 2011. 81 pages. Master's Thesis (in Czech) supervisor: Ing. Ladislav Polak

[4] CIBULKA, T. *Simulation of the DVB-C and DVB-C2 Transmission and Their Comparison.* Brno University of Technology, Faculty of Electrical Engineering and Communication, 2013. 56 pages. Master's Thesis (in Czech) supervisor: Ing. Ladislav Polak

[5] KOBLISCHKA, V. *Measurement of Diversity Broadcasting in DVB-T2 Standard.* Brno University of Technology, Faculty of Electrical Engineering and Communication, 2014. 50 pages. Bachelor Thesis (in Czech) supervisor: Ing. Ladislav Polak, Ph.D.

[6] NOGHE, P. *Video Stream Objective Quality Evaluation in MATLAB.* Brno University of Technology, Faculty of Electrical Engineering and Communication, 2011. 51 pages. Bachelor Thesis (in Czech) supervisor: Ing. Ladislav Polak

[7] KRMELA, T. *Subjective Quality Evaluation of Video Sequences.* Brno University of Technology, Faculty of Electrical Engineering and Communication, 2012. 81 pages. Master's Thesis (in Czech) supervisor: Ing. Ladislav Polak

The next work in this field focused on a comparison of advanced video codecs VP9 and H.265 by objective metrics and subjective tests[8]. Moreover, a new laboratory exercise was proposed for the master course *Digital Television and Radio Systems*, in which students are able to try to evaluate the quality of a set of video sequences subjectively. Finally, a complex measurement workplace[9] to measure the quality and errors of digital video in MPEG-2 transport stream at the DVB-T receiver was realized. It also enables continuous monitoring of errors of digital video in MPEG-2 transport stream and save the results for further analysis. All the above briefly presented works helped to extend laboratory exercises in the master courses *Digital Television and Radio Systems*, and *Video and Multimedia Technology.*

Advanced laboratory measurement workplaces and appropriate measurement methodologies to measure different coexistence scenarios between DVB-T/T2 and LTE systems[10] and between LTE and WLAN systems[11] were proposed and realized, respectively. Moreover, in both cases, new laboratory exercises were prepared for the master course *Digital Television and Radio Systems.* It is important to note, that main outputs of the work[10] were successfully presented at the *TSP2016* conference [7]. Both works directly supported the applicant's research activities and extended outputs of several research projects.

A part of several bachelor and master's thesis[7,8,10,11] were also successfully presented at the conferences for young designers and researchers Electrical Engineering, Information and Communication Technologies (EEICT) between 2012 and 2017 under the applicant's supervision. In addition, the applicant aided as a supervisor on the work[12], which was presented at the EEICT conference in 2018.

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[8] FENDRICH, V. *Comparison of VP9 and H.265 Encoding Standards.* Brno University of Technology, Faculty of Electrical Engineering and Communication,Faculty of Electrical Engineering and Communication, 2017. 65 pages. Bachelor Thesis (in Czech) supervisor: Ing. Ladislav Polak, Ph.D.

[9] KADLČEK, J. *Measurement of Quality and Errors of Digital Video in MPEG-2 TS at DVB-T Reception.* Brno University of Technology, Faculty of Electrical Engineering and Communication, 2011. 92 pages. Bachelor Thesis (in Czech) supervisor: Ing. Ladislav Polak

[10] PLAISNER, D. *Co-existence of the still used and upcoming Digital Terrestrial Television and Mobile Communication Services.* Brno University of Technology, Faculty of Electrical Engineering and Communication, 2015. 100 pages. Bachelor Thesis (in Czech) supervisor: Ing. Ladislav Polak, Ph.D.

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5.2 Scientific Activities

From 2009 to 2017, the applicant led two projects and was a member of a team in several projects of fundamental research. In the following paragraphs, a brief description of a few projects and the applicant's role in these projects is described.

In 2011, the applicant led the project *Education Workplace for Mobile Digital TV and 2^{nd} Generation DVB Systems (1303/2011/G1)* founded by *FRVŠ*. Within the frame of this project, new laboratory exercises, containing software tools and instructions, were realized to explore performances of digital mobile TV standards (DVB-H/SH) and 2^{nd} generation DVB standards (DVB-S2/C2/T2). In 2011 and 2012, the applicant participated in two other *FRVŠ* projects, namely *Innovation of Laboratory Exercises of the Curse Digital Television and Radio Systems (1283/2011/F1/a)* (led by prof. Tomas Kratochvil) and *Innovation and Extension of the Practical Education of the Curse Video and Multimedia Technology (2370/2012/F1/a)* (led by assoc. prof. Martin Slanina). In both projects, the applicant dealt with modernizing and extending practical education in the master courses *Digital Television and Radio Systems*, and *Video and Multimedia Technology.*

From 2010 to 2014, the applicant was a member of a team in a fundamental research project financed by the Czech Scientific Foundation (GAČR), *P102/10/1320 - Research and modeling of Advanced Methods of Image Quality Evaluation* (co-led by prof. Tomas Kratochvil). This project focused on the research of image quality assessment in technical image systems, where a human observer is the final evaluator. One of the main outputs of this project was the creation of a database of typical image distortions and artifacts in systems for sensing, transmission, reproduction, retrieving and processing of image information. In addition, the project was solved in close relation to Video Quality Experts Group (VQEG) activities. The applicant, within the framework of the project *P102/10/1320*, focused on the research of signal processing in DVB-T/H/T2 standards, objective and subjective video image quality evaluation, and dealt with the realization and evaluation of several subjective tests.

From 2012 to 2014, the applicant was a member of a team in a fundamental research project, financed by the Ministry of Education, Youth and Sports (MEYS), *LD12005 - Quality of Experience Aspects of Broadcast and Broadband Multimedia Services (QUALEXAM)* (led by prof. Tomas Kratochvil). It was oriented to analyzing and modeling of current and emerging video coding and transmission tools, used for broadband multimedia services, with the aim of exploring their impact on the subjective quality of the resulting video. Its scope was closely related to the COST Action IC 1003 QUALINET (2010-2014). The applicant within the framework of the project *LD12005* focused on the evaluation of image video quality services in DVB-T/T2 systems on PHY level by objective and subjective metrics.

From 2011 to 2014, the applicant was a member of a team in an applied research project, financed by MEYS, *7H11097 - Agile RF Transceivers and Front-Ends for Future Smart Multi-Standard Communications Applications (ARTEMOS)* (CZ cluster coordinator prof. Tomas Kratochvil). This project focused on developing architectures and technologies for implementing agile RF transceiver capacities in future radio communication products. The applicant within the framework of the project *7H11097* focused on the study of possible coexistence scenarios between digital broadband TV and mobile systems.

From 2014 to 2016, the applicant was a member of a team in a fundamental research project financed by MEYS, *LF14033 - Coexistence of RF Transmission in the Future (CORTIF)* (CZ cluster coordinator prof. Tomas Kratochvil). Project *CORTIF* focused on the study of possible coexistence scenarios between advanced wireless communication systems on both technology (the same PCB board) and application level (the same location). The applicant within the framework of the project *LF14033* focused on defining and measuring coexistence scenarios between wireless communication systems in a wide range of the RF spectrum. There were proposed and realized a measurement setup and methodology to evaluate the robustness of coexisting systems. Furthermore, in collaboration with company *IMA*[13], the technology Bluetooth Low Energy (BLE) for localization purposes was explored.

From 2015 to 2016, the applicant led the project *LD15020 - Quality Optimized Coding and Transmission of Stereoscopic Sequences (QOCIES)*, financed by MEYS. Project *QOCIES* dealt with research of efficient techniques for 3D video coding and its Quality of Experience (QoE) evaluation in modern multimedia systems. Its scope was closely related to COST Action IC 1105 3D-ConTourNet (2012-2016). The project explored algorithms for encoding of different kinds of 3D image/video contents and their optimization with focus on the maximally achievable QoE for a fixed transmission scenario.

In 2017, the applicant was a member of a team in a fundamental research project financed by MEYS, CORTIF II *LTE117004 - Coexistence of RF Transmission in the Future (CORTIF II)* (CZ cluster coordinator prof. Tomas Kratochvil). Project *CORTIF II* focused on the study of BLE localization performances in indoor scenarios based on a received signal strength (RSS) parameter. The applicant within the framework of the project *LTE117004* proposed a measurement testbed and a method to evaluate the accuracy of localization on the number of BLE beacons.

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[13] `http://www.ima.cz`

6 PRACTICAL RESULTS AND PRODUCTS

This section contains a brief overview of the practical results which were realized within basic research projects. The applicant took part in several basic research projects and he has co-authored several products and software applications. The realized products are briefly listed in the following subsections. Full records of products are available at websites[1].

6.1 Player for Subjective Tests of Video Sequence Quality

A player was created for subjective tests of video sequence quality (authored by: M. Slanina, L. Polak, O. Kaller and T. Kratochvil)[2] allowing for playback of video sequences on MS Windows and Linux platforms with concurrent communication with a peripheral device via USB or serial interfaces. The peripheral is a slider device which replies to a text query with a number representing the position of the slider between 1 and 100. In accordance with the recommendation of ITU-R BT.500, the scores are scanned and recorded twice a second. The designed software can perform precise time synchronization of the video sequences played back and the recorded slider positions. The software has been developed in the JAVA language and is distributed under the GNU GPL license. This product was created in 2011 for the *P102/10/1320* project *Research and modeling of Advanced Methods of Image Quality Evaluation* (2010-2014), solved at the Centre of Sensor, Information and Communication Systems (SIX).

6.2 Slider Device for Subjective Quality Evaluation of Picture and Video

A slider device (electronic recording handset), realized in 2013 (authored by: L. Polak, O. Kaller, L. Bolecek, M. Slanina and T. Kratochvil)[3], allows a subjective quality assessment of images and short video sequences, according to the ITU-R BT.500 standard. For the communication between the PC (or notebook) and the unit (user) a USB bus is used, from which it is simultaneously supplied.

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[1] `https://www.vutbr.cz/en/people/ladislav-polak-83338/tvurci-aktivity`

[2] `http://www.urel.feec.vutbr.cz/index.php?page=software&lang=eng`

[3] `http://www.urel.feec.vutbr.cz/web_documents/produkty/2013/Polak_DEIMOS_Pot_vzor_EN.pdf`

The peripheral slider device contains a universal FT232 circuit for the conversion of data communication between the USART and USB interface. The range of the slider is linear and its length corresponds to the recommendations of the ITU-R BT.500 standard. The slider device replies to a text query responds with a number, representing the position of the slider between 0 and 100. For the correct evaluation of the slider's position a complete algorithm (firmware) was written and implemented. The designed device, with an appropriate application, is independent to the used operation system (Windows, Linux). This product was created for the *P102/10/1320* project *Research and modeling of Advanced Methods of Image Quality Evaluation* (2010-2014), solved at the SIX research Centre.

6.3 Control Software for A Bond Wire Tester

Control software for a bond wire tester (authored by: J. Petrzela, T. Gotthans, R. Sotner, J. Drinovsky, T. Kratochvil and L. Polak)[4] was developed in MATLAB and is dedicated to control six-channel bond wire tester. It uses an internal PCI card National Instruments 6251 supplemented by professional interface from the same company. The program with a GUI has two parts: a part for test sequence generation and a part focused on measurement. The first script allows the generation of an arbitrary pulse sequence where up to nine bursts can be connected; each with a different time window and pulse widths, inserting cooling delays and signal inversion. Data sequences are not directly described in time domain; the time scale is chosen separately and thus can be used for expansion or compression while the overall shape of the signal is preserved. The main program is aimed to address and sequentially measure up to six bond wires with up to six different currents of power source. Bonding wires are addressed digitally by using three bits. For each adjusted current it is possible to use another four bits to control gains of a cascade connection of two amplifiers (13 possible combinations) for amplifying voltage drop across bond wires. Measurement can be considered as single channel to monitor robustness of the bond wires or two-channel for calculating the change of resistance. Results are stored in text file. A time vector can be added to the output file. The entire testing procedure can be stored and automatically loaded before starting the main program. For the purpose of hardware debugging, all digital outputs can be set manually and independently on the state of the measurement. This product was created in 2014 for the *FP7-ICT no. 619166* project *Nanoelectronic COupled Problems Solutions (nanoCOPS)* (2014-2016), solved at the SIX research Centre.

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[4] `http://www.urel.feec.vutbr.cz/web_documents/software/2014/Petrzela_bondwire_software_EN.pdf`

6.4 UHF Linear Power Amplifier

A UHF linear power amplifier (authored by: J. Sebesta, O. Kaller, L. Polak and A. Povalac)[5] was realized for the bands from 650 MHz up to 850 MHz with an output power of 5 W. The gain of the amplifier is at least 34 dB in the entire band. The amplifier is based on an RA0608 series RF hybrid circuit, with the optimum setting of the operating point to achieve linear mode. The amplifier is integrated into the instrument case with a power supply of 230 VAC and an SWR measurement module including display elements. The amplifier is primarily dimensioned for researching DVB-T/T2 signal propagation and its coexistence with other wireless communications systems in the defined UHF bands. However, it may be used for other measurements. This product was created in 2015 for the *LF14033* project *Coexistence of RF Transmissions in the Future (CORTIF)* (2014-2016), solved at the SIX research Centre.

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[5] `http://www.urel.feec.vutbr.cz/web_documents/produkty/2015/Cortif_HW_EN.pdf`

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LIST OF ABBREVIATIONS

3GPP	Third Generation Partnership Project
ANOVA	Analysis of Variance
AP	Access Point
AWGN	Additive White Gaussian Noise
BCH	Bose-Chaudhuri-Hocquenghem
BER	Bit Error Rate
BLE	Bluetooth Low Energy
BLER	Block Error Rate
CQI	Channel Quality Indicator
C/N	Carrier-to-Noise Ratio
CINR	Carrier-to-Interference-Plus-Noise Ratio
DTT	Digital Terrestrial Television
DVB-H	Digital Video Broadcasting-Handheld
DVB-T	Digital Video Broadcasting-Terrestrial
DVB-T2	2nd Generation Digital Video Broadcasting-Terrestrial
DVQ	Digital Video Quality
eNodeB	Evolved Node B
EPA	Extended Pedestrian A
EVM	Error Vector Magnitude
FEC	Forward Error Correction
FDD	Frequency Division Duplexing
GB	Guard Band
GSM	Global System for Mobile Communication
HeNB	Home eNodeB
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ISM	Industrial, Scientific and Medical
ITU	International Telecommunication Union
LDPC	Low-Density Parity-Check
LTE	Long Term Evolution
MAC	Media Access Control
MATLAB	Matrix Laboratory
MER	Modulation Error Ratio
MISO	Multiple Input Single Output
MIMO	Multiple Input Multiple Output
MR100	Motorway Rural
M-QAM	M-ary Quadrature Amplitude Modulation

NthG	Nth Generation of Mobile Telecommunication Technologies
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PCFICH	Physical Control Format Indicator Channel
PDCCH	Physical Downlink Control Channel
PHICH	Physical Hybrid ARQ Control Channel
PHY	Physical Layer
PI	Pedestrian Indoor
PP	Pilot Pattern
QoE	Quality of Experience
QoS	Quality of Service
RF	Radio Frequency
RSS	Received Signal Strength
SC-FDMA	Single-Carrier Frequency Division Multiple Access
SDR	Spectral Density Ratio
SIR	Signal-to-Interference Ratio
SLR	Spectral Level Ratio
SNR	Signal-to-Noise Ratio
SFU	Single Frequency Unit
SISO	Single Input Single Output
SSCQE	Single Stimulus Continual Quality Evaluation
TDD	Time Division Duplexing
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
USB	Universal Serial Bus
USRP	Universal Software Radio Peripheral
VU30	Vehicular Urban
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Network
WRC	World Radio Conference

ENCLOSED COPIES OF PAPERS

[1] POLAK, L., KALLER, O., KLOZAR, L., SEBESTA, J., KRATOCHVIL, T. Mobile Communication Networks and Digital Television Broadcasting Systems in the Same Frequency Bands: Advanced Co-Existence Scenarios. *Radioengineering*, 2014, vol. 23, no. 1, pp. 375–386. ISSN: 1210-2512. (55%)

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 ÷ 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].

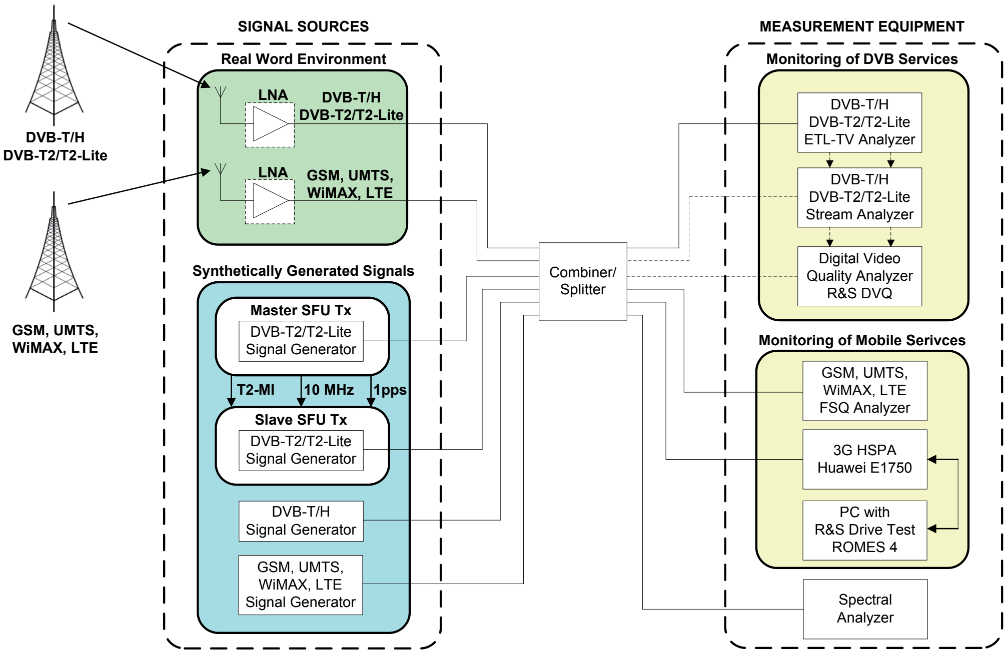


Fig. 1. General block diagram of a workplace for measuring interactions between wireless mobile networks and DVB services.

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.

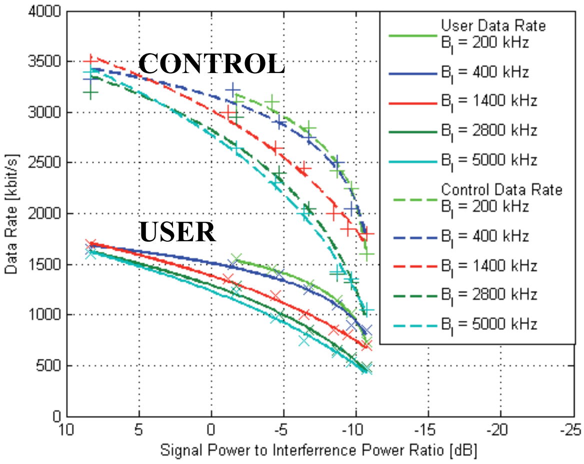


Fig. 2. Dependences of "User" and "Control" data rates on the signal to interference power ratio (PR) for different bandwidth of interfering signals.

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].

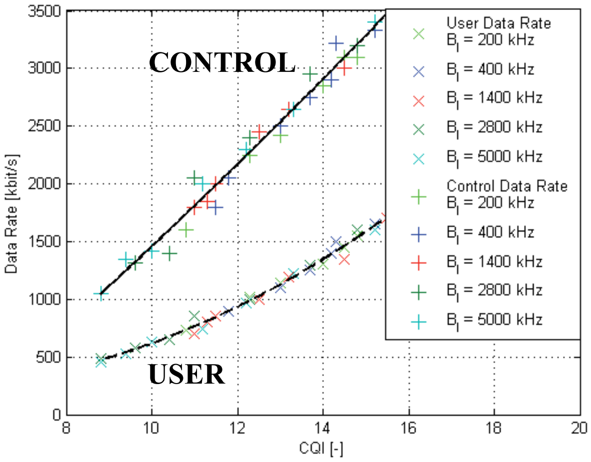


Fig. 3. User data rate (USR), Control information data rate (SCCH) on MAC layer in dependence of the CQI values for different bandwidth of interfering signals.

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].

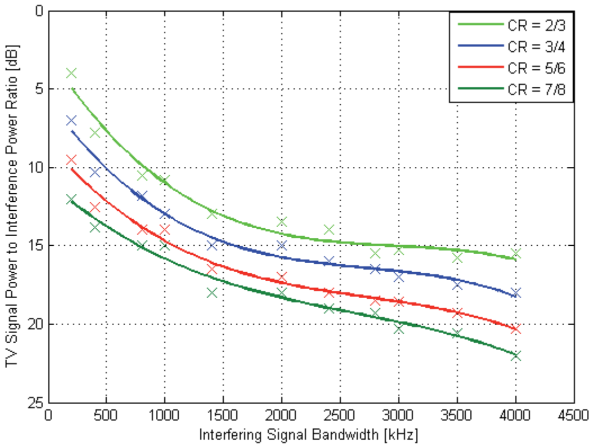


Fig. 4. Dependence of the TV signal power to interference power ratio on interfering signal bandwidth. The measurement was done for the FEC code rates (CR) which are the most widely used in DVB-T/H.

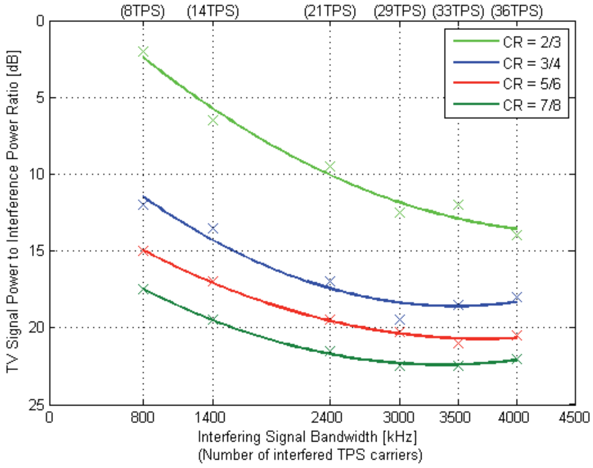


Fig. 5. Dependence of the TV signal power to interfering signal power ratio on the interfering signal bandwidth for dedicated TPS interfering signals. The measurement was done for the FEC code rates (CR) which are the most widely used in DVB-T/H.

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).

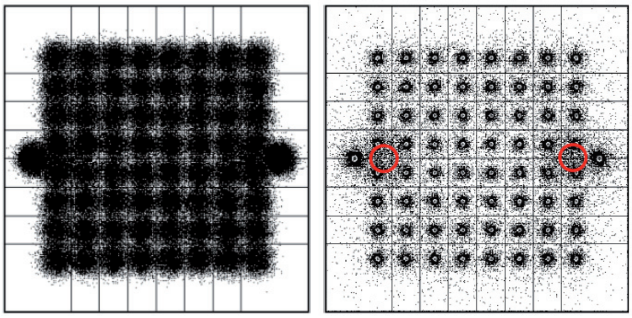


Fig. 6. Constellation diagram of 64QAM in the DVB-T/H system, when the DVB-T/H RF signal is highly affected by the GSM/LTE network (left). Picture on the right shows the interfered TPS carriers (denoted by red circles). The MERs are equal to 19 dB and 25 dB, respectively.

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.

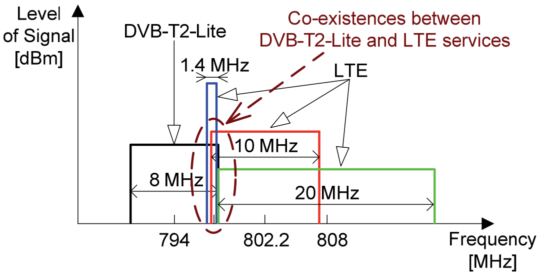


Fig. 7. Spectrum of analyzed co-existence scenarios between LTE (marked by blue, red and green colors) and DVB-T2-Lite (marked by black color) services.

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].

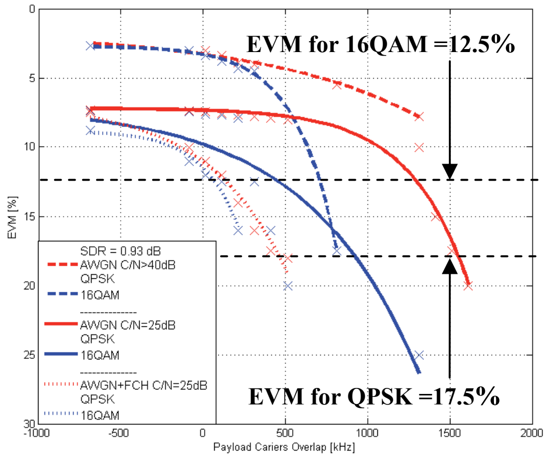
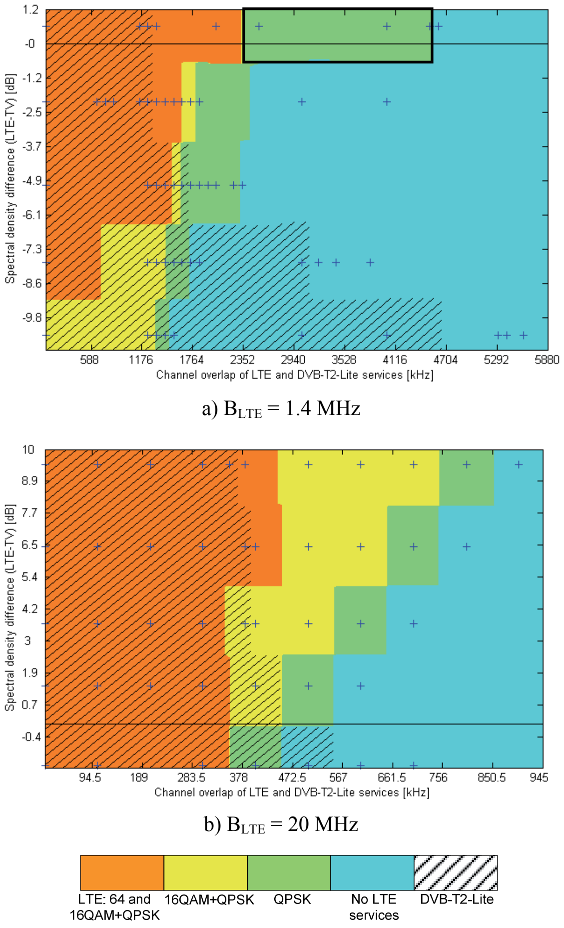


Fig. 8. EVM dependency, using QPSK and 16QAM modulations in the LTE system, on the level of frequency overlap between the DVB-T2-Lite and LTE services, working abreast in the same frequency band at ideal and portable (PI and EPA 5Hz) fading channel conditions.

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.



a) B_{LTE} = 1.4 MHz

b) B_{LTE} = 20 MHz

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, subframes 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].

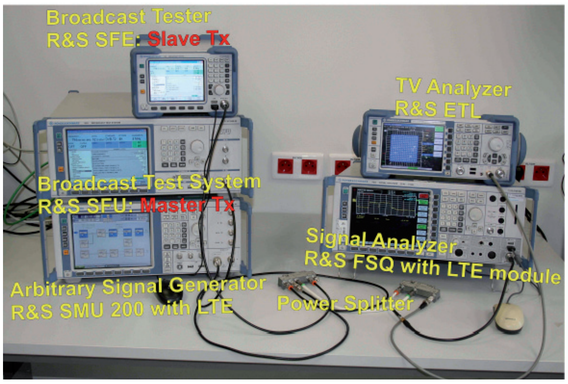


Fig. 10. Realized laboratory workplace for measuring the interaction between DVB-T2 (SISO and MISO configuration) and LTE-CR networks.

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.

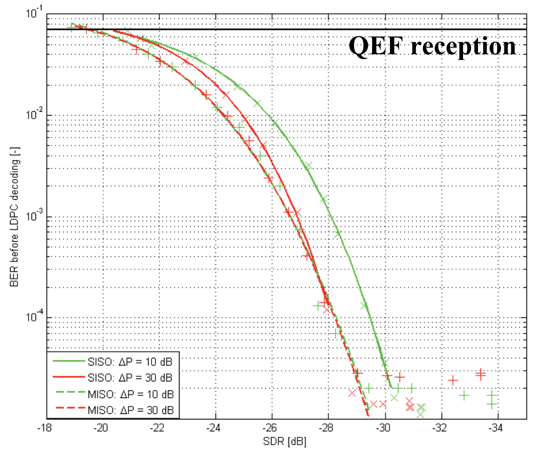


Fig. 11. Dependences of channel errors in DVB-T2 on the SDR ratio, when DVB-T2 and LTE services are co-existing. DVB-T2 services are broadcasted by SISO and/or MISO technique, when transmitted powers of TV transmitters are different (power imbalance). The bandwidth of LTE signal is 10 MHz.

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.

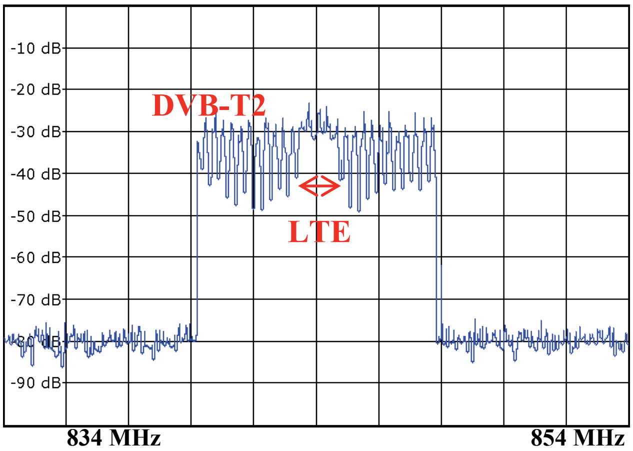


Fig. 12. RF spectrum of co-existing DVB-T2 (SISO technique) (TX1 = TX2 = 72 dBμV) and LTE-CR (70.8dBμV) services. The limit for an error-free reception in the DVB-T2 is not fulfilled. The B_{LTE} is equal to 1.4 MHz.

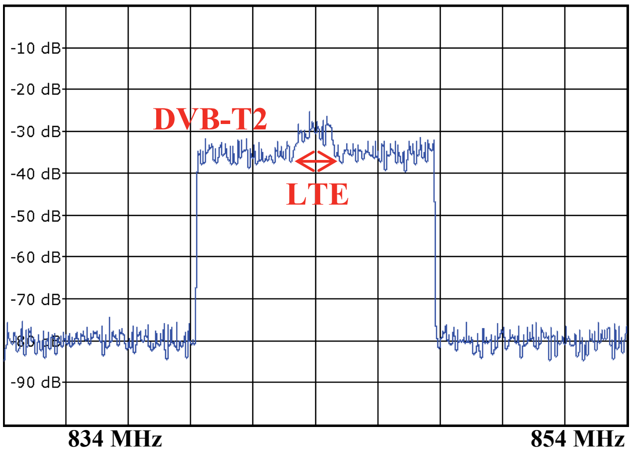


Fig. 13. RF spectrum of co-existing DVB-T2 (MISO technique; TX1 = 42 dBμV and TX2 = 72dBμV) and LTE-CR (70.8 dBμV) services. The limit for an error-free reception in the DVB-T2 is not fulfilled. The B_{LTE} is equal to 1.4 MHz.

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.

Acknowledgements

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Exploring and Measuring Possible Co-Existences between DVB-T2-Lite and LTE Systems in Ideal and Portable Fading Channels

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ABSTRACT

From the point of technical innovations the development and standardization of Digital Video Broadcasting - 2nd Generation Terrestrial (DVB-T2) and Long-Term Evolution (LTE) systems are definitely the most significant results in the last decade. These systems have a very high potential to fulfill the highest user requirements, but they can operate in the same frequency spectrum. As a result, different co-existence scenarios can occur. In this paper, we explore and measure the co-existence between DVB-T2-Lite (e.g. portable TV) and LTE multimedia services in ideal and portable fading channel models. Theoretical backgrounds of the investigated co-existence scenarios, proposal and realization of an appropriate workplace for their measuring and evaluation are presented and described. Moreover, deeper investigation of the mutual influence of the DVB-T2 system on the LTE one is also explored and graphically illustrated. The obtained results show that these co-existences could be critical for both systems from the point of providing multimedia services with a constant level of Quality of Services (QoS).

Keywords: DVB-T2-Lite, LTE, Co-existence of wireless systems, portable fading channels, SDR, BER, EVM, MER.

1. Introduction

The use of advanced wireless and mobile networks has expanded into the daily life of people. They can provide many useful services which people use every day and their life without these services is unimaginable. However, demands from users on these services are higher and higher. The concept “access to anyone, anywhere, at any time” is nowadays the main target of each mobile and broadcast system. Hence, increasing demand for steady wireless multimedia services is a key feature of modern markets. Consequently, research for next generation wireless communication standards is focused on the development of robust, but also effective transmission systems which can operate in a high range of the frequency spectrum [1]-[3].

To fulfill these requirements, 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 as from 2015, and allowed several Europe regions before 2015. However, from a technical and market perspective, this decision will give rise to creating new interference scenarios and co-existence between two types of services, using the same or adjacent frequency bands. In our concrete case, these two services should be the newest mobile (e.g. LTE) and TV broadcast services (DVB-T2) [1], [4], [5].

Based on recent research results and a set of commercial requirements, the Digital Video Broadcasting (DVB) consortium has successfully developed the second generation of satellite (DVB-S), cable (DVB-C) and terrestrial (DVB-T) standards, marked as DVB-S2/C2/T2. From the point of features, the DVB-T2 technology will be the most used DVB standard that could provide increased capacity and robustness in the terrestrial environment, mainly for high definition TV (HDTV) broadcasting. Moreover, within the DVB-T2 standard a new profile DVB-T2-Lite has been developed. It allows simple implementations of the receiver for low capacity applications, like mobile or portable TV broadcasting. It is based on the same core of technology as the DVB-T2 standard, but only uses a limited number of available modes. More precisely, it avoids modes which require the most complexity and memory and allows more efficient receiver designs (power consumption, smaller silicon size) to be used. More technical details and recommendations for the DVB-T2-Lite profile can be found in [6]-[8]. DVB-T2/T2-Lite services, such as DVB-T, are operating within the existing VHF (174 ÷ 230 MHz) and UHF (470 ÷ 870 MHz) spectrum.

The development in the field of mobile communications is also rapidly increasing. The goal of this development is to increase the capacity and speed of wireless data networks (its redesign and simplification), using new techniques and modulations. The result is a very perspective Long-Term Evolution (LTE) system that will definitely replace the current GSM/UMTS standards in the future. The LTE, as defined by the 3GPP (3rd Generation Partnership Project), is a very flexible radio interface that offers a high scale of adjustable system parameters [9]-[11], higher than also very perspective High Speed Packet Assess (HSPA) [3]. The LTE services can be operated in the frequency bands that are already available for existing 3G networks (880 ÷ 960 MHz). Moreover, additional ranges (2.5 ÷ 2.7 GHz), and frequencies (791 ÷ 821 MHz), are allocated for usage [4].

Thanks to significant technical innovations DVB-T2-Lite and LTE systems have a great potential to give wireless multimedia services in high quality. However, both of them can work in the same frequency bands [4]. Hence, there are possible different co-existence and unaware interference scenarios. The focus of this paper is to explore and measure the possible co-existences between DVB-T2-Lite and LTE services and their impact on the quality (on the physical layer) of both services. Moreover, in our measurement we will consider not only an ideal channel environment, but also portable fading channel conditions.

The rest of this paper is organized as follows. After the introduction, the state-of-the-art in this field is presented in Section 2. The explored co-existence scenarios, considered portable fading channel models, and used system parameters are outlined in Section 3. This section also contains a brief description of our proposed and realized workplace and method for measuring interactions between the explored mobile services. Section 4 contains the evaluation and discussion of the results, obtained from our measurements. Finally, the paper concludes in Section 5.

2. Background and related works

Unwanted co-existence scenarios between different wireless systems which work in the same or adjacent frequency spectrum is not a new phenomenon [12]-[14]. The impact of the co-existence and interferences between different wireless communication services on the capacity and Quality of Services (QoS) is still being explored today. The topicality of this issue is evidenced by a lot of studies and research.

In literature many works can be found which deal with this topic and, in general, they can be divided into 2 main groups. First group of these works focuses on the investigation of the co-existence and adjacent channel interferences between different but same kind of wireless systems, e.g. mobile systems and networks [15]. In [16] authors proved that in advanced mobile networks between femto cells which share common frequency spectrum with macro cells so-called cross-tier interferences can occur. Brief study of intra/inter interferences which may occur from the co-existence between Worldwide Interoperability for Microwave Access (WiMAX) and LTE at uplink were presented in [17]. The common result of the mentioned studies was that these mutual interferences [18] can decrease the quality and the capacity of the considered 3G/4G mobile networks (GSM, UMTS, WIMAX and LTE).

The second group includes studies which deal with investigation, modeling, simulating and measuring of interference scenarios, occurring between different communication standards [19], e.g. DVB and mobile system. In [1], [5], [20], [21] different types of interferences (e.g. blocking interference, spurious emissions interference and adjacent channel interference) are investigated, not only on DVB-T/H (Terrestrial/Handheld), but between DVB-T/H and other types of wireless services operating in the UHF frequency band. Furthermore, authors in [20] and [22]-[24] deal with possible cross-border interferences which can occur when UMTS and LTE mobile systems interfering into DVB-T broadcasting system, respectively.

As can be seen from presented references, exploring interferences, as a product of different co-existence scenarios of different multimedia technologies, is a perspective and hot topic. In our last works [25], [26], we explored the influence of mobile network interfering products on DVB-T/H broadcasting services. In this extended paper (based on [27]), we focus on measuring interactions between DVB-T2-Lite and LTE services. Both of these services are potential candidates to provide multimedia services in high quality for mobile terminals and both of them can be operated in the same frequency range.

3. Explored co-existence scenarios and proposed experimental measurement

As it was mentioned above, we are mainly focusing on the co-channel scenarios where the wanted (useful) and the unwanted (interfering) signals are located in the same frequency band. In this part, behind the outlined co-existence scenarios, the proposed and realized workplace and the measurement setup are introduced.

3.1 Conception and analyzed co-existence scenarios

We consider a co-existence scenario, when an LTE base transceiver station (BTS), transmitting a downlink signal, acts as an interferer on the digital TV (DTV) receiver and vice versa. The general scenario is clearly illustrated in Fig. 1. We have a common cell for DVB-T2-Lite and LTE services. The owner of a tablet is receiving DVB-T2-Lite services at a frequency of 794 MHz. At the same time, another user of a smartphone is receiving LTE services, provided from a mobile operator at a frequency of 802.2 MHz. In the case, when the bandwidth of the LTE signal is 10 MHz, then it can interfere with the upper spectrum side of the T2-Lite signal (from 794 to 798 MHz). It means visible artifacts in the DTV reception or complete failure to receive the wanted (DVB-T2-Lite) signal. Of course, the level of the impact of occurred interferences depends on the level of the unwanted signal. Other possible co-existence scenarios, which are considered in this work, are plotted in Fig. 2.

3.2 Considered fading channel models

In mobile/terrestrial wireless communications, the transmitted radio waves often do not reach the receiving antenna directly. In real terrestrial transmission scenarios, the line-of-sight (LOS) path is always affected by different obstacles (e.g. trees, hills, buildings, moving cars). Distribution of the DVB-T2-Lite and LTE mobile multimedia services by way of terrestrial transmitters is the natural technology of broadcasting. The received signal should be interpreted as the overall effect, the sum of various influences created by noise, interference and Doppler shift and type of distribution (spectrum) [28].

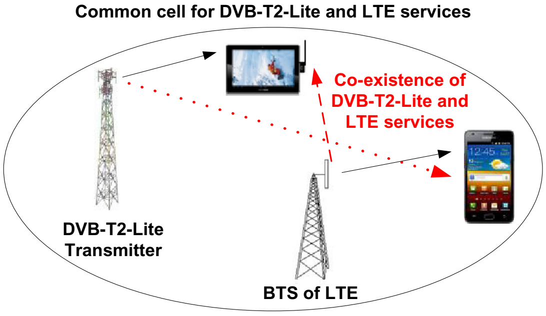


Figure 1. Possible co-existence scenario, when DVB-T2-Lite and LTE services are operated in the same frequency band.

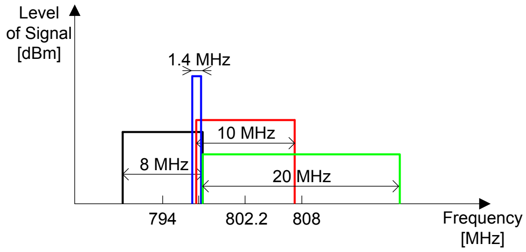


Figure 2. Spectrum of analyzed co-existence scenarios between DVB-T2-Lite (black color) and LTE (blue, red and green colors) services.

In this paper we will investigate the above described co-existence scenarios in the portable fading channel too. We considered that both T2-Lite and LTE services are transmitted/received in a pedestrian indoor environment. Therefore, in our experiments we used pedestrian indoor (PI) and extended pedestrian A (EPA 5Hz) fading channel models, respectively.

The PI channel model has been developed by the Wing-TV project for describing slowly moving (at a speed approx. 3 km/h) handheld indoor TV reception [28]. 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 [29]. When the working frequency is 794 MHz, then the maximal Doppler shift is approx. equal to 2.2 Hz.

Particularly, in the LTE system, the EPA channel model is used to model the reference environment characterized by a low delay spread [30]. The main parameters of this model are specified in [31]. 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 5Hz. Impulse response of both fading channel models are plotted in Fig. 3 and Fig. 4.

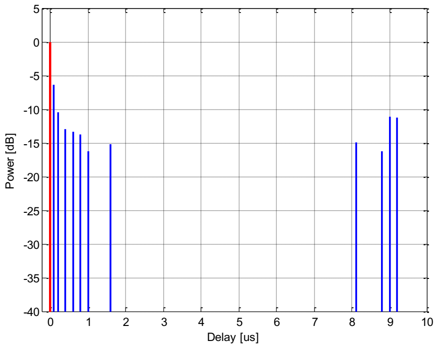


Figure 3. Impulse response of the PI channel.

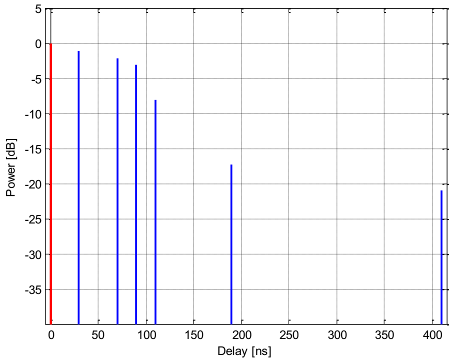


Figure 4. Impulse response of the EPA 5Hz channel.

3.3 Measuring setup and principle of the measuring

Our purpose is to measure the impact of the interfering LTE services on the degradation of performance of the DVB-T2-Lite ones and vice versa when these services are operating in the same frequency band. The proposed general block diagram of the realized measurement of co-existences between both mobile services is shown in Fig. 5. Based on this conception, a laboratory workplace (in the Laboratory of Mobile Communication Systems, Brno University of Technology) was realized with appropriate measurement equipment (see Fig. 6), supported by the SIX research center [32].

The basic principle of our measurement method is as follows. In our case, the interfered DVB-T2-Lite signal is generated at a frequency of 794 MHz. It has a classic 8 MHz bandwidth, works in 2K orthogonal frequency division multiplexing (OFDM) and uses 16QAM inner non-rotated modulation. The measuring technique consists of keeping a constant level of T2-Lite signal and increasing the level of the interfering signal. We set the level of the DVB-T2 signal at a value of -55.8 dBm [33].

The generated LTE services, which negatively affect broadcasted mobile TV services, operate at frequencies from 791 MHz to 821 MHz [3]. In this frequency spectrum, LTE transmits in the downlink using frequency-division duplexing (FDD) duplex mode. The LTE signals, which interact with DVB-T2-Lite mobile services, are produced in R&S SMU200A. LTE uses QPSK, 16QAM and 64QAM modulation formats along with scalable channel bandwidths from 1.4 MHz to 20 MHz. Hence, we have generated different LTE signals with different bandwidths and types of modulations. Ten sub-frames were generated, where the used modulation types were equally used (3xQPSK; 3x64QAM and 4x16QAM). The bandwidths of LTE signals were 1.4, 10, and 20 MHz, respectively.

After sufficient generation of both wireless services, they are combined and then the splitter is used for dividing both signals, which are measured with appropriate measuring devices (see Fig. 6). More detailed system settings, which were used for our measurement, are summarized in Table 1.

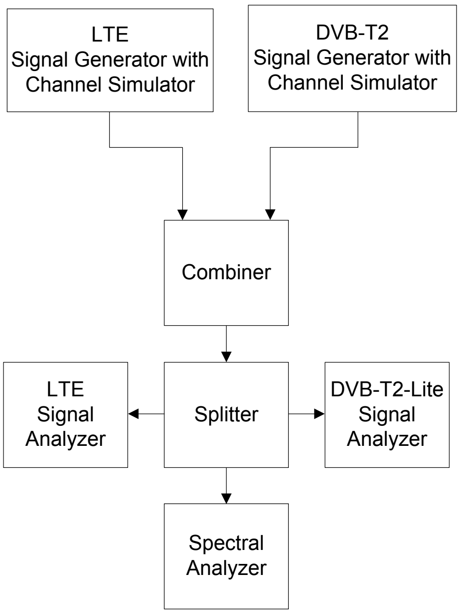


Figure 5. General block diagram of workplace for measuring the interaction between DVB-T2-Lite and LTE networks.

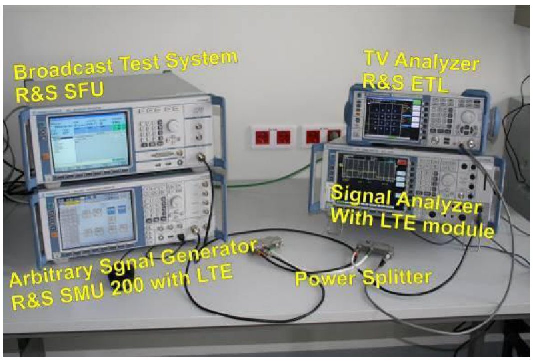


Figure 6. Realized laboratory workplace for measuring the interaction between DVB-T2-Lite and LTE services (LTE generator, SFU DVB-T2-Lite transmitter, DVB-T2-Lite test receiver and analyzer and spectral analyzer).

4. Measurement results and their evaluation

To evaluate the QoS of the DVB-T2-Lite system we used two criterions. The first one is the classic Quasi Error-Free (QEF) operation [7], defined at BER after LDPC decoding less or equal to 1.10-^{7}. QEF is a minimal limit in DVB-T2 standard for achieving video service availability without noticeable pixelization in the video. The second criterion is based on the feature of the LDPC decoding. The performance of LDPC codes, and therefore the performance of DVB-T2-Lite, can be improved by increasing the number of decoding iterations. However, a higher number of decoding iterations has a larger impact on the power consumption of the user terminal. It is an important fact from the point of the mobile and portable TV reception. Therefore, we also focus on how the occurred co-existences influence the amount of repeated LDPC decoding, needed for successful achieving of QEF limit.

Settings	DVB-T2-Lite	LTE
Code Rate (CR)	2/3 (LDPC+BCH)	1/3 (Turbo)
FFT Size/ Channel Bandwidth	2048 (8 MHz)	128 (1.4 MHz) 1024 (10 MHz) 2048 (20 MHz)
Modulation	16QAM	QPSK 16QAM 64QAM
Constellation rotation	no yes	-
Guard Interval	56 us	4.7 us
Transmission Technique	SISO (Broadcasting)	SISO (Downlink)
RF Level [dBm]	-55.8	-62.2 ÷ -50.9
Frequency	794 MHz	791 to 821 MHz
Channel/Band	C53	Band 20
Channel Models	PI3	EPA 5Hz
Method of Decoding	LDPC (hard decision)	Max Log-Map
Number of Decoidng Process	automatically depends on the channel conditions	automatically depends on the channel conditions

Table 1. Settings used for exploring the co-existence between DVB-T2-Lite and LTE services.

To evaluate the performance and QoS of the LTE system, EVM (Error Vector Magnitude) was used. In general, EVM is a measure used to quantify the performance of a communication system. In the area of LTE, it is a measurable vector in the IQ constellation diagram between the ideal constellation point and the point, received by the receiver. For each modulation, used in LTE, there is a defined EVM limit, for which the transmitted signal has an acceptable quality. This limit is equal to 17.5 for QPSK, 12.5 for 16QAM and 8.0 for 64QAM in [%], respectively [9].

The EVM dependency of QPSK, 16QAM and 64QAM modulations on the frequency overlap of the payload carriers are shown in Fig. 7 a) and b). The expression “frequency overlap” defines the level of channel overlaps between the co-existing LTE and DVB-T2-Lite channels in kHz and “payload” is represents the useful data (carriers). The obtained results are related to spectral density ratio (SDR) ratio, equaling 6.5, -1.8 and -5.0 dB when bandwidth of LTE signal is 1.4, 10 and 20 MHz, respectively. The SDR is defined as the power ratio between LTE and DVB-T2-Lite per unit of the used bandwidth. Its value is calculated as follows:

$$SDR = P_{\mathrm{LTE}} - 10\log B_{\mathrm{LTE}} - (P_{\mathrm{TV}} - 10\log B_{\mathrm{TV}}), \qquad (1)$$

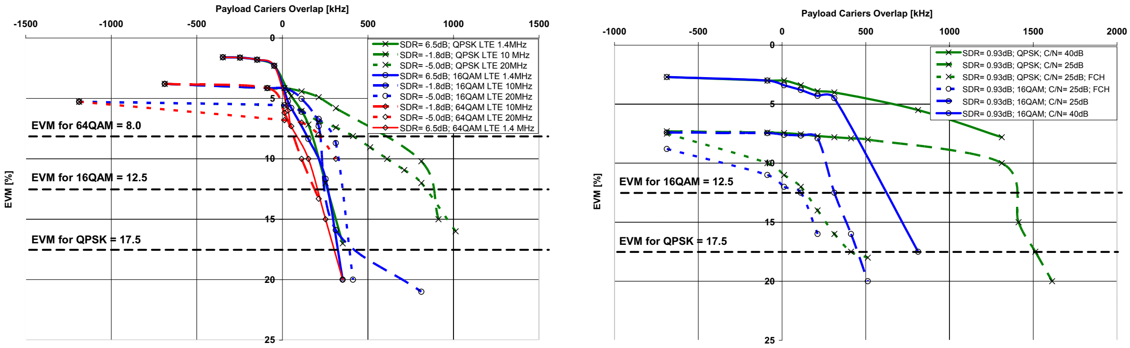
where P_{LTE} is the power of the LTE signal, B_{LTE} expresses the bandwidth of the used LTE channel, P_{TV} is the power of DVB-T2 signal (-55.8 dBm) and B_{TV} presents the bandwidth of the used TV channel (8 MHz).

Firstly, all measurements were done at ideal channel conditions (see Fig. 7 a)). It means that the carrier-to-noise (C/N) ratio is higher than 40 dB. From the obtained results, it is clearly seen that the level of the frequency overlap of the explored co-existing systems has a large impact on the availability of the modulations in the LTE system. Based on the minimal requirement [9], [30], the critical limit of EVM of the considered types of modulations (see bold black dashed lines in Fig. 7), at which the transmission in the specific sub-frames is without problems, is also dependent on the robustness of the type of modulation and used channel bandwidth. From this point of view, QPSK and 64QAM modulations have the highest and lowest resistance against frequency overlap, respectively. In general, the performance of transmission in each sub-frame, independently on the type of modulation used, fell down slowest and fastest when B_{LTE} is equal to 1.4MHz and 20 MHz. When we used an LTE system with a signal bandwidth of 20 MHz, then the values of EVM for all types of modulations were high. In the case when B_{LTE} = 20 MHz at *SDR* = -5.0 dB, the sub-frames, which use QPSK modulation, work without problem, when the frequency overlap is less than 1000 kHz.

Secondly, the same measurements were done for the above considered and briefly described channel models and the results are plotted in Fig. 7 b). All measurements were done with two channel environments. The Gaussian (AWGN) channel was used as a reference (C/N = 25 dB). The PI (DVB-T2-Lite) and EPA 5 HZ (LTE) fading channel models were used as a second considered transmission environment. In the legend of Fig. 7 b) this fact is marked by the abbreviation “FCH” (fading channel). The C/N ratio was equaled to 25 dB in all cases. The SDR is equal to 0.93 dB (the spectral density of the T2-Lite level is lower than the level of LTE services) and the B_{LTE} was 10 MHz. Moreover, we explored the situation, during co-existence scenarios, when the power level of the LTE signal was less, equal or higher than that of the DVB-T2-Lite signal.

As can be seen, the obtained results are significantly different when compared with results from the ideal channel environment. Thanks to higher delays and the Doppler spectrum features, the resistance of both communication systems to the noises during co-existence is much less. For example data transmission, using 16QAM modulation (in fading channels), has not fulfill EVM requirements at channel overlap higher than 125 kHz. In Fig. 7 b), one other interesting effect is also visible. When we consider the EPA 5 Hz channel model (at C/N = 25 dB) in the LTE system, then 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. 7 b).

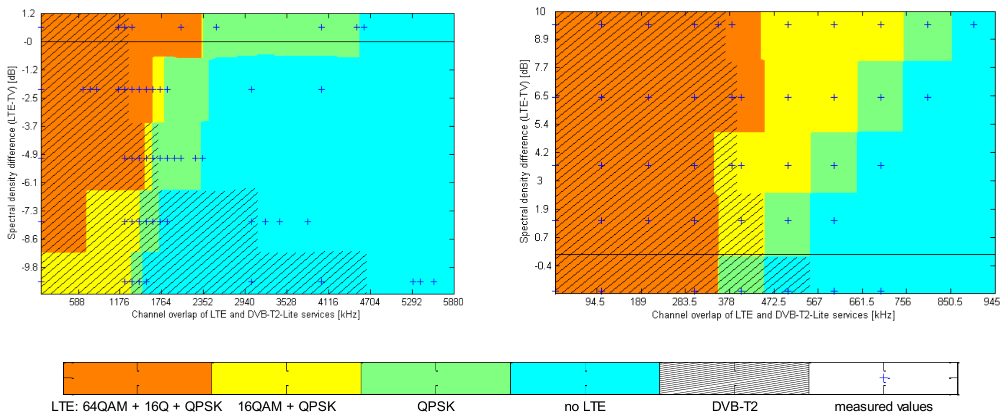
After that, we explored the dependence of the SDR ratio on the level of channel overlap of co-existing DVB-T2-Lite and LTE services. All results were obtained in both the ideal and portable fading channels and are shown in Fig. 8 a) and b). Negative values of SDR parameter present the case, when the spectral density of the TV level is higher than the level of LTE services. From these pictures it is seen that we explored possible situations which can occur at overall channel overlaps of considered services (DVB-T2-Lite vs. LTE and vice versa). Possible situations are clearly explained in the legend of Fig. 8 a) and b). For a better explanation of these results, we describe a specific example (marked by black rectangular in Fig. 8 a)).



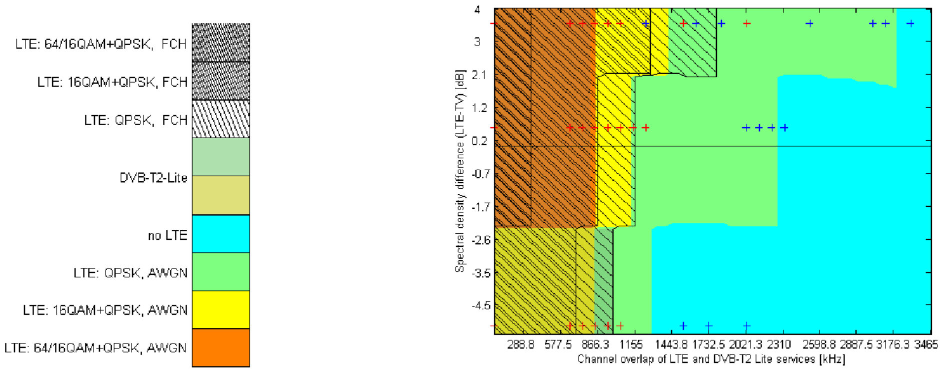
a) Ideal channel conditions.

b) Gaussian and considered fading channel models.

Figure 7. EVM dependency of the QPSK, 16QAM and 64QAM modulations (using 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 (a) and portable fading channel conditions (b).



a) Ideal channel conditions (B_{LTE} = 1.4 MHz (left) and 20 MHz (right)).



b) Gaussian and considered fading channel models (B_{LTE} = 10 MHz).

Figure 8. Graphical presentation of performance of the co-existing LTE and DVB-T2-Lite services as a dependence of SDR on the level of the channel overlap of explored services at ideal (a) and portable fading channel conditions (b).

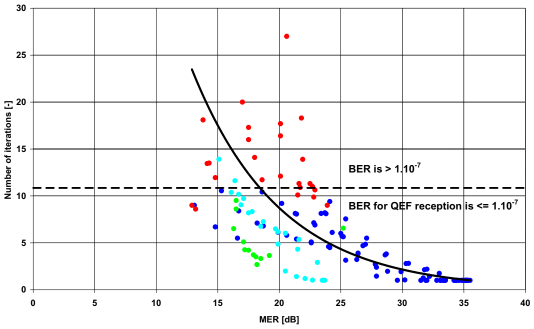


Figure 9. Dependence of the amount of repeated (number of iterations) LDPC decoding on the MER, at which the *BER* is less or equal to 10^{-7} (limit for QEF reception) at ideal and portable fading channels.

For example, we consider two fields with yellow color (see Fig. 8 (a) right, when B_{LTE} = 20 MHz), where the spectral density of LTE is higher than the spectral density of T2-Lite. More precisely, we focus on the fields where the channel overlap is approx. from 560 kHz to 661.5 kHz and the spectral density differences are from 5.2 dB to 10 dB, respectively (marked by black rectangular). As can be seen from the legend, in LTE system, only sub-frames using QPSK and 16QAM modulations will be received and demodulated correctly. Sub-frames using 64QAM modulation at these conditions can not be successfully processed. Furthermore, this field also indicates that the services of DVB-T2-Lite are completely noised (there are no hatched parts). Similar graphical representation of co-existences is achieved for the considered portable fading channels (see Fig. 8 b).

We also investigated the overall performance of DVB-T2-Lite, when it is affected by LTE services, which work in the adjacent frequency band. Our attention is focused on the dependence of the amount of repeated LDPC decoding on MER (Modulation Error Ratio). MER [7] is a measure for evaluation used to quantify the performance of a digital transmitter or receiver in a communications system using digital modulation. In the area of DVB, it is a measure of the sum of all interference effects, occurring in the transmission link. Results, obtained from our measurement, are shown in Fig. 9. Once again, the results were obtained at ideal and different portable fading channel conditions, respectively. At ideal channel conditions, the measurements were done for LTE services with different bandwidths. In the remaining channel models, the measurements were repeated for LTE with a 10 MHz bandwidth only.

For better evaluation, we divided the results into two parts. This division is marked in Fig. 9 by a bold dashed line. Below the dashed line is the area, where BER after LDPC decoding was less or equal to 10^{-7}. More precisely, this area marks where the limit for QEF reception is fulfilled. At this part it can be seen that the number of needed iterations is low and the MER is high. Generally, higher *MER* ratios mean less unwanted interfering and noising effects in transmission/reception (dark blue dots in Fig. 9). In this part the absolute MER limit for the QEF reception is equal to 18.5 dB at the BER (after LDPC decoding) 1.10^{-7}. This value was achieved maximally after ten decoding processes.

In the case of the aforementioned fading channels, (light green dots in Fig. 9), the MER is less, but the needed amount of decoding iterations are only slightly less than that at ideal and Gaussian (light blue dots) channel conditions. This could be caused by the equalization applied on the received DVB-T2-Lite signal before LDPC decoding.

Above the dashed line (see Fig. 9) the values of the measured modulation error ratio presents the situation, when the limit for QEF operation was not fulfilled in the ideal and non-ideal transmission environments. This part represents two states. The first one is where BER after LDPC decoding is higher than 10^{-7}, but the quality of the received signal (dots in the field near to the bold dashed line) is still good. In the second field of this part, the MER values (marked by red dots) are low (hence BER after LDPC decoding is high) and the quality of received signal is bad. At this part, the “cliff-off” effect [7] occurred many times.

Finally, snapshots of the RF spectrums of the DVB-T2-Lite and LTE services in all considered transmission scenarios are shown in Fig. 10 to. Fig. 15. Units in the ordinate are related to bandwidth of RBW filter 10 kHz. The RF spectrums at reference and non-ideal channel conditions were obtained at C/N=40 and 25 dB, respectively. The RF spectrum of DVB-T2-Lite and LTE signals working in the same frequency band in reference (Gaussian) and PI and EPA 5 HZ portable channel models (without any co-existence) are shown in Fig. 10 and Fig. 11, respectively. The case when the T2-Lite services are highly affected by LTE ones in fading channel conditions is plotted in Fig. 12. Due to the considered channel conditions (deep fadings in the spectrums) and high interaction between both services, the quality of provided mobile services in both standards is quickly decreasing. Finally, mutual interactions between T2-Lite and LTE services in Gaussian and portable TV and mobile fading channels, when the signal level of the LTE is less or higher than T2-Lite, are plotted in Fig. 13 to Fig. 15.

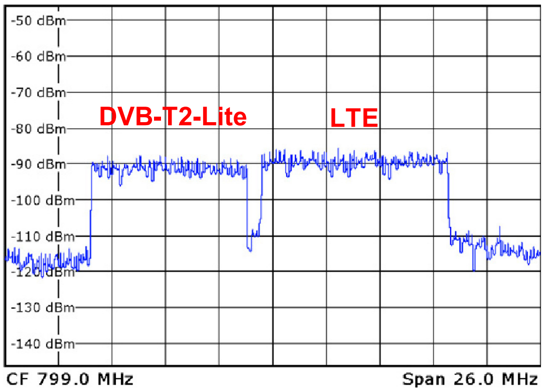


Figure 10. RF spectrum of DVB-T2-Lite and LTE services (equal signal levels) in Gaussian (reference) channel and without any co-existence.

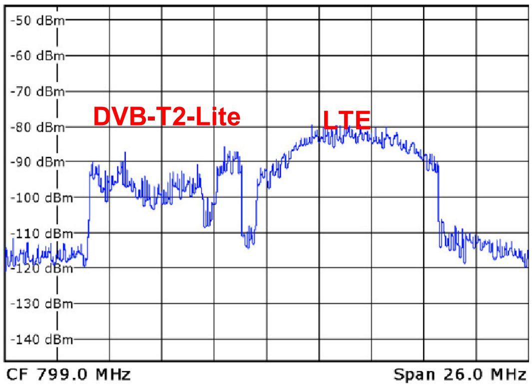


Figure 11. RF spectrum of DVB-T2-Lite and LTE services (equal signal levels) at considered portable fading channel conditions and without any co-existence.

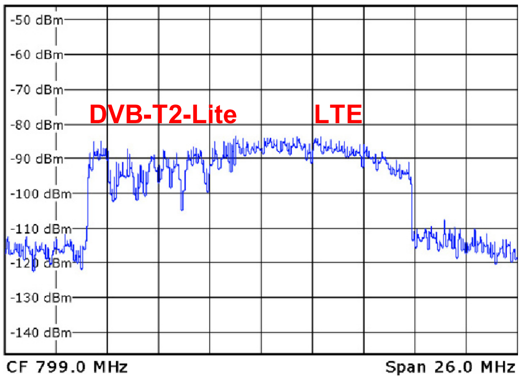


Figure 12. RF spectrum of co-existing DVB-T2-Lite and LTE services (equal signal levels) at considered portable fading channel conditions.

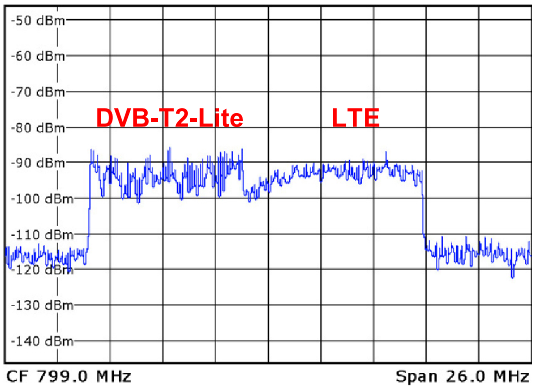


Figure 13. RF spectrum of co-existing DVB-T2-Lite and LTE services (signal level of LTE is less than T2-Lite one) at considered portable fading channel conditions.

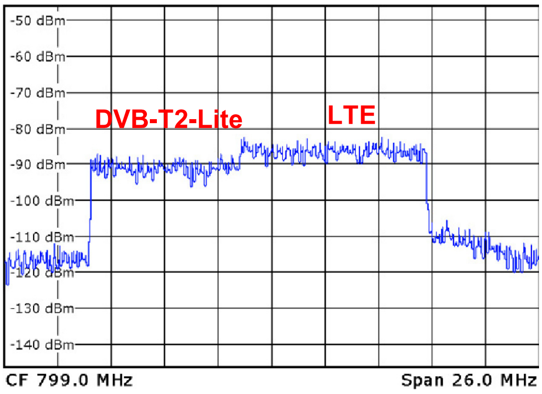


Figure 14. RF spectrum of co-existing DVB-T2-Lite and LTE services (signal level of LTE is higher than T2-Lite one) in Gaussian (reference) channel.

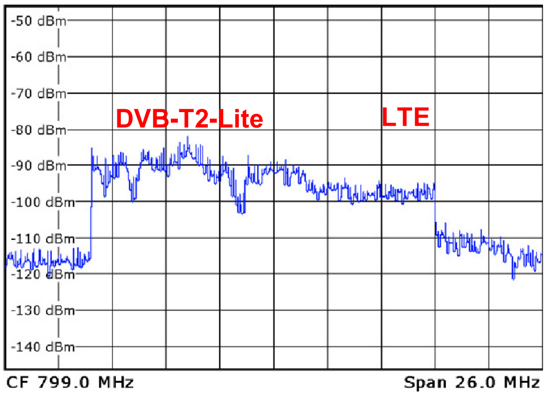
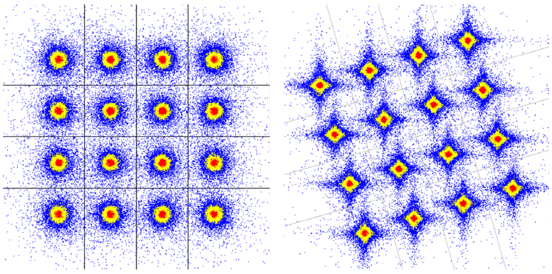
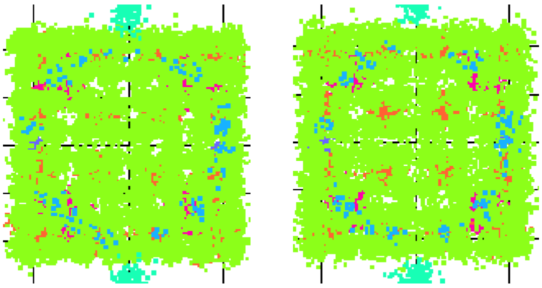


Figure 15. RF spectrum of co-existing DVB-T2-Lite and LTE services (signal level of LTE is higher than T2-Lite one) at considered portable fading channel conditions.



a) Non-rotated 16QAM. b) Rotated 16QAM.

Figure 16. Non-Rotated (a) and rotated constellation diagram (b) of 16QAM in the T2-Lite system, when the DVB-T2-Lite signal is highly affected by the LTE, (BER after LDPC decoding=2.10^{-5}; MER=19.6 dB). At this point the limit for QEF reception (1.10^{-7}) is not fulfilled.



a) AWGN+EPA 5Hz. b) Co-existence with T2-Lite.

Figure 17. Constellation diagrams in the LTE system (downlink) in considered channel models (a) and at co-existence with DVB-T2-Lite services (b). There are shown all types of modulations in one constellation diagram (BPSK, QPSK, 16QAM and 64QAM).

In addition, in the case of DVB-T2-Lite, we repeated all our measurements for the case where the rotated constellation technique is used. The rotated constellation [6]-[8] in the DVB-T2 standard introduces a new technique to improve performance in channel with frequency selective fading or in the case of possible co-existence with other kinds of services. However, the obtained results proved that significant improvement in the performance of DVB-T2-Lite has not happened. Consequently, from the point of higher resistance of the DVB-T2-Lite profile against possible co-existences, the usage of rotated-constellation technique has negligible effect.

Typical results and the example or illustration of the constellation diagrams for the co-existence scenario (high channel overlap), including the used channel models, are shown in Fig. 16 and Fig 17. In Fig. 16, it is clearly seen how LTE services (operating in the same frequency band) can affect the T2-Lite services. Large distortions are visible in the non-rotated and rotated constellation diagrams. Figure 17 shows all types of modulations used in the LTE system and their distortions for downlink in one common constellation diagram.

5. Conclusions

In this paper the co-existence of the DVB-T2-Lite and LTE mobile services, operating in the same frequency band, was explored and measured in ideal and portable fading channel models. For this purpose (see Fig. 5), an appropriate measurement workplace was realized (see Fig. 6).

Firstly, the influence of channel overlap of co-existing services (DVB-T2-Lite and LTE) on LTE services was explored in ideal and portable fading channel models, respectively. For evaluating this influence we used the EVM parameter, related to modulations of LTE. The results in the considered fading channel models were worse, which is mainly caused by their features (higher path delay and time varying conditions). This was mainly true for sub-frames used 64QAM modulation, which at critical frequency overlap were quickly corrupted.

Secondly, we focused on deeper analysis of the co-existence scenarios such as dependence of SDR on the level of the frequency overlap. More precisely, we explored scenarios where both or only one mobile system worked without significant errors. From the results which were obtained in fading channels (see Fig. 8) it can be seen that at BLTE = 10 MHz the DVB-T2-Lite services are corrupted already at less frequency overlap. Overall from these results it can be seen that the decreasing performance of DVB-T2-Lite is highly depending on the power of the LTE signal and its channel bandwidth.

Finally, we investigated the performance of the DVB-T2-Lite system. We explored the dependence of the iteration number of repeated LDPC decoding on MER needed for achieving QEF operation.

This work will continue by finishing and improving the proposed method for measuring interactions between mobile DVB-T/H/T2 and LTE services in different transmission scenarios [28], [29], [34]-[37]. Moreover, we also consider extending our research with real filed measurements.

Acknowledgments

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Study of coexistence between indoor LTE femtocell and outdoor-to-indoor DVB-T2-Lite reception in a shared frequency band

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Abstract

Nowadays, the demand for high-quality multimedia services (video, audio, image, and data) is rapidly increasing. The Digital Video Broadcasting - terrestrial (DVB-T) standard, its second-generation version (DVB-T2), and the Long-Term Evolution (LTE) standard are the most promising systems to fulfill the demand for advanced multimedia services (e.g., high-definition image and video quality), especially in Europe. However, LTE mobile services can operate in a part of the UHF band allocated to DVB-T/T2 TV services previously. The main purpose of this work is to explore the possible coexistences of DVB-T2-Lite and LTE systems in the same shared frequency band (co-channel coexistence) under outdoor-to-indoor and indoor reception conditions. Furthermore, an applicable method for evaluating coexistence scenarios between both systems is shown with a particular example. These coexistence scenarios can be noncritical and critical. In the first case, both systems can coexist without significant performance degradation. In the second one, a partial or full loss of DVB-T2-Lite and/or LTE signals can occur. We consider an indoor LTE femtocell and outdoor-to-indoor DVB-T2-Lite signal reception in a frequency band from 791 up to 821 MHz. Simulations of combined indoor and outdoor signal propagation are performed in MATLAB using 3rd Generation Partnership Project (3GPP) channel models, separately for both DVB-T2-Lite and LTE systems. Correctness of path loss simulation results is verified by measurements. Afterwards, an appropriate linear model is proposed which enables to evaluate the impact of coexistence on performance of both systems in outdoor-to-indoor and indoor-to-indoor reception scenarios. The results are related to an actual location in the building and are presented in floor plans. The floor plans include different coexistence conditions (different power imbalance and different amount of overlay of the radio channels). Service availability of both systems is verified again by measurements. The resulting maps help better understand the effect of coexistence on achievable system performance under different indoor/outdoor reception situations considering real transmission conditions.

Keywords: Channel model; Coexistence; DVB-T2-Lite; Indoor and outdoor-to-indoor propagation; LTE femtocell; Path loss; QEF; EVM; CQI; RF measurement

1 Introduction

Advanced wireless communication systems can provide users with any type of multimedia. Thanks to this, the idea to ‘connect, upload, download, share and transfer anything at anytime and anywhere’ is not a futuristic vision [1,2]. From the viewpoint of service providers, efficient usage of limited resources in the radio frequency (RF) spectrum is one of the biggest challenges. Hence, the increasing density of wireless networks and the increasing volume of user equipment (UE) terminals in use escalate the risk of unwanted coexistence scenarios [3,4].

In the near future, the next-generation digital terrestrial television broadcasting (DVB-T2/T2-Lite) and Long-Term Evolution (LTE) systems will be deployed to provide multimedia services for mobile and portable scenarios, mainly in Europe. DVB-T2-Lite [5-8] is a new profile which was added to the DVB-T2 system specification in April 2012. This subset within DVB-T2 is very perspective for mobile and portable TV broadcasting as it is designed to support

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low-capacity applications for advanced handheld receivers [9]. It is based on the same core of technologies as the DVB-T2 standard but uses only a limited number of available modes. By avoiding the modes, which require the most computational power and memory [6], the necessary complexity of T2-Lite-only receivers is reduced. DVB-T2-Lite, compared to the first-generation DVB-T/H [10], can support TV content delivery with higher flexibility. Moreover, it can operate in VHF (from 174 up to 230 MHz) and UHF (from 470 up to 870 MHz) bands, allocated earlier for DVB-T/H. From the viewpoint of system flexibility, spectral efficiency, and available transmission scenarios, DVB-T2-Lite is the system of choice for the next-generation terrestrial mobile and portable digital TV broadcasting.

Third Generation Partnership Project (3GPP) LTE [11-13] technology brings a new concept, based on the Orthogonal Frequency Division Multiple Access (OFDMA), into mobile communications. LTE supports high data rates and flexible system configuration in order to adapt transmission parameters to the actual state of a radio link. LTE architecture involves a specific type of cells called femtocells. These short ranges, mainly indoor cells, improve coverage in desired areas, especially buildings. Femtocells are served by a special type of base station called Home eNodeB (HeNB). LTE can exploit the same UHF frequency bands which are already available for existing 2G/3G networks (e.g., bands: 800, 900, 1,800, and 2,600 MHz). Moreover, additional ranges (from 2.5 up to 2.7 GHz) and the 700-MHz band are also allocated for LTE usage. The European Union decided to harmonize the '800 MHz band' in favor of the LTE services, starting from January 2013 [4]. Consequently, DVB-T/T2 and LTE services can occupy either the same or adjacent frequency spectrum. As a result, unwanted coexistence between DVB-T/T2 and LTE services can occur [4,14].

This work deals with the study of possible co-channel coexistence between DVB-T2-Lite (outdoor-to-indoor reception) and LTE services (provided by the femtocell) under fixed indoor reception conditions.

The paper is organized as follows. An overview of related work in the field of different wireless standards' coexistence, especially DVB and LTE, is presented in Section 2. This section also includes a detailed list of aims and contributions of this work. A description of the explored coexistence scenario and the considered DVB-T2-Lite system parameters are presented in Section 3. Section 4 contains a description of the applied simulation method and the proposed measurement testbed together with its detailed setup. Results obtained from simulation and measurements are presented and discussed in Section 5. Finally, Section 6 concludes the paper.

2 Related works

Undesirable interactions between similar or different kinds of wireless communication systems, operating in adjacent or shared frequency bands, are not a new phenomenon [3,15-18]. The exploration, monitoring, measurement, and possible suppression of interferences are a hot topic. This fact is also evidenced by many published studies available. Authors of [19] studied the possible inter-band interferences between UMTS and GSM systems. In another work [20], the coexistence between advanced wireless systems and International Mobile Telecommunication-Advanced (IMT-A) services is explored. Different kinds of coexistence scenarios in LTE networks are analyzed in [21-23]. Possible methods to mitigate or suppress interferences from coexistence between two different wireless systems are outlined in [24-26].

In the last decade, researchers' attention has been devoted to the study of different coexistence scenarios between the DVB-T/T2 and LTE/LTE-A standards.

Table 1 summarizes the previously explored coexistence scenarios between such systems. From the presented works, it is clearly seen that many times the researchers use either only simulation tools or only different measuring methods to explore the coexistence scenarios. Furthermore, in most works, a scenario is considered in which macrocells are used to provide LTE service coverage, coexisting with DVB-T2-Lite services in the same or adjacent frequency band. The main aim of this research article is to explore the interaction of DVB-T2-Lite and LTE in a shared frequency band, such that femtocells (HeNB) are used to provide LTE indoor coverage. Attention is devoted to availability monitoring of DVB-T2-Lite and LTE services in different locations under fixed indoor reception conditions. For this purpose, an appropriate simulation model is proposed and verified by measurement. Based on these results, non-critical (both DVB-T2-Lite and LTE system working) and critical (partial or full loss of DVB-T2-Lite and/or LTE signals) coexistence scenarios can be identified and the general conclusions are outlined. To the best of our knowledge, no similar exploration in this form has been presented in any scientific or technical paper so far.

3 Considered coexistence scenario

The investigated coexistence scenario between the DVB-T/T2 and LTE RF signals in the fixed indoor transmission scenario is shown in Figure 1. The main system parameters of DVB-T2-Lite and LTE systems, considered in this work, can be found in Table 2. The DVB-T2-Lite TV signal is broadcast in a single frequency network (SFN) at a center frequency of 794 MHz and received by UE1 in a building. In the same building, LTE femtocells are deployed and the HeNB provides mobile connectivity in a channel belonging to Band 20 (from 791 up to 821 MHz). A user of UE2

Table 1 Comparison of explored coexistence scenarios between DVB-T/T2 and LTE systems

Reference	Coexistence scenario (TV broadcast scenario)	Type of interference	Results	Evaluation parameters
[42]	DVB-T vs. LTE (fixed)	Mutual co-channel	Simulation	SNR, SINR, QoS
[43]	LTE vs. DVB-T (fixed, portable)	Adjacent channel	Simulation	PR, CR
[44]	DVB-T vs. LTE (fixed)	Adjacent channel	Simulation	BER, PF, PR
[45]	DVB-T vs. LTE (fixed)	Intersystem	Simulation	IPL, spectral overlap
[27]	LTE-A vs. DVB-T (fixed)	Intersystem	Simulation	ADL, FO
[46]	LTE vs. DVB-T (fixed)	Intersystem (co-channel)	Measurement	Data throughput, RSRQ
[47]	DVB-T vs. LTE (fixed)	Co-channel	Simulation	I/N, C/(N+I)
[48]	DVB-T/H vs. LTE (fixed)	Co-channel	Measurement	SSIM, QEF, SIR
[30]	LTE vs. DVB-T2-Lite (mobile)	Adjacent channel	Measurement	SDR, QEF, EVM, MER
[31]	DVB-T/T2 vs. LTE (partly mobile, fixed)	Co-channel and adjacent channel	Measurement	SDR, BER, EVM, MER
This study	DVB-T2-Lite vs. LTE (fixed)	Co-channel (partial overlapping)	Simulation/Measurement	QEF, partly CQI, EVM

Abbreviations: ADL, antenna discrimination loss; PER, packet error ratio; BER, bit error ratio; PF, picture failure; CI, carrier-to-interference ratio; PR, protection ratio; CR, correction factor; QEF, quasi error-free; CQI, channel quality indicator; QoS, quality-of-service; C/(N+I), carrier-to-noise+interference ratio; RSRQ, reference signal received quality; EVM, error vector magnitude; SDR, spectral density ratio; FO, frequency offset; SIR, signal-to-interference ratio; IPL, interference power level; SINR, SIR plus noise-ratio; I/N, interference associated to new sources; SNR, signal-to-noise ratio; MER, modulation error ratio; SSIM, structural similarity.

establishes connection with HeNB at downlink frequency band from 795 (797.2 MHz) to 805 MHz (817.2 MHz). We consider that the bandwidth of the LTE signal is 10 or 20 MHz, and intersystem frequency overlapping is from 0.8 up to 3 MHz. Consequently, coexistence between HeNB (supporting 3GPP LTE Release 9) and DVB-T2-Lite system can occur. As a specific type of coexistence, a partial overlapping scenario is assumed. It means that the channel of the interferer (in this case LTE) partially overlaps with the channel of the victim (in this case DVB-T2-Lite) [27]. It is assumed that both UEs are stationary.

4 Simulation and measurement setup

In this section, the simulation method, used to explore the coexistence of digital TV and mobile RF signals under outdoor-to-indoor and indoor-to-indoor conditions, is presented. Furthermore, the proposed measurement testbed and its setup, used in this work, are introduced. The simulation and measurement campaign consists of the following:

1. Simulation (propagation loss) and measurement of LTE performance in different locations (indoor and outdoor environment);
2. Simulation (propagation loss) and measurement of DVB-T2-Lite performance in different locations (indoor and outdoor environment);
3. Simulation and measurement of simultaneous transmission (signal propagation) of both LTE and DVB-T2-Lite RF signals in order to evaluate the

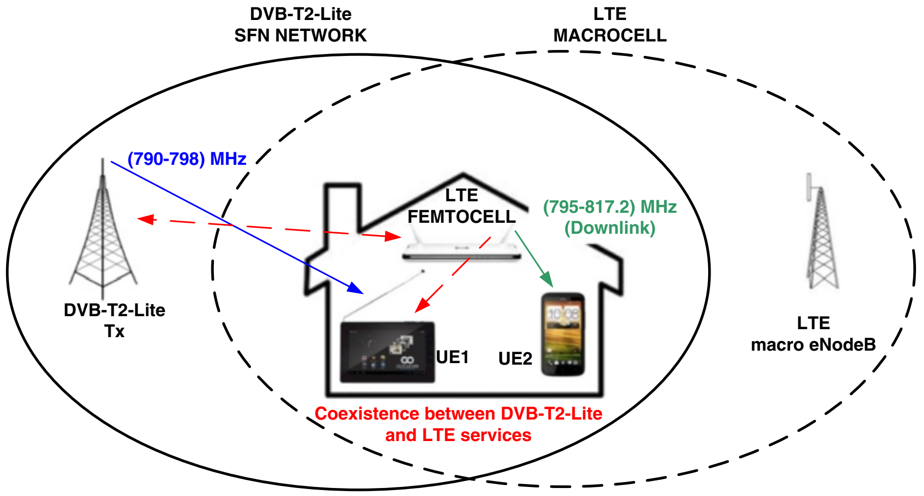

Figure 1 Unwanted coexistences between DVB-T2-Lite and LTE services at fixed indoor transmission scenario. Supposed scenario where LTE femtocell is indoors and DVB-T2-Lite signal penetrates from outdoor transmitter and affects performance.

Table 2 DVB-T2-Lite and LTE main system parameters considered in this study

Definition of parameters	DVB-T2-Lite	LTE (Release 9)
Type of FEC scheme	BCH and LDPC	Turbo
FEC code rate	2/3	1/3
Type of modulation	16QAM	QPSK 16QAM 64QAM
Constellation rotation	No	-
IFFT size	2,048 (2K)	1,024 (10 MHz) 2,048 (20 MHz)
Type of PP pattern	PP2	-
Guard interval duration	28 μs	4.7 μs
Transmission mode	SISO	SISO
Carrier frequency (MHz)	794	Downlink (791 ÷ 821)
Channel bandwidth	8 MHz	10 MHz, 20 MHz
RF power	(0.1 to 5) W	(0.01 to 0.06) W
Channel environment	Outdoor-to-indoor	Indoor (indoor-to-outdoor)
FEC decoding method	1D LLR [6]	Max Log-map
Tx antenna height (m) (above floor)	2	1
Rx antenna height (m) (above floor)	1	1
LTE user equipment	-	Huawei e389u-15 (LTE UE category 3)

BCH, Bose-Chaudhuri-Hocquenghem; LLR, log likelihood ratio; FEC, forward error correction; PP, pilot pattern; IFFT, inverse fast Fourier transform; SISO, single-input single-output; LDPC, low-density parity-check.

influence of coexistence on the performance of both systems (on physical layer (PHY) level); and

4. Identification of the noncritical (both systems can coexist) and critical (partial or full loss of DVB-T2-Lite and LTE signal) coexistence scenarios for both systems.

4.1 Simulation setup

The considered coexistence scenario was briefly outlined in the previous section. In this work, we assume that transmitters and receivers are located on the seventh floor (the top floor) in the building of Brno University of Technology (BUT), Faculty of Electrical Engineering and Communications (FEEC) in Brno. Laboratories of Digital TV Technology and Radio Communications, and Mobile Communications of the Department of Radio Electronics (DREL) are located on this floor. The floor plan of the seventh floor is shown in Figure 2. Approximate dimensions of the floor are 50 × 25 m. The HeNB is located in the Laboratory of Mobile Communication Systems (room 7107), and the DVB-T2-Lite transmitter is located outdoor on the terrace.

The whole simulation model is realized in MATLAB. Propagation of the LTE and DVB-T2-Lite RF signals are simulated separately. The simulation of separate propagation loss of LTE and DVB-T2-Lite RF signals will be used as the reference (no coexistence).

The simulation model consists of three main parts for both LTE and DVB-T systems. The first part represents the simulation of a link budget, according to the 3GPP recommendation for system level simulations [28,29] for both coexisting systems. Signal strength in the receiver can be expressed as follows:

$$P_{\mathrm{RX}} = P_{\mathrm{TX}} - L_{\mathrm{TXC}} + G_{\mathrm{TXA}} - PL + G_{\mathrm{RXA}} - L_{\mathrm{RXC}} \qquad (1)$$

where P_{TX} is transmitter power, L_{TXC} are wiring losses, G_{TXA} is transmitting antenna gain, G_{RXA} is receiving antenna gain, L_{RXC} are wiring losses, and finally, P_{RX} is received signal level. Path losses in wireless transmission are denoted as PL (for details see Equation 3). Value of P_{TX} is known from the transmitter setup. Values of L_{TXC}, L_{RXC}, G_{TXA}, and G_{RXA} are constants depending on the used equipment (for details see Subsection 4.2). The second part represents the validation of obtained results from the simulation according to the performed measurement and their interpretation in a map. Details are in Subsections 4.1 and 4.2. The last part compares power imbalance of tested radio channels and computed achievable performance of both systems in certain locations. Details are given in Section 5.

The propagation scenario of the LTE RF signal in femtocell involves indoor-to-indoor line-of-sight (LOS) propagation for the same room where HeNB is located (room 7107) and non-LOS (NLOS) for other indoor locations. Path losses are modeled according to the 3GPP recommendation for indoor LTE femtocell as described in [28], denoted as UE to HeNB, where UE is inside the same building as HeNB. In order to model indoor-to-outdoor propagation from the HeNB to the measurement points on the terrace, the original equation was extended with outdoor wall penetration loss. On the other hand, the recommendations in [28] are generally valid for frequencies around 2 GHz, but we exploit an 800-MHz band in this study. Therefore, it is necessary to perform a correction as described in [29]. This correction defines the correction factor for 800 MHz as follows:

$$PL_{\mathrm{COR}} = 20\log_{10}(f_c) \qquad (2)$$

where f_c is carrier frequency in MHz.

The resulting path loss equation is:

$$\begin{aligned}\mathrm{PL} = {} & 38.46 + 20\log(d) + 0.7d_{\mathrm{in}} + \mathrm{LP}_{\mathrm{floor}} \\ & + qL_{\mathrm{INwall}} + nL_{\mathrm{OUTwall}} + \mathrm{PL}_{\mathrm{COR}}\end{aligned} \qquad (3)$$

where d is the distance between the HeNB and the UE, d_{in} is indoor propagation distance, LP_{floor} is penetration

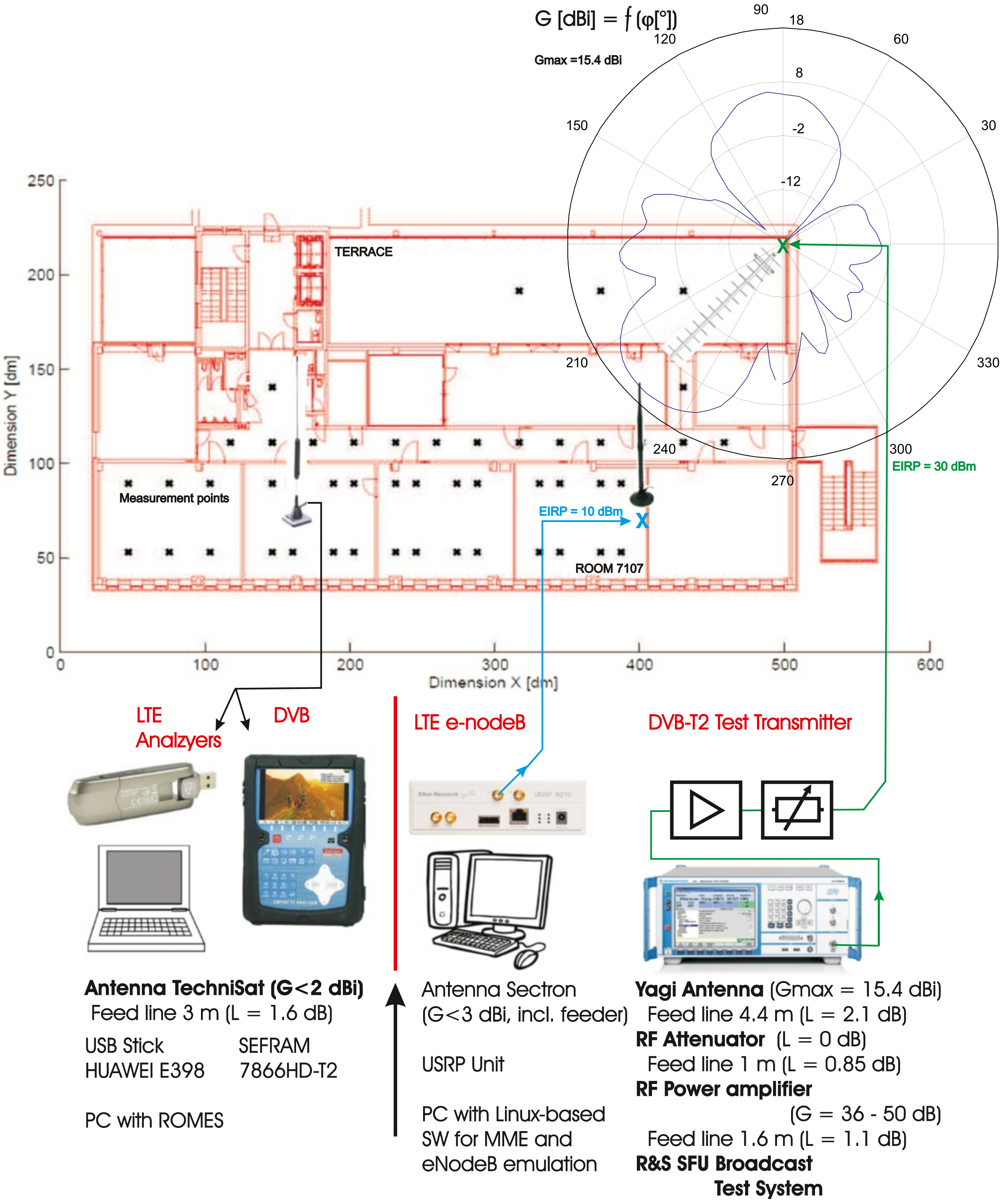

Figure 2 Floor plan and general block diagram. Floor plan of the seventh floor in the building of BUT, FEEC, DREL and general block diagram of the measurement testbed.

loss due to propagation through the floor (it is equal to zero because a single-floor propagation scenario is assumed), parameter q is the number of indoor walls separating the transmitter and receiver, L_{INwall} is the penetration loss due to walls inside the building, n is the number of outside walls, L_{OUTwall} is the penetration loss of the exterior wall, and PL_{COR} is the frequency correction factor as defined in [29] and shown in Equation 2. In our case $d_{\mathrm{in}} = d$, $LP_{\mathrm{floor}} = 0$ (single floor), $q > 0$ (in the case of the NLOS scenario), $L_{\mathrm{INwall}} = 5$ dB, n is between 0 and 5 (depending on the concrete position on the floor) and $L_{\mathrm{OUTwall}} = 10$ dB.

The propagation scenario between the DVB-T2-Lite transmitter and TV receiver is considered as outdoor-to-indoor urban femtocell propagation, where the UE is outside as described in [29]. The DVB-T2-Lite RF signal attenuation with frequency correction can be calculated similarly to Equation 3 as:

$$\begin{aligned} \mathrm{PL} &= \max\left(15.3 + 37.6\log_{10}(d), 38.46 + 20\log_{10}(d)\right) \\ &\quad + 0.7d_{\mathrm{in}} + LP_{\mathrm{floor}} + qL_{\mathrm{INwall}} + nL_{\mathrm{OUTwall}} + \mathrm{PL}_{\mathrm{COR}} \end{aligned} \tag{4}$$

where all variables have the same meaning as in Equation 3.

No fading was included in the data displayed in Figures 3 and 4, however, both fast fading and shadowing were computed according to recommendations in [29].

Figures 3 and 4 show the results of LTE and DVB-T2-Lite radio signal propagation obtained from simulation, respectively. System parameters determined according to the simulation results prove accessibility of wireless services in all tested locations.

Path loss model data provides the basis for coexistence simulations. We have provided a detailed description of LTE and DVB-T2-Lite coexistence in our previous works [30] and [31]. Based on data collected from the mentioned measurements, we made a dense description (linear model) of coexistence. There are two types of input parameters for the models: global and local. The global parameters are mainly represented by the settings of both systems' PHY, such as modulation used in DVB-T2-Lite, inverse fast Fourier transform (IFFT) size, and the Forward Error Correction (FEC) code rate of both systems. Obviously, the overlapping bandwidth is also a global parameter. Local parameters, used as the model input, are mainly local power levels of signals, background noise, and the local fading model employed. These parameters are input into the linear model, which maps them to the Quality-of-Service (QoS) parameters. More details can be found in Subsection 5.1.

4.2 Measurement setup

For evaluating the interaction of the described coexistence scenarios between DVB-T2-Lite and LTE RF signals, the same measurement testbed was used as described in our previous works ([30] and [31]). The whole measurement campaign was implemented on the seventh floor of the building of BUT, FEEC, DREL (see Figure 2). The measurement campaign and the basic principle of our measurement method are as follows.

Firstly, the parameters and performance of the 3GPP LTE network are measured in different locations on the seventh floor. At the time of LTE measurement, T2-Lite services were not broadcasted. The HeNB is located in room 7107, and its antennas are placed on top of a table (approximately 1 m above the floor). The HeNB consists of two main hardware components, namely a PC with the Fedora Linux operating system and universal software radio peripheral (USRP) N210 from Ettus, equipped with an SBX daughter card. The PC runs the commercial software package Amari LTE [32], implementing functions of LTE Mobile Management Entity (MME) and eNB (both are 3GPP LTE Release 9 compliant). A detailed configuration of the LTE network is summarized in Table 2. The receiving UE is Huawei e398-u15 (Huawei, Shenzhen, China) (LTE UE Cat. 3) [33], connected via USB port to a laptop equipped with the Rohde & Schwarz drive test software ROMES4. For receiving LTE services, the TechniSat Digiflex TT1 mobile antenna (TechniSat, Vulkaneifel, Germany) was used ($G < 2$ dBi). The length of its feed line is 3 m. The UE is connected to an external antenna placed on a wooden cart approximately 1.0 m above the floor. We set up the connection between UE and HeNB and performed simultaneous full buffer transmissions in uplink and downlink. The measurement was carried out in fixed points distributed on the seventh floor as shown in Figure 2. The receiving antenna was kept still for 2 min at each measurement point and in each location we have collected approximately 100 samples of each network parameter of interest (including RSS, Channel Quality Indicator (CQI), Error Vector Magnitude (EVM), etc.).

Secondly, we have measured the performance of the DVB-T2-Lite signal in different locations on the seventh floor. At the time of T2-Lite measurement, LTE services were not provided. By using the R&S single frequency unit (SFU) broadcast test system, an appropriate video transport stream for portable TV scenarios was generated. Then, the DVB-T2-Lite complete system configuration was set up, and the output signal was RF modulated (to the frequency of 794 MHz). For its amplification, a custom-built RF power amplifier (PA), based on hybrid module Mitsubishi RA20H8087M (Mitsubishi Electric, Tokyo, Japan) [34], was applied. This RF three-stage module is primarily destined for transmitters using FM modulation that operate in the range 806 up to 870 MHz, but it may also be applied in linear systems by setting the proper drain quiescent current with externally settable gate voltage. The PA was assembled according to the recommendations of the producers and thoroughly tested. The comprehensive measurement demonstrates that this PA can be used in a wider band, circa from 650 to 900 MHz, and can be used in the presented coexistence test. The gain of the PA strongly varies in the introduced frequency range from 36 to 50 dB, but in a

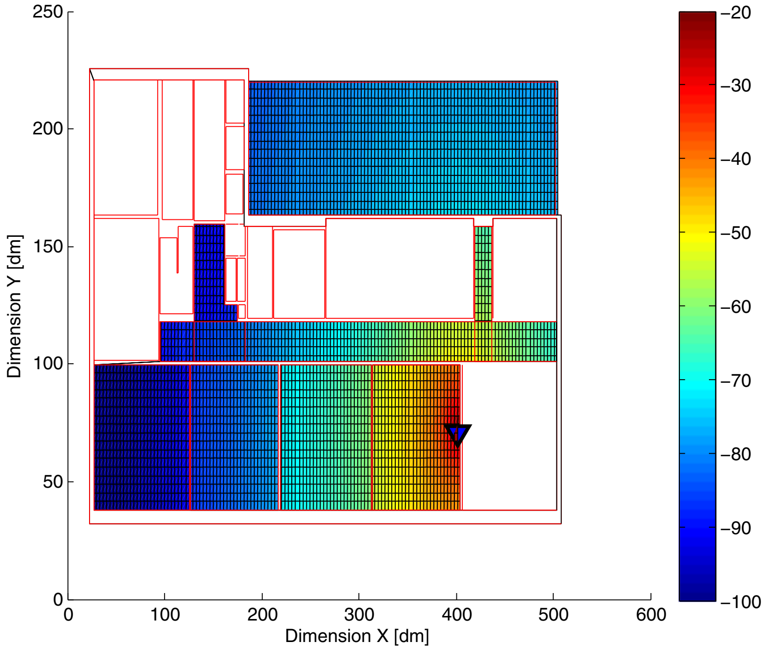

Figure 3 Simulation of LTE RF signal propagation. The HeNB is located in room 7107 (the blue triangle), and network parameters are as described in Table 2. The path loss model was adopted from [28] and extended for the 800-MHz band according to [29] (see Equations 2 and 3). All values are in dBm.

narrow band, the gain is quite stable (max. 1.5 dB in 10 MHz bandwidth). The maximum output power of this amplifier is around 30 W. However, we practically used only 1 W (5 W was used for the scenario where power imbalances were equal to 20 dB) with quiescent drain current 4 A, gate bias voltage 4.3 V, and supply voltage 13.8 V to achieve high linearity for reliable application in the mentioned setup. Accordingly, the power efficiency in this setting is only 2%. On the other hand, reaching linearity is the fundamental parameter which needs to be set for minimizing any nonlinear distortion. For the used testing DVB-T2-Lite frequency (794 MHz), the

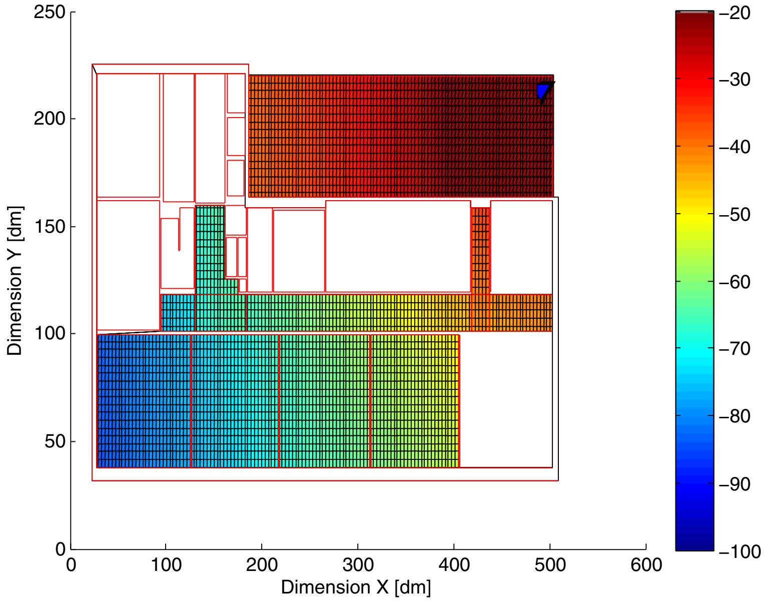

Figure 4 Simulation of DVB-T2-Lite RF signal propagation. The DVB-T2-Lite transmitter is located on the terrace (the blue triangle), and its parameters are described in Table 2. The path loss model was adopted from [28] and extended for the 800-MHz band according to [29] (see Equations 2 and 4). All values are in dBm.

measured 1 dB compression of this PA is 37.9 dBm (6.2 W), two-tone third-order intermodulation distortion (IMD3) (tone offset 1 MHz) is better than −38 dBc at the output power of 1 W, which corresponds to output intercept point (OIP3) 49 dBm. Between the PA and the antenna, there is an attenuator in the signal path. It serves as PA protection in the case of antenna switch-off or strong reflections in the antenna near the field. The JFW Industries 50BR-104 N attenuator (JFW Industries, Indianapolis, IN, USA) was used which was set to 0 dB during measurement. The mentioned nonlinear distortions caused by PA are not considered in our simulation model.

The used antenna is a multi-element Yagi antenna ($G_{\max}$ = 15.4 dBi) whose horizontal radiation pattern is shown in Figure 2. The feed line for the TV transmitter chain is a coaxial cable RG58 C/U which has a power loss of approximately 0.35 dB/m on the tested bandwidth. Attenuation of the auxiliary connection between 'N' and 'BNC' connectors is approximately 0.5 dB/m.

For the LTE system (HeNB), the Sectron AO-ALTE-MG5S antenna (Sectron Inc., Ormond Beach, FL, USA) was used. In our case, it was used as an omnidirectional antenna in vertical polarization ($G < 3$ dBi). After setting up the testbed, we moved with the Sefram 7866HD-T2 analyzer (Sefram Instruments and Systems, Saint-Étienne, France) to measure the received TV signal through all measuring points. The same antenna setup was used as is outlined above for LTE downlink. Once again, we spent 2 min at each measurement point for correctly evaluating the performance of the received DVB-T2-Lite RF signal (to avoid fast fading by averaging).

Figures 5 and 6 show measured and extrapolated values of RSS. Figure 5 shows the results of LTE radio signal propagation while Figure 6 shows the results of T2-Lite radio signal propagation obtained from measurement. System parameters determined according to the simulation results proves accessibility of wireless service in all tested locations. As we can see, results from measurement, shown in Figures 5 and 6, correspond with simulation results shown in Figures 3 and 4. This experimental result proves our simulation technique valid for coexistence applications.

Afterwards, the whole measurement campaign was repeated, but now both wireless services (DVB-T2-Lite and LTE) were provided together at the same time. The above outlined QoS parameters of both services, caused by coexistence between them, were measured separately with Rohde & Schwarz devices.

5 Experimental results

5.1 Parameters to evaluate the performance of DVB-T2-Lite and LTE

Before evaluating and discussing the obtained results, it is necessary to briefly define the most important measured parameters which were used to evaluate the performance of T2-Lite and LTE systems. To evaluate the quality of the received and decoded TV services, the Quasi Error-Free (QEF) reception conditions were monitored. QEF is a minimal limit defined in the DVB-T2-Lite standard for achieving video service availability without noticeable errors in the video. To fulfill such requirements, the bit error ratio (BER) after FEC decoding must be less than or equal to 1×10^{-7} [6].

To evaluate the performance of LTE, the RSS, CQI, and EVM parameters were monitored. The CQI contains information sent from the UE to the HeNB to indicate a suitable downlink transmission data rate. It is based on the observed signal-to-interference-plus-noise ratio (SINR) and used by the HeNB for downlink scheduling and link adaptation [28]. There are 15 different CQI values (numbered from 1 up to 15). The connection between them and the modulation scheme can be found in [35] (Table 7.2.3-1).

EVM, the second parameter, is a measure used to quantify the performance of an LTE communication link. It is the RMS value of the distance in the IQ constellation diagram between the ideal constellation point and the point received by the receiver. For each modulation, there is a defined EVM limit, for which the transmitted signal has an acceptable quality. This limit is equal to 17.5% for quadrature phase-shift keying (QPSK), 12.5% for quadrature amplitude modulation (16QAM), and 8.0% for 64QAM [11,28].

5.2 DVB-T2-Lite and LTE performance evaluation

In Subsection 4.1, it has been mentioned that the linear coexistence model maps input parameters from simulations and measurements to the area of QoS states. We have defined the following QoS states for the coexisting services. For DVB-T2-Lite, there are two states: correct reception and no reception. In the case of correct reception, the above defined condition for QEF reception is satisfied. For LTE, we have defined four QoS states which differ in user bitrate and potential radio access network (RAN) throughput. These parameters obviously increase with M in M-QAM modulation of subcarriers. The LTE system changes the modulation scheme adaptively according to the channel parameters (e.g., CQI, EVM). To be more precise, the highest useable M-state for the defined interfered radio channel sets the QoS state of LTE. Four states correspond to maximal M equaling 64 (64QAM), 16 (16QAM), and 4 (QPSK), and the state when providing LTE services is not possible.

The considered coexistence scenarios between DVB-T2-Lite and LTE services were described above. Furthermore, we also consider various system parameters. The complete list of assumed scenarios is clearly summarized in Table 3. There are three main parameters: bandwidth of the LTE RF

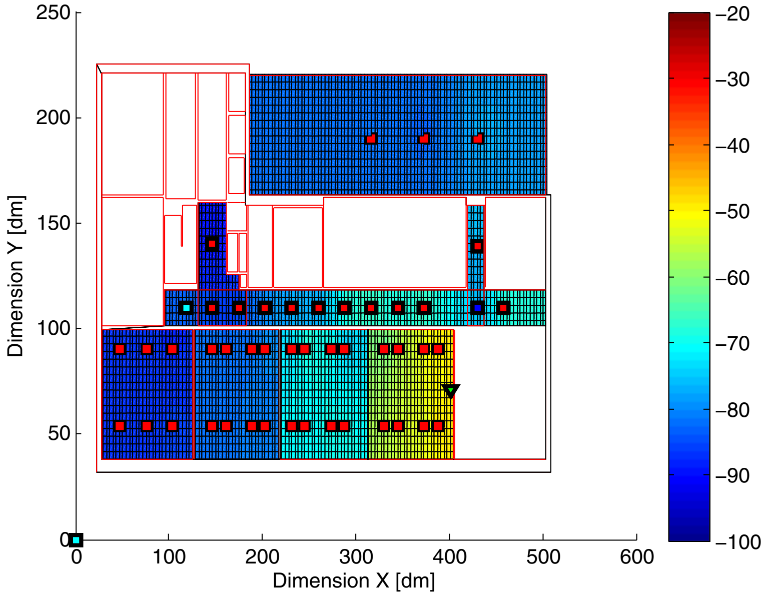

Figure 5 Measurement of LTE RF signal propagation. The HeNB is located in room 7107 (the blue triangle), and network parameters are described in Table 2. The measurement was carried out in highlighted points and extrapolated using MATLAB. All values are in dBm.

channel (marked as B_{LTE}), overlap of coexisting channel (B_{OVER}), and the power imbalance between transmitted powers (ΔP).

The last one is calculated as follows:

$$\Delta P\,[\text{dB}] = \text{EIRP}_{\text{LTE}} - \text{EIRP}_{\text{TV}} \tag{5}$$

where equivalent isotropically radiated power $(\text{EIRP})_{\text{LTE}}$ and EIRP_{TV} denote the channel power of LTE and T2-Lite RF signals, respectively.

Figure 7 shows the simulated results of six map representations of QoS states in DVB-T2-Lite and LTE systems. Each map (from (a) to (f)) corresponds to the

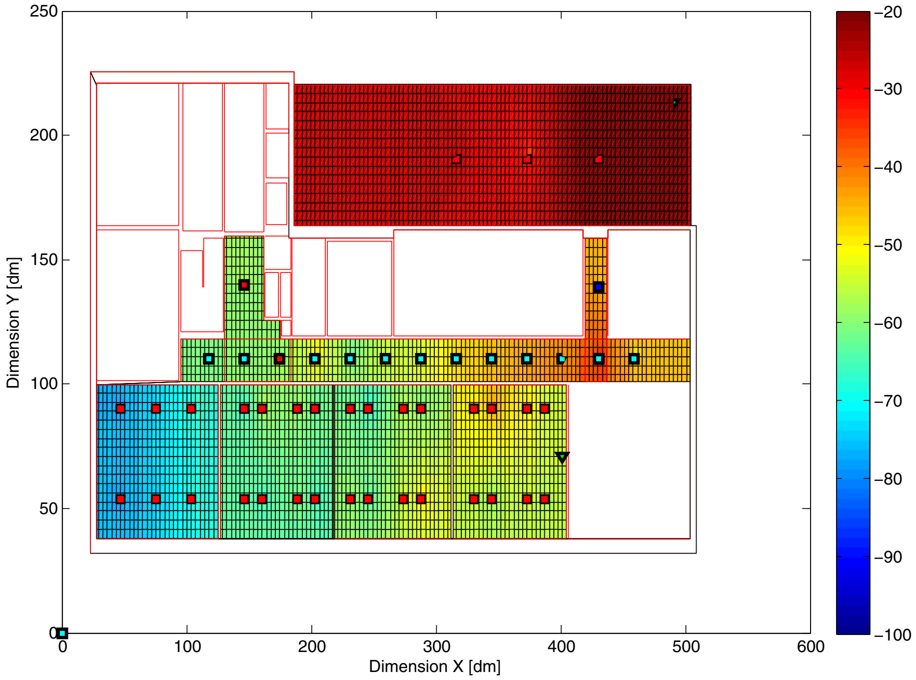

Figure 6 Measurement of DVB-T2-Lite RF signal propagation. The HeNB is located in room 7107 (the blue triangle), and network parameters are described in Table 2. The measurement was carried out in highlighted points and extrapolated using MATLAB. All values are in dBm.

Table 3 Variable parameters of DVB-T2-Lite and LTE for assumed coexistence scenarios

Map	B_{LTE} (MHz)	B_{OVER} (kHz)	Power imbalance (ΔP) (dB)
a	10	800	0
b	20	800	0
c	20	1,600	0
d	20	1,600	−10
e	20	1,600	−20
f	20	3,000	0

considered system parameters and coexistence scenarios which are presented in Table 3. In the floor plan of the university, for each point in the explored areas, the state of both coexisting systems is indicated.

Performances of T2-Lite and LTE systems can be clearly explained in the legend of Figure 7. Four colors represent the LTE maximum useable internal modulations: orange - 64QAM, yellow - 16QAM, and green - QPSK, and unavailable LTE services are indicated by a cyan color. The performance of DVB-T2-Lite services is indicated by a crosshatch in the same maps. The presence of a hatch means that the QEF limit of mobile TV reception is fulfilled. For a better explanation of the obtained results, we describe a specific example.

For example, we consider a partial overlapping coexistence scenario between T2-Lite and LTE services when B_{LTE} = 20 MHz, B_{OVER} = 1,600 kHz, and ΔP is equal to 0 dB (see line (c) in Table 3). Performances of coexisting systems for these parameters are plotted in Figure 7c. As can be seen from the legend, at the 1.6-MHz channel overlapping, in the LTE system, only sub-frames using QPSK and 16QAM modulations will be received and demodulated correctly (yellow color in the legend) on the left side of the corridor. It means that only at these modulations EVM errors do not exceed the permitted limit values [11]. In the remaining rooms, the highest 64QAM modulation (highlighted by orange color) is used in the LTE system. Consequently, CQI values can be 10 or higher. Furthermore, this field also indicates that the services of DVB-T2-Lite are highly noised and conditions for QEF reception are not fulfilled (there are no hatched parts). The situation result is the opposite on the terrace where DVB-T2-Lite services are broadcasted. At this place, the provided LTE services are not available (blue color). In this case, the LTE system could not decode the received signal and the CQI value is the lowest. Interestingly, in the small corridor, located between the terrace and the main floor corridor, partial coexistence between T2-Lite and LTE systems is possible. It means that at this place, both wireless systems can coexist. The QEF limit for DVB-T2-Lite is still fulfilled. However, in the LTE system, only sub-frames using QPSK modulation can be successfully processed. Hence, the CQI indicator values will be in the range from 1 up to 6 [35]. Similar graphical representations of considered coexistences are plotted in Figure 7a,b,c,d,e,f.

Now, let us focus on the first two charts (see Figure 7a,b). Their parameters differ just in the used LTE channel bandwidth (B_{OVER}), but the disparity in state map is high. From the point of B_{LTE} = 20 MHz LTE channel (see Figure 7b), the 800 kHz interference bandwidth is quite narrow and almost no effect can be seen on LTE inside the building. Outside, LTE works correctly with 16QAM. However, when B_{LTE} is equal to 10 MHz (see Figure 7a), then the LTE channel, affected by the same interference bandwidth (800 kHz), is occupied by almost twice the interfering RF power. In this case, the LTE system still works correctly, but only 16QAM and QPSK (indoor/outdoor) modulations can be used. Furthermore, mobile TV reception is also more affected by LTE services because LTE interference power is concentrated into a narrower channel. In real RANs, where power limits are more likely set to 1 Hz of occupied bandwidth, the impact on the reception of mobile TV services would be the same. The influence of channels overlapping and the effect of different EIRP unbalances could be investigated from the remaining charts.

Figure 8 shows six map representations of QoS states in DVB-T2-Lite and LTE systems from measurements. In general, in most measuring points, the defined states of QoS correspond with simulation results. However, there are some minor differences caused by the accumulation of two types of uncertainties. The first ones are caused by path loss channel modeling, and these are even multiplied by the second ones, caused by the proposed linear model. Most probably, the largest influences are due to inhomogeneity in walls (doors, windows and various types of material), underestimation of noise level, and impact of multipath propagation. It is obvious that the simulation and measurement results in scenario (e) have the lowest difference. This state is caused by the highest signal level (in the above mentioned scenario) which brings reduction of noise background impact and increase the influence of intersystem jamming simultaneously for all transmission paths.

6 Conclusions

The main aim of this paper is to investigate the impact of coexisting DVB-T2-Lite and LTE systems in a shared frequency band on their system performances in the outdoor-to-indoor reception scenario. To be more precise, a scenario was considered where an indoor LTE femtocell (HeNB) and outdoor-to-indoor DVB-T2-Lite services are provided in an 800-MHz frequency band (see Figures 1 and 2). We have performed separate simulations of both LTE and DVB-T2-Lite RF signal propagation in MATLAB. Further, we have carried out measurements

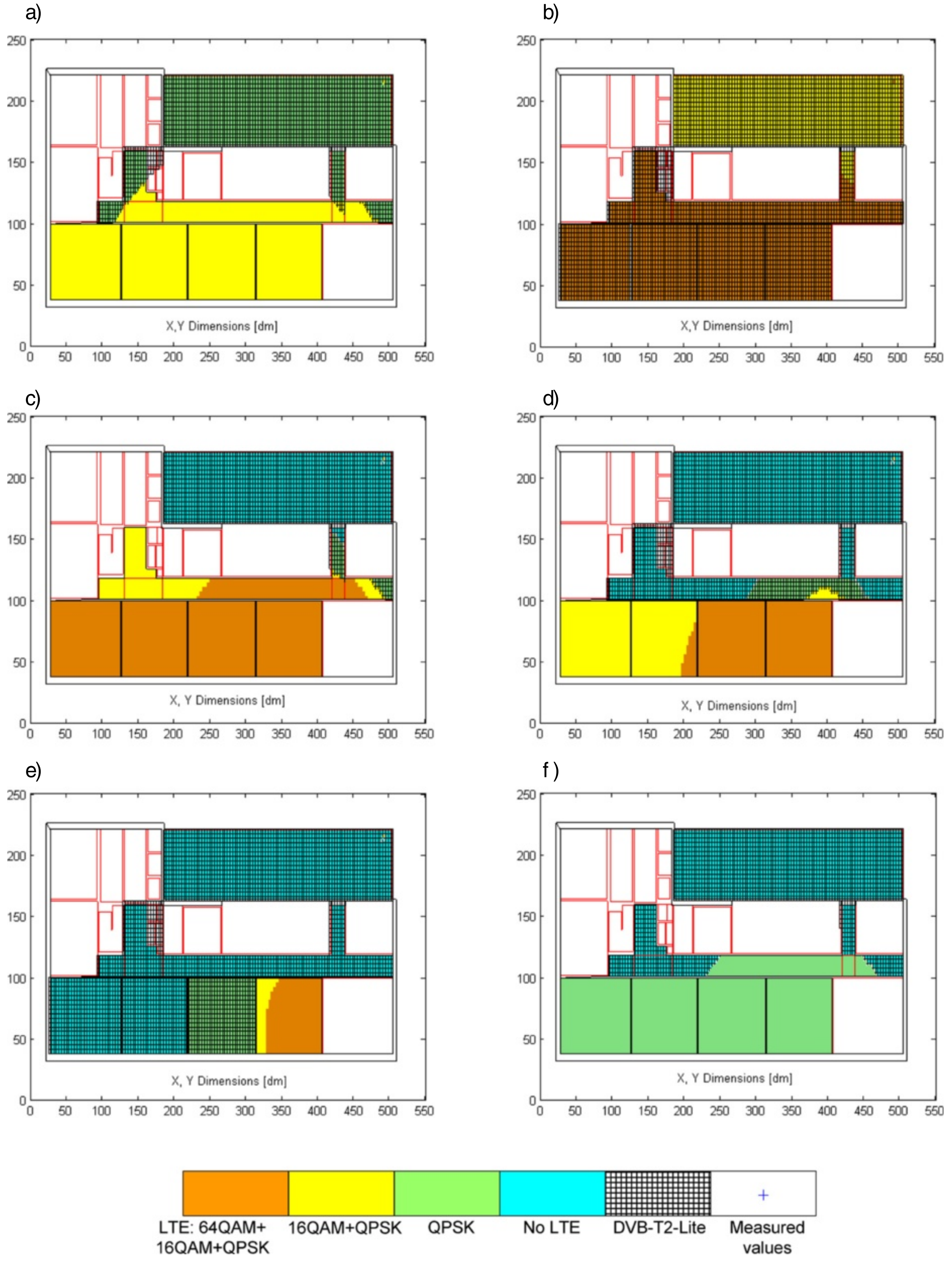

Figure 7 Simulation - the map representation of QoS states of coexisting systems **(a-f)**. Specific map parameters are summarized in Table 3.

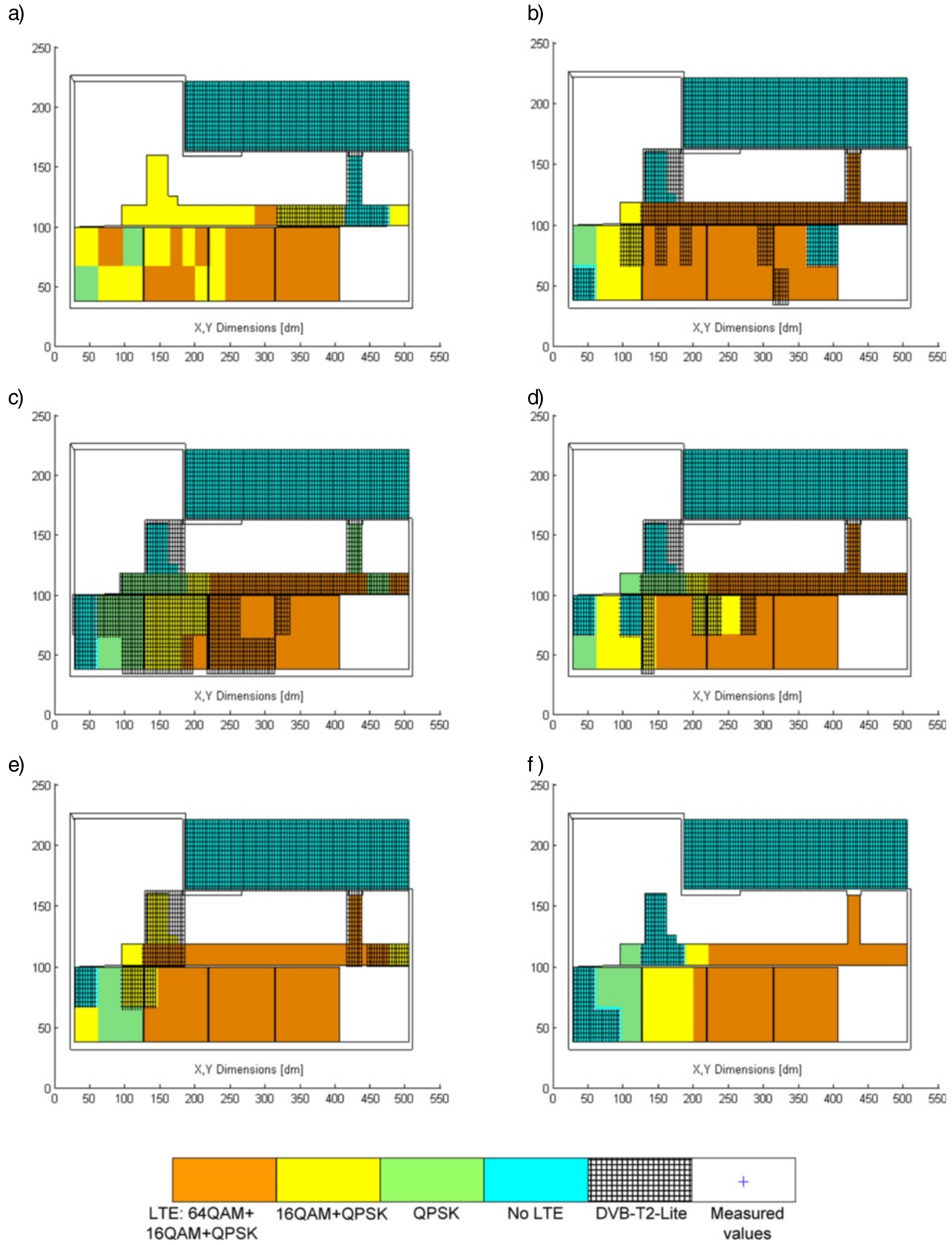

Figure 8 Measurement - the map representation of QoS states of coexisting systems **(a-f)**. Specific map parameters are summarized in Table 3.

of both wireless systems in order to evaluate the reliability of the simulation model. Results are shown in Figures 3, 4, 5, 6 and correlate well.

According to the achieved results in our previous works ([31] and [28]), we have created a linear model to map outputs of the path loss model to defined QoS states. This model considers the relation between the value of RF channels overlapping and the power imbalance of the investigated radio channels. A detailed description is outlined in Subsection 4.1.

The presented results are expressed in a set of maps (floor plans of the building) with colored areas which determine availability or non-availability of coexisting services and achievable performance. Specific values of these parameters in the considered scenarios are presented in Table 3. The effect of coexistence on valid signal reception is quantified by the change of used modulation scheme and simultaneous availability of services. A detailed description of the color maps is described in Section 5. In the proposed linear model for both systems, we assume good channel conditions (global parameters): signal-to-noise ratio (SNR) ≥35 dB for both systems and also no multipath propagation and no Doppler frequency have been set. Once again, the proposed linear model was proved by measurements (see Figures 7 and 8). In several cases, less correspondence between the simulation and measurement results is explained.

An analysis of the obtained results from the considered coexistence scenarios leads to the following general conclusions:

a) The impact of DVB-T2-Lite system performance on the LTE system performance and vice versa in their co-channel coexistence scenario in a shared frequency band highly depends on the level of their channels overlapping and on the power imbalance between RF signals.
b) The outdoor-to-indoor penetration of the T2-Lite signal is highly critical on indoor-to-indoor reception of LTE services when the power imbalance between the RF levels is high. In these cases, the T2-system acts as a co-channel interferer to indoor LTE femtocell and vice versa.
c) Digital TV fixed indoor reception is more vulnerable to interferences than fixed outdoor reception.

The main aim of our future work will be to extend our proposed linear coexistence model with more global parameters (different kinds of fading channel models and Doppler shift [36-39]) for more realistic modeling of different coexistence scenarios between DVB-T2-Lite and LTE services and vice versa. Moreover, in our future work, we will consider a larger range of system parameters (code rate, IFFT length, guard interval, and higher M-QAM modulations and bandwidth) [40,41].

Competing interests

The authors declare that they have no competing interests.

Acknowledgement

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Co-Channel Coexistence between DVB-T/H and LTE Standards in a Shared Frequency Band

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***Abstract*—In the near future, besides the first and second generation Digital Video Broadcasting –Terrestrial (DVB-T/T2) standards, the Long-Term Evolution (LTE) system will be the most widespread to provide multimedia services in excellent quality, mainly in Europe. These systems can operate in a shared UHF frequency band and significantly affect the performance of the systems colliding. This paper deals with the study of co-channel coexistence between DVB-T/H and LTE systems in a shared frequency band. To measure the impact of the interfering LTE RF signal (with various bandwidths and RF signal levels) on the DVB-T/H one, an appropriate measurement testbed is realized. Objective parameters (namely bit and modulation error ratio) are used to evaluate the overall influence of the LTE mobile services on the DVB-T/H digital TV services. Finally, to explore the impact of the interference effects on DVB-T/H TV signal a digital video quality analyzer is used.**

Keywords—DVB-T/H; LTE; Co-Channel coexistence; BER; MER; subjective picture quality analysis; SSCQE

I. INTRODUCTION

Requirements on multimedia services are rapidly increasing. In general, these services can be provided by two different systems. First one is based on the broadcast TV systems while the second one is based on point-to-point IP delivery in mobile communication networks. In Europe, these techniques are dominantly represented by Digital Video Broadcasting (DVB) and GSM and UMTS systems, respectively [1], [2].

In the family of DVB standard there exist several options to broadcast digital TV (DTV) services [1]. From the point of terrestrial DTV broadcasting, DVB-T/H standard [3] is still a leading system that allows delivery of a wide range of multimedia services (image, video, audio and data). It is a well-known system to broadcast TV services in case of mobile and fixed reception scenarios. In Europe, the DVB-T system services can operate in the VHF (from 174 to 230 MHz) and UHF (from 470 to 870 MHz) frequency bands.

In the last decade, the world of mobile communications has been characterized by a rapid technological evolution [4]. The main goal of this development is to propose new wireless networks and increase the data throughput with advanced transmission techniques. A perspective Long-Term Evolution (LTE) system [4] has a high potential to replaced still used mobile telecommunication systems. This is mainly caused by its flexible system parameters and more effective usage of radio frequency (RF) spectrum. The LTE can be operated in the frequency bands that are already available for existing 3G networks (from 880 MHz up to 960 MHz). Furthermore, additional ranges, as the 2.5 GHz to 2.7 GHz band, and the 700 MHz band, are allocated for usage [5]. How it can be seen, many RF bands, originally allocated to provide DTV services, will be allocated for LTE system too. Consequently, numerous coexistence scenarios are possible.

The risk of coexistences between different wireless systems can negatively affect the quality of their provided services [6], [7]. Nowadays, the attention in this field is more focused on the study of coexistence scenarios between DVB-T/H and LTE systems. General interaction between mobile telecommunication and DTV services is studied in [8]. Authors in [9] and [10], focused on the exploring of possible adjacent channel interference of the LTE mobile system (at downlink) into DVB-T services at fixed reception scenario. Different coexistence scenarios between DVB-T/H and LTE services was explored in [11] while authors in [12] and [13] focus on the measuring and exploring the interactions of the unwanted LTE services and upcoming 2nd generation DVB terrestrial (DVB-T2) system.

The main aim of this paper is to explore the interaction between LTE (Release 8) and DVB-T/H services in a shared frequency band when co-channel coexistence scenario is considered. Attention is devoted on the study of the influence of LTE mobile services on DVB-T/H fixed TV services (on the PHY level) with focus on its objective and subjective performance indicators.

This paper is organized as follows. A description of the explored coexistence scenario and the considered system parameters are presented in Section II. In Sections III a brief description of realized measurement testbed and its setup is outlined. Obtained results are evaluated and discussed in Section IV. Finally, the paper concludes in Section V.

II. COEXISTENCE BETWEEN DVB-T/H AND LTE SYSTEMS

There is considered a coexistence scenario when an LTE eNodeB, transmitting a downlink signal, acts as an interferer on the DTV receiver (fixed reception scenario). Providers of DTV services and mobile networks (LTE) are located in the same frequency band. The DVB-T/H services are broadcasted

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This work was supported by CATRENE under the project named CORTIF CA116, the MEYS of the Czech Republic no. LF14033, no. CZ.1.07/2.3.00/20.0007, and by the BUT project no. FEKT-S-14-2177. The described research was performed in laboratories supported by the SIX project; no. CZ.1.05/2.1.00/03.0072, the operational program Research and Development for Innovation. Research described in this paper was financed by Czech Ministry of Education in frame of National Sustainability Program under grant LO1401. For research, infrastructure of the SIX Center was used.

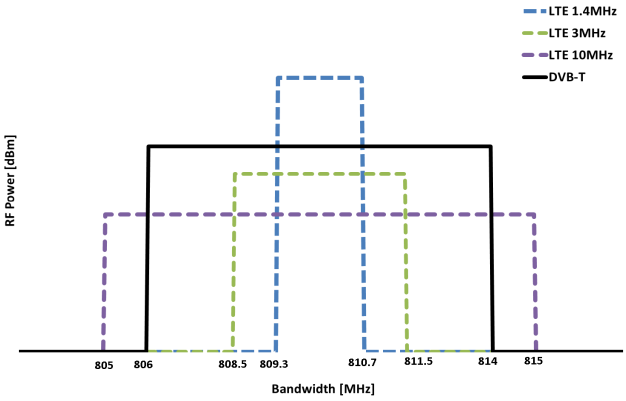


Fig. 1. The RF spectrum of analyzed coexistence scenarios between DVB-T/H and LTE services.

TABLE I. CONSIDERED DVB-T/H AND LTE SYSTEMS CONFIGURATION

Settings	**DVB-T/H**	**LTE**
Type of FEC	Reed-Solomon Convolutional	Turbo
Code Rate	2/3	1/3
IFFT size	8K	128 (1.4 MHz) 256 (3MHz) 1024 (10MHz)
Inner modulation	OFDM	OFDMA
Guard interval	1/8	normal
RF frequency band [MHz]	810	(791-821)
Channel number	C63	Band 20
Channel bandwidth [MHz]	8	1.4, 3, 10
RF level [dBm]	-23	(-40 ÷ 5)
Channel conditions	ideal	ideal
Transmission mode	SISO	SISO

at a frequency of 810 MHz while the LTE ones are provided in the RF band from 791 MHz to 821 MHz. We consider that the LTE mobile services are provided on the same carrier frequency than DTV services. It means that, as a type of coexistence a full overlapping scenario is considered and the receiver of DTV services is located at edge of cell coverage for LTE eNodeB [5], [11]. In this case the level of the impact of occurred interferences depends on the level of the unwanted LTE signal and its channel bandwidth. Hence, in this work, constant RF level of DVB-T/H signal and variable RF level of the LTE signal are considered. Furthermore, the bandwidth of the LTE signal, marked as B_{LTE}, will be different; concretely 1.4 MHz, 3 MHz and 10 MHz (see this outline in Fig. 1).

Detailed system settings, which were used for the study of the co-channel coexistence between DVB-T/H and LTE services, are summarized in Table I. In all cases, an ideal channel conditions are assumed.

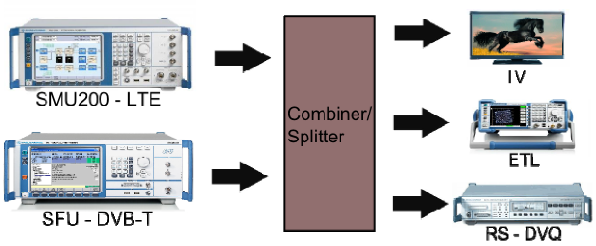


Fig. 2. Proposed block diagram for measuring coexistence bewteen DVB-T/H and LTE services.

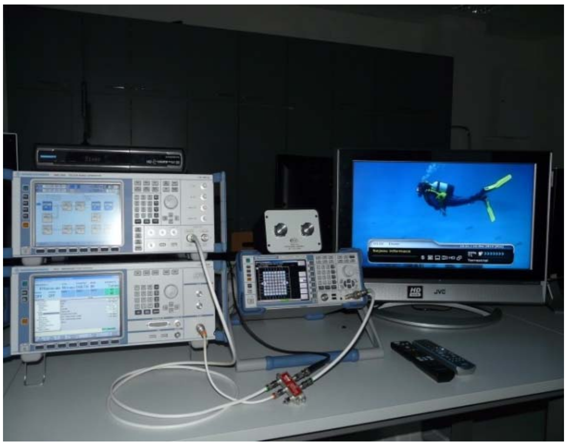


Fig. 3. Realized laboratory workplace for measuring the interaction between DVB-T/H and LTE networks (R&S SMU200 LTEsignal generator, R&S SFU DVB-T/H transmitter, R&S ETL TV analyzer, Set-Top-Box and TV screen).

III. PROPOSED MEASUREMENT WORKPLACE AND ITS SETUP

For the measurement of the interaction of briefly described coexistence scenarios between DVB-T/H and LTE services there were proposed a general block diagram (see Fig. 2) [11] After that a concrete laboratory workplace with appropriate measurement devices was realized, as it is shown in Fig. 3.

A principle of the measurement is follows. Firstly, by using the R&S SFU broadcast test system; an appropriate test video sequence is generated. After that the complete DVB-T/H system parameters are set and the RF signal is generated at frequency 810 MHz. The interfering LTE signals with different bandwidths are produced by R&S SMU200A (once again see Table I). The level of LTE signal is set gradually. Finally, these two RF signals are combined in combiner Toner DSU-4 4 way splitter, and the influence of the LTE services on DVB-T/H ones are monitored and measured with appropriate devices.

How it is mentioned in [14], there is often no direct way to identify BER or transport stream (TS) errors for concrete receivers. In this case, the picture failure (PF), the audio failure (AF) and the subjective failure points (SFP) metrics are used to assess the interference effects [10]. In this work, we used the R&S Digital Video Quality Analyzer (DVQ) for the assessment of video picture quality according to real-time measurement method [15].

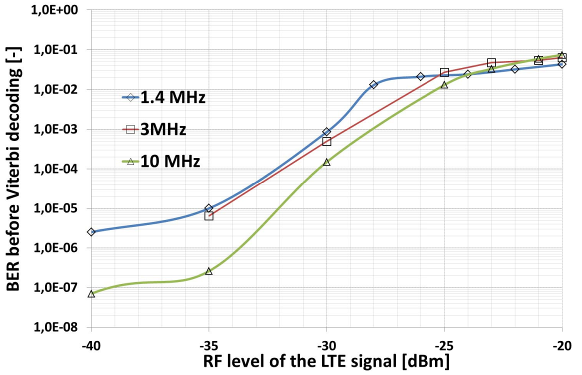


Fig. 4. Dependences of BER before Viterbi decoding (in the DVB-T/H system) on the RF level of unwatned LTE signal with different channel badnwidths (1.4MHz, 3MHz and 10MHz).

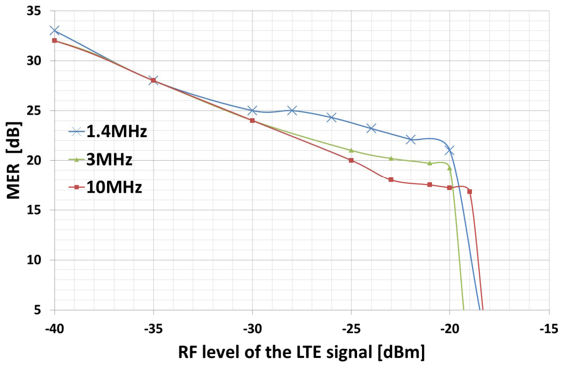


Fig. 5. Dependences of MER (in the DVB-T/H system) on the RF level of unwatned LTE signal with different channel badnwidths (1.4MHz, 3MHz and 10MHz).

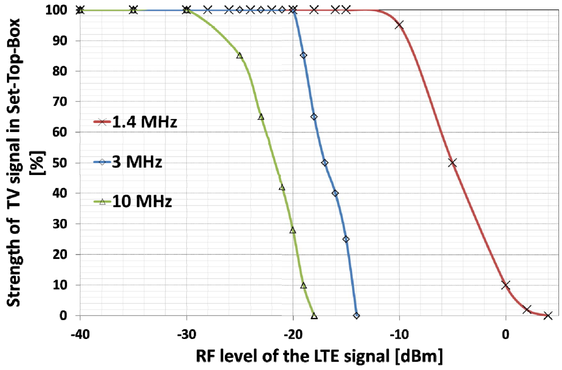


Fig. 6. Dependences of RF signal level in the set-top-box (in the DVB-T/H system) on the RF level of unwatned LTE signal with different channel badnwidths (1.4MHz, 3MHz and 10MHz).

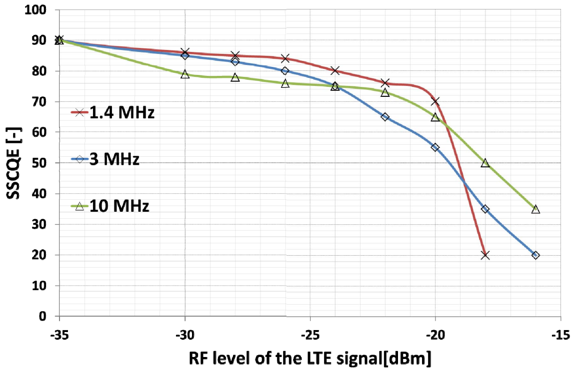


Fig. 7. Dependences of SSCQE values (measured by R&S DVQ) on the RF level of unwatned LTE signal with different channel badnwidths (1.4MHz, 3MHz and 10MHz).

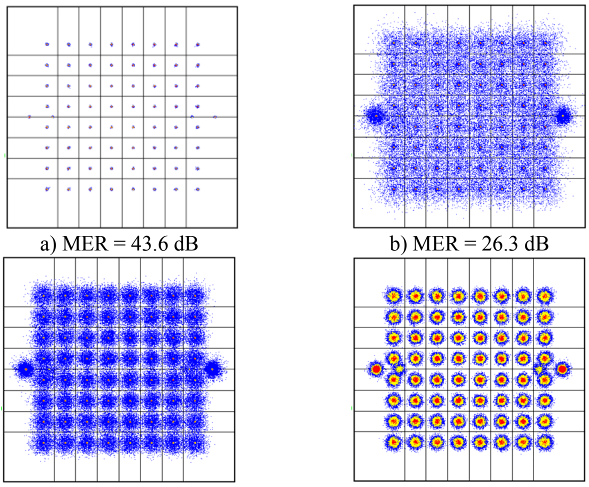
IV. EXPERIMENTAL RESULTS

To evaluate the influence of the interfering LTE RF signal on the DVB-T/H one, three objective parameters are used: bit error rate (BER) before and after Viterbi decoding and modulation error rate (MER). The BER values before Viterbi decoding represent raw errors which occur during the broadcasting in the transmission environment. The measure of the BER values after Viterbi decoding is used for the assessment of a correctly received DTV signal. By this, the fulfillment of the condition for quasi-error-free (QEF) reception is closely related. In general, QEF is represented by BER leading to no more than one perceivable error event in the decoded video per hour [16]. The limit for the QEF operation in the DVB-T/H standard is defined at BER equal to 2.10^{-4} after Viterbi decoding [3].

Possible artefacts in DTV video signal, caused by interferences from described coexistence scenario, lead to a change in the video quality evaluation. For real-time monitoring of degradation of the video picture quality the digital video quality level-weighted (DVQL-W) test value was used. For the picture quality analysis the Single Stimulus Continual Quality Evaluation (SSCQE) method/scale is adopted [15], [16]. There is used a simple 100-point continuous scale in the range from 0 to 100, where intervals “100-80”; “80-60”; “60-40”; “40-20”; “20-0”; mark “Excellent”; “Good”; “Fair”, “Poor” and “Bad” picture video quality, respectively.

Dependences of BER before channel decoding on the RF level of the LTE signal at different B_{LTE} values are plotted in Fig. 4. From the presented results it can be clearly seen that the robustness of DVB-T/H system to unwanted and disturbing LTE signal is the highest when the bandwidth of the LTE is the lowest one (1.4 MHz). On the other hand, at LTE RF level from -26 dBm to -20 dBm the BER values in DVB-T/H system (approx. 3E-2) are almost the same and not depending on the considered B_{LTE} value. Obtained results show that the interfering LTE signal with lower level, but different channel bandwidth, fundamentally affects performance of the DVB-T/H signal decoding and presentation in the DTV receiver. Continuously with raw BER values (before Viterbi decoding), BER after Viterbi decoding was measured. The maximum RF levels of interfering LTE signal, where condition for QEF reception of TV signal is still fulfilled, are -24 dBm, -21 dBm and -20 dBm at B_{LTE} values 1.4 MHz. 3 MHz and 10 MHz, respectively.

Dependences of MER ratios on the RF level of the LTE signal at different B_{LTE} values are graphically shown in Fig. 5. The MER parameter (in [dB]) is an aggregate quantity which includes all possible individual errors and thus completely describes the performance of the transmission link [12], [16].



a) MER = 43.6 dB
b) MER = 26.3 dB
c) MER = 24.8 dB
d) MER = 25.3 dB

Fig. 8. Constellation diagram of 64QAM in the DVB-T/H system, when the DTV signal is non (a) or highly affected by the LTE RF signal (-77 dBm) with bandwidth 1.4 MHz (b), 3 MHz (c) and 10 MHz (d).

Higher MER value means lower interference effects in the DVB-T/H transmission. When it is considered less RF level of the LTE signal (from -40 dBm to -30 dBm) then its influence on the DVB-T/H performance is independent on the assumed B_{LTE} values.

Dependences of the TV signal strength that is measured in [%] in Set-Top-Box (STB) on the RF level of LTE signal with different bandwidths are shown in Fig. 6. In our experiments STC600HD PVR STB was used made by Icecrypt Company. From the obtained dependences, as this was predicted, is clearly seen that interfering signal with narrower band has less impact on the TV signal strength. The strength of TV signal is the highest (100%) at LTE RF level from -40 dBm to -30 dBm and not depending on the considered B_{LTE} value.

The overall performance of picture video quality, measured by R&S DVQ, at all considered B_{LTE} values as SSCQE versus RF level of LTE signal are shown in Fig. 7. With increasing level of the unwanted LTE RF signal the video quality of DTV signal is gradually decreasing. The video picture quality can be evaluated as “Excellent” or “Good” at LTE RF signal with level from -35 dBm to -24 dBm. However, after -24 dBm the picture video quality is significantly decreasing to “Fair”, “Poor” and even “Bad”.

Snapshots of 64QAM constellation diagrams, influenced by different B_{LTE} values are shown in Fig. 8.

V. CONCLUSION AND FUTURE WORK PLANS

In this work, the influence of the interfering LTE system on the DVB-T/H system at co-channel coexistence scenarios was studied. Objective (BER and MER) and subjective (SSCQE scaling quality levels) metrics were used to explore the impact of the level of overlaying interfering LTE services on the DVB-T/H ones. There was shown that the performance degradation of the DVB-T/H system is highly depending on the bandwidth of the LTE signal and its RF level.

This work will continue by investigation of the influence of LTE signal on the DVB-T/H signal and vice versa at advanced coexistence scenarios [10]-[13], [17]. Moreover, in our future works we will consider different transmission scenarios (fading channel models) for both systems.

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Influence of LTE Uplink System on DVB-T System at Different Coexistence Scenarios

Ladislav Polak, Denis Plaisner, Ondrej Kaller and Tomas Kratochvil

Abstract—**The main purpose of this paper is to explore the influence of Long-Term Evolution (LTE) system (as interfering) on the Digital Video Broadcasting-Terrestrial (DVB-T) system (as victim) at different coexistence scenarios. Three coexistence scenarios are considered, namely: non-overlapping (adjacent channel with no guard band), partial overlapping and full overlapping RF spectrum. To measure the interaction between the LTE RF signal (with various bandwidths and RF power levels) on the DVB-T RF signal, a laboratory measurement testbed is used. Dependences of bit and modulation error ratios (BER and MER) on the signal density ratio (SDR) are used to evaluate the influence of the LTE uplink mobile services on the DVB-T digital TV services. Experimental results show that the DVB-T performance is differently depending on the considered coexistence scenario.**

Keywords—**DVB-T, LTE uplink, Coexistence, Interferences, RF measurement, SDR, BER, MER.**

I. INTRODUCTION

IN the field of the Digital Video Broadcasting (DVB) standards, the DVB-T (Terrestrial) [1] technology is one of the most popular solutions to broadcast digital TV (DTV) content, mainly in Europe. It enables to provide TV services in different video image quality (from standard to high definition). However, its system flexibility and spectral efficiency are not meeting today's technical requirements on multimedia services [2]. Hence, it will be completely replaced by its second generation standard, marked as DVB-T2 [3], in the near future. Nevertheless, nowadays, DVB-T system is still the main distribution platform in many EU countries.

In the field of the mobile telecommunication networks, the Global System for Mobile Communications (GSM) with Universal Mobile Telecommunications System (UMTS) for cellular networks are still the main technologies to ensure mobile services between users. However, similarly to the case of DTV broadcasting, these systems will be replaced by a very promising Lon-Term Evolution (LTE) [4] system in the near future. Between the main reasons are facts that LTE is a more flexible system and utilizes radio frequency (RF) spectrum more efficiently than its predecessors.

LTE can exploit the same UHF frequency bands (from 700 MHz up to 900 MHz) which were previously allocated for providing DTV services [5]. Consequently, both systems can occupy either the same or adjacent RF spectrum and this coexistence can decrease their performances.

Monitoring and measurement of the coexistence between wireless systems is evidenced by many studies [6]-[8]. Nowadays, focus in this field is devoted on the exploring of the coexistence problems between DVB-T/T2 and LTE systems. In [9], authors explored performance degradation of DTV services, broadcasted by DVB-T system, when mobile services, provided by LTE system, are operating in the adjacent frequency bands. As a metrics the protection ratios and overloading thresholds are considered. The impact of the interfering LTE signals on DVB-T fixed DTV services and their possible suppression with different kind of filters are studied in [10]. Influence of the unwanted coexistence between LTE and DVB-T services has been investigated in [11] and [12] while authors in [13] generically analyzed the coexistence problem between LTE-UL (Uplink) and DVB-T2 signals in the 700 MHz band. On the other hand, overall study of different coexistence scenarios between DVB-T and LTE systems and their impact on DVB-T performance, evaluated by objective metrics, is still missing. Hence, in this paper, influence of LTE uplink system on DVB-T system at different coexistence scenarios is investigated.

The structure of this paper is organized as follows. Brief description of considered coexistence scenarios and system parameters for measuring interactions between DVB-T and LTE services are presented in Section II. Description of proposed and realized workplace and measuring method is outlined in Section III. Section IV contains the evaluation and discussion of the obtained results. Finally, the paper concludes in Section V.

II. TYPES OF COEXISTENCE SCENARIOS

When two wireless systems operate in the same frequency band then, depending on their carrier frequency and channel bandwidth, between them different coexistence scenarios can occur. In this work, we consider three different scenarios: non-overlapping (adjacent channel with no guard band) partial overlapping and full overlapping RF spectrum [14]. General illustration of these scenarios is shown in Fig. 1.

In the case of non-overlapping (adjacent channel with no guard band) DVB-T and LTE systems can coexist by an adjacent channel with zero additional bandwidth. It means

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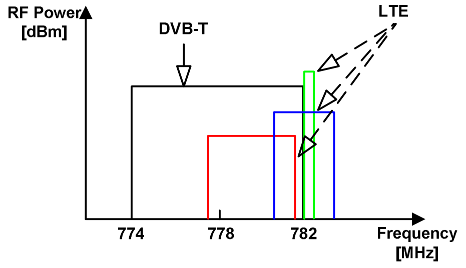

Fig. 1. General graphical presentation of non-overlapping - adjacent channel with no protection band (green), partial overlapping (blue) and full overlapping (red) coexistence scenarios between DVB-T and LTE services.

TABLE I
SETTINGS USED FOR EXPLORING THE COEXISTENCE SCENARIOS BETWEEN DVB-T AND LTE SERVICES

Settings	DVB-T	LTE
Type of FEC	Reed-Solomon + Convolutional	Turbo
Code Rate (CR)	3/4	1/3
Type of modulation	64QAM	QPSK
Transmission mode	OFDM	SC-FDMA (uplink)
IFFT size	8192	128 512 1024
Channel bandwidth	8 MHz	1.4 MHz 3 MHz 5 MHz
Transmission technique	SISO	SISO
Guard Interval (GI)	112 us	4.7 us
Channel conditions	Rice	Ideal

that there is no guard band between them (see green rectangular in Fig. 1). Guard band is an unused part of the radio spectrum between RF radio bands, for the purpose of preventing interference.

Partial overlapping coexistence scenario can occur when the RF channel of the interferer (in this case LTE) system partially overlaps with the RF channel of the victim DVB-T system (see blue rectangular in Fig. 1).

As a last one, there is considered a full overlapping coexistence scenario. It can occur when the RF channel of the LTE system is completely overlapped with RF channel of the DVB-T system (see red rectangular in Fig. 1).

In this work, we explore the performance degradation of DVB-T fixed TV services, influenced by LTE uplink (from user to eNodeB) services in above briefly presented coexistence scenarios. Detailed system settings, which were used for our measurement, are summarized in Table I.

III. MEASUREMENT CAMPAIGN

The proposed general measurement testbed, based on [12], of the realized measurement of coexistence between DVB-T and LTE services is shown in Fig. 2. The measurement workplace was realized in the Laboratory of Digital Television and Radio Systems, Brno University of Technology. The measurement campaign and the basic principle of our measurement method are as follows.

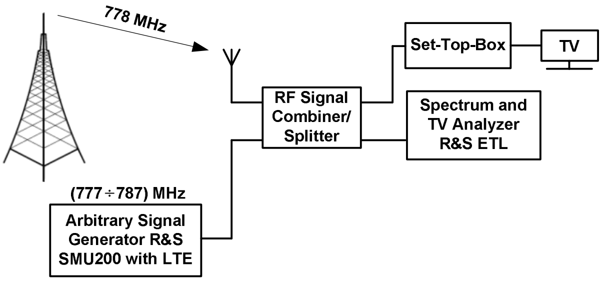

Fig. 2. Block diagram for measuring the interaction between DVB-T (fixed scenario) and LTE (uplink) services at different coexistence scenarios.

The DVB-T RF signal, broadcasted from TV tower (see Fig. 2), is received at a frequency of 778 MHz (Chan. 59). All main system parameters, presented in Table I, were measured by ETL TV analyzer from Rohde & Schwarz (R&S). As a DVB-T receiver one set-top-box (tuned on 778 MHz) connected to TV set was used. The level of the received DVB-T signal was equal to -50.7 dBm.

To emulate the LTE uplink signal, an arbitrary signal generator (SMU200) is used from R&S. The generated LTE services, which negatively affect TV services at fixed reception, operate at frequencies from 777 MHz to 787 MHz (Band 13). At this band, LTE transmits in Frequency-Division Duplexing (FDD) mode, works in Single Carrier – Frequency Division Multiplexing (SC-FDMA).

In this experiment, we have generated LTE signals with different bandwidths (1.4 MHz, 3 MHz and 10 MHz). One sub-frame was generated where only QPSK modulation was used [15]. The working frequency of the LTE RF signals is always depending on the considered coexistence scenario. In the case of non-overlapping scenario, the LTE RF carrier frequency is equal to 782.7 MHz, 783.5 MHz and 784. 5 MHz when LTE channel bandwidths (in this work marked as B_{LTE}) are 1.4 MHz, 3 MHz and 5 MHz, respectively. LTE services (for all considered B_{LTE} values) at partial overlapping coexistence scenario are operated on 782 MHz. Finally, at full overlapping scenario, the working frequency of LTE RF signal for all B_{LTE} values is 779 MHz.

After sufficient generation of both wireless services, they are combined and then Wilkinson splitter is used for dividing the interfered DVB-T signals for the measurement of objective parameters by ETL TV and for the observing of picture distortions (set-top-box and TV set).

IV. EVALUATION OF EXPERIMENTAL RESULTS

There are used three objective parameters to evaluate the influence of the interfering LTE RF signal on the DVB-T one: bit error rate (BER) before and after Viterbi decoding and modulation error rate (MER).

The BER values before forward error correction (FEC) represent raw errors which occur during the broadcasting between the transmitter and receiver. The measure of the BER values after Viterbi decoding is used for the assessment of a correctly received DTV signal. This condition is called Quasi Error-Free (QEF) reception and it is fulfilled when BER after Viterbi decoding is less or equal to 2.0×10^{-4} [1]. The MER parameter, measured in dB units, used to evaluate the overall

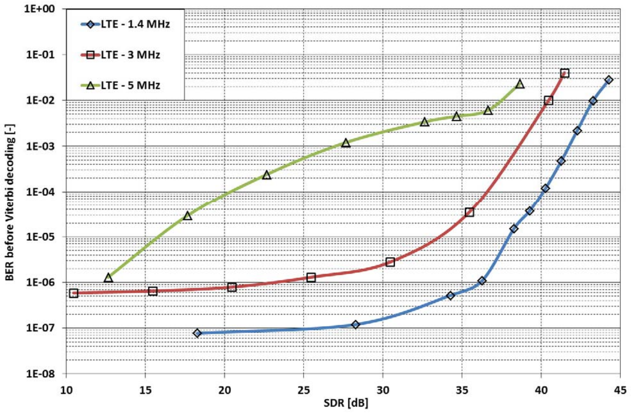

Fig. 3. Dependences of BER at the input of FEC decoder in DVB-T on the SDR ratio when non-overlapping coexistence scenarios are assumed. The bandwidth of the LTE signals are 1.4, 3 and 5 MHz, respectively.

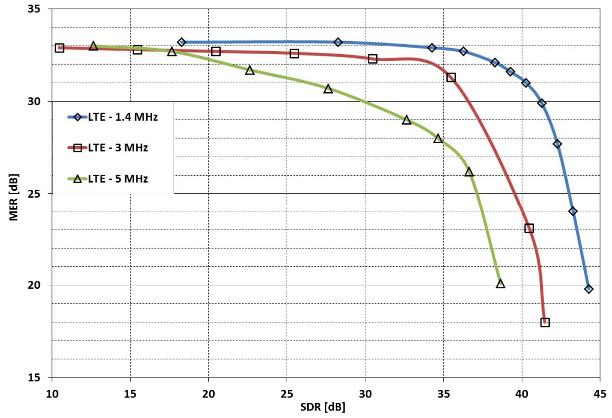

Fig. 6. Dependences of MER in DVB-T on the SDR ratio when non-overlapping coexistence scenarios are assumed. The bandwidth of the LTE signal are 1.4, 3 and 5 MHz, respectively.

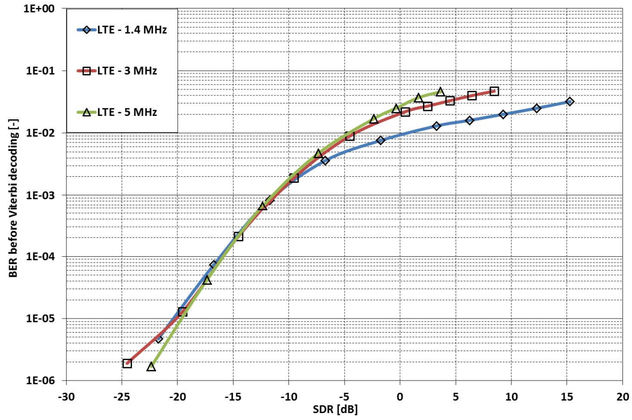

Fig. 4. Dependences of BER at the input of FEC decoder in DVB-T on the SDR ratio when partial overlapping coexistence scenarios are assumed. The bandwidth of the LTE signals are 1.4, 3 and 5 MHz, respectively.

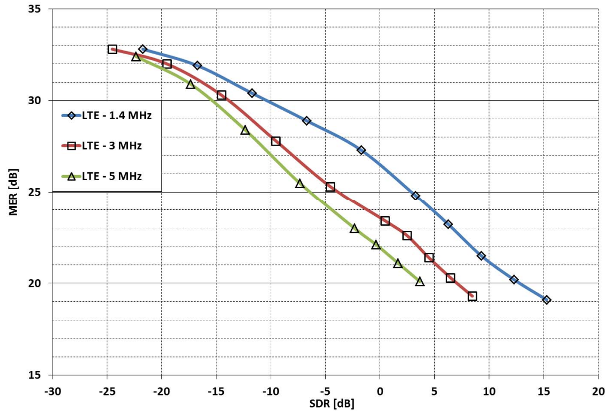

Fig. 7. Dependences of MER in DVB-T on the SDR ratio when partial overlapping coexistence scenarios are assumed. The bandwidth of the LTE signal are 1.4, 3 and 5 MHz, respectively.

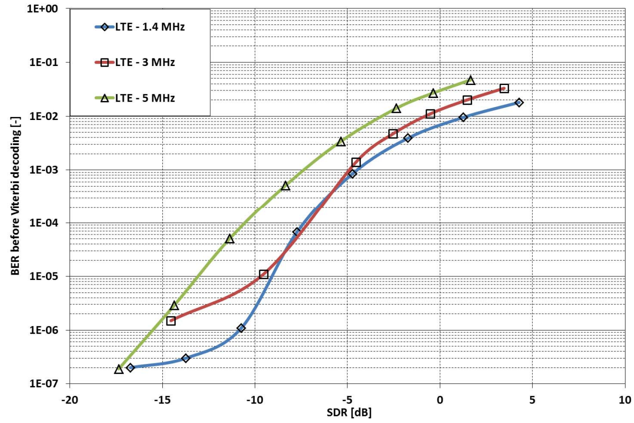

Fig. 5. Dependences of BER at the input of FEC decoder in DVB-T on the SDR ratio when full overlapping coexistence scenarios are assumed. The bandwidth of the LTE signals are 1.4, 3 and 5 MHz, respectively.

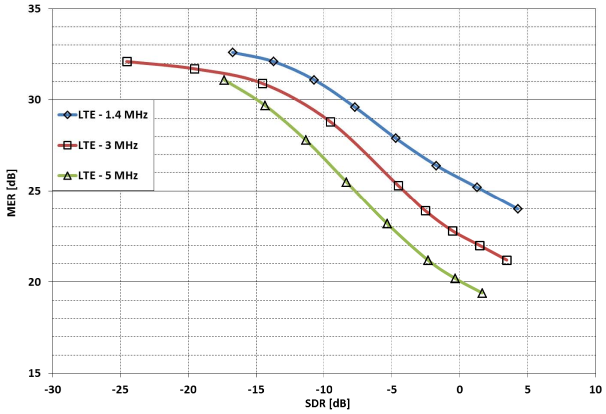

Fig. 8. Dependences of MER in DVB-T on the SDR ratio when full overlapping coexistence scenarios are assumed. The bandwidth of the LTE signal are 1.4, 3 and 5 MHz, respectively.

performance of DVB-T system in the transmission link.

Obtained results were analyzed as dependence on the spectral density ratio (SDR). The SDR is defined as the power ratio between DVB-T and LTE signal per unit of the used bandwidth. Such value is calculated as follows [16]:

$$SDR = P_{LTE} - 10\log B_{LTE} - (P_{TV} - 10\log B_{TV}), \tag{1}$$

where P_{LTE} is the power level of the LTE uplink signal, B_{LTE} expresses the bandwidth of the used LTE channel, P_{TV} is the power level of the received DVB-T signal from the

TABLE II
SDR RATIOS WHERE CONDITIONS FOR QEF IN DVB-T ARE FULFILLED

LTE channel bandwidth (B_{LTE})	**Coexistence scenario and SDR ratio**		
	Non-overlapping	***Partial overlapping***	***Full overlapping***
1.4 MHz	43.5 dB	4.5 dB	0.9 dB
3.0 MHz	41.0 dB	2.1 dB	0.5 dB
5.0 MHz	38.0 dB	-0.4 dB	-1.8 dB

considered TV towers and B_{TV} represents the bandwidth of the used TV channel. From the (1) it can be clearly seen that the spectral density of the TV level is higher than the level of LTE with negative SDR values.

Dependences of BER before Viterbi decoding on the SDR ratio at different B_{LTE} values, when non-overlapping scenario is considered, are shown in Fig. 3. In this scenario the side band of the DVB-T RF channel (at 782 MHz) is touched by side band of the LTE RF channel (from 782.7 MHz to 784.5 MHz). It means that there is no guard band between them. From the obtained results can be clearly seen that the robustness of DVB-T system to LTE system is highly depending on the considered B_{LTE} and P_{LTE} values. The power of the LTE signal was in the range of (-40 ÷ -14) dBm.

Fig. 4 shows the BER versus SDR values at the DVB-T channel decoder input when partial overlapping scenario is assumed. In all cases, a half of the LTE RF channel is overlapped by the DVB-T RF one. It can be observed that at SDR values from -20 dB up to -6 dB the influence of interfering LTE signal on the BER values is not depending on its channel bandwidth (B_{LTE}). Slightly higher differences can be explored at SDR values above 0 dB. The power of the LTE signal was in the range of (-80 ÷ -43) dBm.

The same dependences, but this time for full overlapping scenarios, are plotted in Fig. 5. It is visible that narrowband interfering LTE signal has lower impact on DVB-T performance than the same level broadband interference. The power of the LTE signal was in the range of (-75 ÷ -51) dBm.

The overall performance of DVB-T services at all considered coexistence scenarios as MER versus SDR are shown from Fig. 6 to Fig. 8. Higher MER [dB] values mean less interference effects in the DVB-T transmission.

Finally, Table II contains the maximum SDR values at considered coexistence scenarios where conditions of QEF reception (related to 2.0×10^{-4}) in DVB-T are still fulfilled.

V. CONCLUSION AND FUTURE WORK PLANS

In this paper, coexistence between DVB-T system (fixed reception) and LTE uplink system were studied. There were considered three different coexistence scenarios, namely: non-overlapping (adjacent channel with no guard band), partial and full overlapping. Obtained results proved that different coexistence scenario has important influence on the overall performance of the DVB-T system.

This work will continue by exploring of the impact of the considered coexistence scenario on DVB-T and DVB-T2 (2nd generation DVB-T) at different reception scenario (mobile, portable and fixed) in different transmission scenarios [16]-[18]. Influence of DVB-T/T2 services on the LTE services at their coexistence will be studied too.

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Coexistence Between DVB-T/T2 and LTE Standards in Common Frequency Bands

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Abstract In the last decade, fulfilling the growing users' expectations on the quality of provided multimedia services is one of the biggest challenges for different wireless communication systems. However, many times, different kinds of wireless systems can operate in the same (shared) frequency band. Such coexistence generally negatively affects the performance of the systems colliding. This is especially true for the widely used Digital Video Broadcasting-Terrestrial (DVB-T) or upcoming DVB-2nd Generation Terrestrial (DVB-T2) and Long-Term Evolution (LTE) standards, operating in Europe. Hence, the aim of this paper is to explore the impact of interfering mobile telecommunication services on the mobile TV services provided by LTE and DVB-T/T2 systems in the same frequency band. For the simulation of the coexistence between the LTE and DVB-T/T2 services on the physical layer level, an appropriate method is proposed and complex simulation tools are coupled. The results, presented as a dependence of modulation error ratio at the receiver input and bit error ratio at the channel decoder input on the spectral level ratio, show comparable performances for DVB-T and DVB-T2 systems. Results from simulations are verified by laboratory measurements and should help to better understand the

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influence of co-channel interferences from LTE mobile networks on DVB-T/T2 networks for mobile transmission scenarios.

Keywords DVB-T/T2 · LTE · Coexistence · LTE interference · PHY layer · RF measurement · SLR · BER · MER · QEF

1 Introduction

Over the previous years, the demand for multimedia services in high quality has been increasing rapidly. People are using many types of different multimedia devices, e.g. tablets, smart phones and TVs. Consequently, the data rates required to carry high quality multimedia services are becoming still higher [1, 2]. Depending on the type of communication standard supported by the user's equipment, there are many ways to provide different wireless multimedia services offering different user experience. However, appropriate frequency bands for these purposes are limited. Hence, new and advanced wireless systems with high flexibility and more efficient frequency spectrum usage have been proposed and developed. There are currently two dominant approaches to providing multimedia services. One approach is based on broadcast television systems (e.g. ATSC, DVB, DTMB, ...) while the other approach is based on point to point IP delivery in mobile telecommunication networks (e.g. GSM, UMTS, LTE, ...). In Europe, the family of first and second generation Digital Video Broadcasting (DVB) standards and GSM and UMTS systems are the most widespread.

The DVB project defined three main standards for broadcasting TV services, denoted as satellite (DVB-S/S2), cable (DVB-C/C2) and terrestrial (DVB-T/T2) [3, 4], among which the DVB-T standard is one of the most widespread. However, from the viewpoint of current technical requirements (flexible system configuration, more efficient source coding and spectrum usage), its efficiency is questionable and thus DVB-T is very likely to be replaced by its very perspective successor DVB-T2 [5, 6] in the near future. In the case of mobile telecommunication networks, the Global System for Mobile Communications (GSM) for cellular networks now reaches more than 90 % of the world's population [7]. In addition, as improved or successor specifications of mobile communication networks are standardized and deployed, such as UMTS Long-Term Evolution and its Advance version (LTE and LTE-A), the importance of the former is likely to decrease in the near future. Among the main reasons for such evolution is that LTE is a very flexible system with many adjustable parameters (e.g. flexible channel bandwidths, frequency band, duplexing, modulation, and advanced audio coding) [8–10]. Furthermore, depending on the user equipment (UE) category (with up to 4 × 4 antennas using 20 MHz of RF spectrum), it enables to achieve high peak downlink/uplink (≈300/75 Mbit/s) bitrates and utilizes the radio frequency (RF) spectrum more efficiently than its predecessors [1].

At the last World Radio Conference (WRC-2007) it was decided to allocate a part of the Ultra High Frequency (UHF) band (790–862 MHz) to International Mobile Telecommunications (IMT) mobile services, including LTE in particular, in several world regions, mainly in Europe [8]. However, in these regions the DVB-T/T2 standards occupy an important part of the UHF band, specifically 470–862 MHz. It is clear that DVB-T/T2 and LTE services can coexist in the same or adjacent RF spectrum. As a result, mobile communication services can negatively influence digital TV broadcasting and vice versa [11, 12].

It is a well known fact that in the limited frequency spectrum unwanted coexistence scenarios can occur between the same or different kinds of wireless systems [13–17]. In recent years, many studies dealt with this topic. Possible coexistence scenarios between Bluetooth and Wireless Fidelity (Wi-Fi) systems, sharing the same industrial, scientific and medical (ISM) frequency bands (around 2.4 GHz) were explored in [18]. In other works [19, 20], researchers investigated inter-system and intra-system interferences in GSM and UMTS systems, set to operate in a common RF band. Furthermore, in [21], coexistence between higher-priority primary and lower-priority secondary networks was investigated, while both of them were using the IEEE 802.11 based distributed coordination function for medium access control (MAC). The common result of the mentioned studies is that the interferences can decrease the data throughput and the Quality of Services (QoS) in the considered networks [22, 23].

Nowadays, attention in the field of wireless systems coexistence research is more focused on the different coexistence scenarios between the DVB-T/T2 and LTE/LTE-A standards. Tekovic et al. [24] measured the LTE downlink system performance degradation caused by DVB-T signal in case both systems are operating in the same digital dividend band. Unwanted interference effects of the LTE downlink signal on DVB-T (when the fixed reception scenario is considered) have been studied in [25, 26]. Moreover, in [25], benefits of several filters to suppress unwanted interference form the LTE signal were investigated.

For defining advanced coexistence scenarios between DVB-T/T2 and LTE/LTE-A systems and proper exploration of such scenarios, appropriate simulation tools and models are needed, respectively. In literature, several such models can be found. Interferences, caused by coexistence of the LTE and DVB-T systems in the digital dividend spectrum, were analysed by Monte Carlo simulations and discussed in [27, 28]. In other works [25, 29], possible coexistence of LTE and DVB services is investigated by the Spectrum Engineering Advanced Monte-Carlo Analysis Tool (SEMCAT).

From this brief state-of-the-art, it is clearly seen that the problem of coexistence among different wireless systems (especially between DVB-T and LTE systems) is a hot topic. In the presented works, the authors used different simulation tools to model and explore different coexistence scenarios between DVB-T and LTE services. However, many times these applications do not give enough information about how the potential interferences from LTE can influence the performance of DVB-T/T2 on the physical layer (PHY). To be more precise, exploring the dependences between DVB-T/T2 objective evaluation parameters on its PHY level (e.g. bit error rate and modulation error rate) and interfering LTE signal has not been deeply explored yet. Hence, in this paper we present an appropriate method to simulate the impact of unwanted interferences from LTE system on the DVB-T/T2 system on the PHY level. For this purposes we use our previously developed applications in MATLAB [30]. The correctness of the proposed method is validated by measurements, based on our earlier experience in the field of coexistence measurement among DVB-T/H/T2 and LTE systems [31–34]. To the best of our knowledge, similar exploration in this form hasn't been presented in any scientific or technical papers yet.

The aim of this research article is as follows:

1. Propose an appropriate method to simulate co-channel coexistence between DVB-T/T2 and LTE systems on their PHY level, when operating in the same frequency band.
2. Explore the influence of the unwanted interferences from the co-channel coexistence between DVB-T/T2 and LTE on the performances of DVB-T and DVB-T2 systems on their PHY level.

3. Verify the simulation results through laboratory measurements.
4. Evaluate the overall impact of possible co-channel coexistence scenarios among DVB-T/T2 and LTE systems on the DVB-T and DVB-T2 performance on their PHY level.

The rest of this paper is organized as follows. The considered coexistence scenarios and system parameters of DVB-T/T2 and LTE systems are outlined in Sect. 2. In Sect. 3, an appropriate method to explore the influence of the interferences from LTE services on DVB-T/T2 system on their PHY level is presented. This section also contains a brief description of the method for verifying simulation results with laboratory measurements. Evaluation of the obtained results from simulations and measurements is discussed in Sect. 4. Finally, some concluding remarks are given in Sect. 5.

2 Explored Coexistence Scenarios Between DVB-T/T2 and LTE

To investigate the impact of unwanted LTE signals on the DVB-T/T2 ones in the same frequency band it is necessary to describe how such a coexistence scenario can occur. In this part, the considered coexistence scenarios are briefly described.

We consider a situation when providers of digital terrestrial TV (DTV) services and LTE mobile services are operating in the same area. As a type of coexistence, we assume a full overlapping scenario. This means that the receiver of DTV services is located at the edge of cell coverage for LTE eNodeB [35]. Such a coexistence scenario is plotted in Fig. 1. The DVB and LTE services are provided at a frequency of 810 MHz. The user of a tablet (in a house), supporting mobile TV services, receives a TV signal from a TV tower Tx located in a Single Frequency Network (SFN). At the same time, another user with a smartphone is receiving LTE services (downlink). As was mentioned, the connection between UE and eNodeB is established at a frequency of 810 MHz. Hence, the LTE RF signal interfering the broadcasted DTV RF signal. In this study, we assume a constant RF

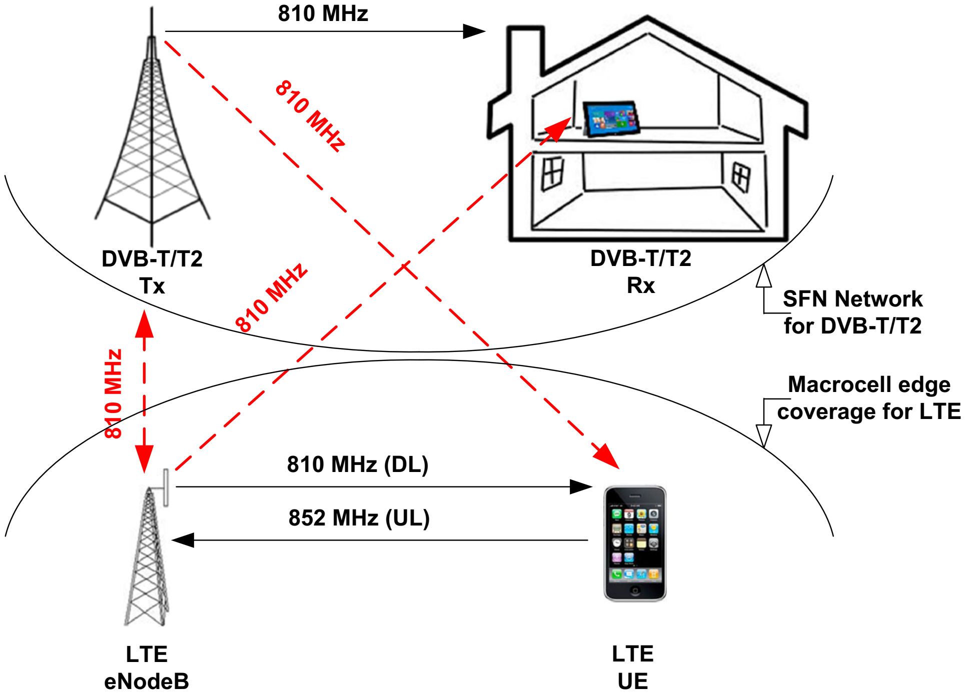
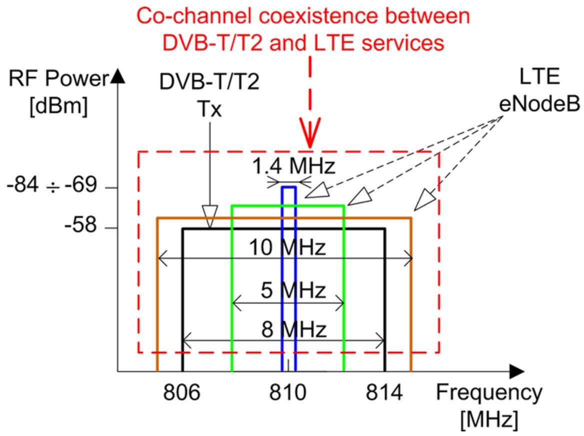


Fig. 1 Coexistence between DVB-T/T2 and LTE services

Fig. 2 The RF spectrum of analyzed coexistence scenarios



signal level of the broadcasted DTV signal and a variable RF signal level of LTE mobile services. Consequently, the level of the impact of mutual interferences will depend on the signal level of the LTE. A detailed graphical representation of the described coexistence scenarios in the frequency spectrum is depicted in Fig. 2. The considered DVB-T/T2 and LTE system parameters can be found in Table 1. From these parameters it is clearly seen that in this work we consider the following inter-system coexistence scenarios:

- Co-channel coexistence of DVB-T and LTE systems, when the bandwidth of the LTE RF signal can be 1.4, 5 or 10 MHz.
- Co-channel coexistence of DVB-T2 and LTE systems, when the bandwidth of the RF LTE signal can be 1.4, 5 or 10 MHz.

3 Modelling the Effect of LTE Downlink Interferences on DVB-T/T2 Services

As outlined above, the main aim of this article is to find an appropriate method to explore the impact of an unwanted LTE signal on the PHY level of DVB-T/T2 in the same frequency band. We have previously developed two MATLAB applications for simulating the performance of DVB-T and DVB-T2 systems [30]. As an LTE simulator, we use the application presented in [36]. It was developed to explore signal processing of a LTE system for uplink and downlink mode on the PHY layer. This simplified simulator is based on the LTE downlink simulator, developed at TU Vienna [37, 38]. Hence, the proposed idea of simulating the coexistence between DVB and LTE is supposed to be implemented using these applications. For the purpose of quantifying interferences, the spectral level ratio (SLR) is used. In this section the calculation of this ratio and its application in our simulators is presented and described.

A flowchart of the proposed model for analyzing the coexistence between DVB-T/T2 and LTE systems is plotted in Fig. 3. The DVB-T/T2 signal is generated by a DVB-T/T2 PHY transmitter (Tx) block. It includes all main functional blocks of both systems, like outer/inner coding and interleaving, mapping and modulation, according to [4, 6]. Before signal transmission, the DVB-T/T2 signal is RF modulated by an IQ modulator. The In-phase (I) and Quadrature (Q) signals are filtered by the Square-Root-Raised Cosine (SRRC) filter and upconverted to the carrier frequency $f_{c_{TV}} = 810\,\mathrm{MHz}$. After the whole IQ modulating process, the upconverted signal is prepared to be sent over the transmission channel.

Table 1 DVB-T/T2 and LTE main system parameters of the presented simulations and measurements

Settings	DVB-T	DVB-T2	LTE (3GPP Release 8)
Forward error correction (FEC)	RS[a] + convolutional	BCH[b] + LDPC[c]	Turbo
Code rate (CR)	2/3	2/3	1/3
Type of modulation	QPSK 16QAM	QPSK 16QAM	QPSK
Constellation rotation [5]	–	No	–
Spectrum access method	OFDM[d]	OFDM	OFDMA[e] (FDD)[f]
IFFT[g] size/channel bandwidth	2 K (8 MHz)	2 K (8 MHz)	128 (1.4 MHz) 512 (5 MHz) 1024 (10 MHz)
Type of PP pattern[h] [5]	–	PP1	–
Duration of the guard interval (GI)	56 us	56 us	4.7 us
Carrier frequency	810 MHz	810 MHz	810 MHz
Transmission scheme	SISO	SISO	SISO
Channel conditions	Ideal	Ideal	Ideal
RF Power	−58 dBm	−58 dBm	(−84 to −69) dBm
Decoding algorithm	Viterbi (soft)	1D LLR[i] (soft)	Max log-map

[a] Reed–Solomon

[b] Bose–Chaudhuri–Hocquenghem

[c] Low-density parity-check

[d] Orthogonal frequency division multiplexing

[e] Orthogonal frequency division multiple access

[f] Frequency division duplexing

[g] Inverse fast Fourier transform

[h] Pilot pattern

[i] Log likelihood-ratio

The overall bandwidth of the RF spectrum where coexistence effects are explored is 12 MHz. The reason is that we investigate the coexistence of DVB and LTE services in a common frequency spectrum at the same carrier frequency. Hence, when the maximum bandwidth of the LTE RF signal (considered in this work) equals 10 MHz, then all interfering effects can be explored in the same RF spectrum domain. The channel bandwidth of DVB-T/T2 services (B_{TV}) is fixed at 8 MHz while for LTE the bandwidth (B_{LTE}) is 1.4, 5 and 10 MHz.

We assume that the power in the considered TV channel P_{TVCH} is −58 dBm (minimum sensitivity) [31]. This value can be converted to dBμV at impedance $Z = 50\,\Omega$ as follows:

$$P_{TV}(\mathrm{dB\mu V}) = P_{TVCH}\,(\mathrm{dBm}) + 107. \tag{1}$$

The spectral level of the TV signal can be calculated as:

$$L_{TV}(\mu\mathrm{V/Hz}) = \frac{10^{\frac{P_{TV}(\mathrm{dB\mu V})}{20}}}{B_{TV}}, \tag{2}$$

where B_{TV} is the 8 MHz bandwidth of the TV signal. Let this TV signal level be a constant value while the level of the LTE signal is variable. We consider the level of the LTE signal being within the interval (−84 to −69) dBm. Once again, the spectral level of the LTE signal can be calculated by the same method as is defined by (1) and (2), respectively,

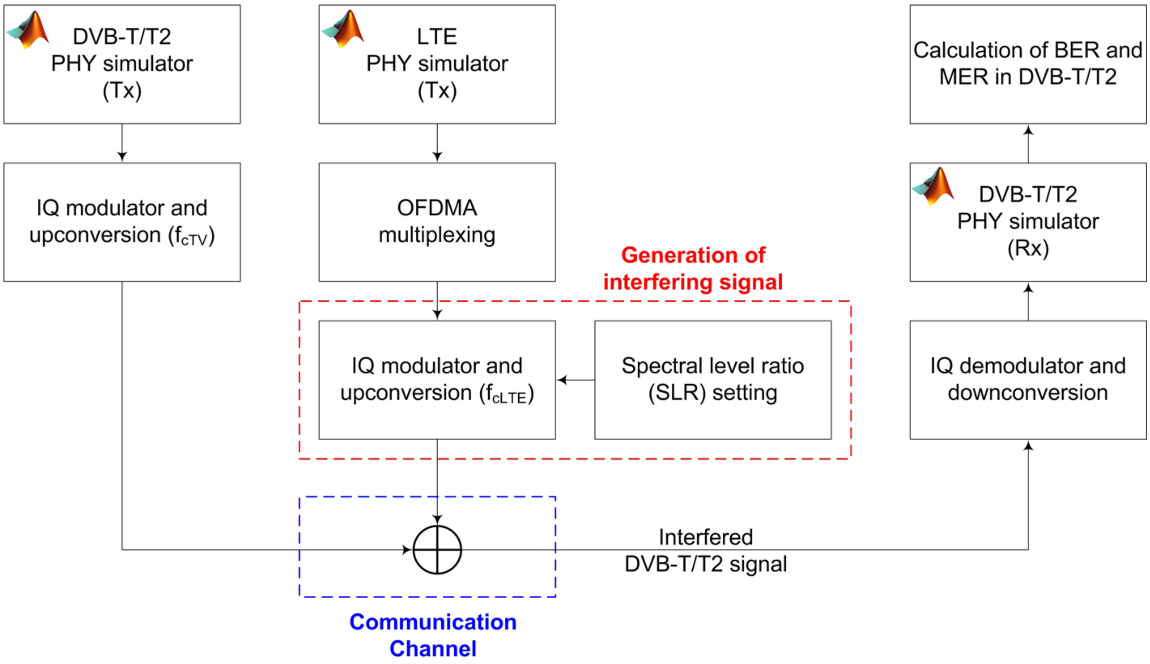


Fig. 3 General flowchart of proposed coexistence analysis model between DVB-T/T2 and LTE systems

$$L_{LTE}(\mu\mathrm{V/Hz}) = \frac{10^{\frac{P_{LTE}(\mathrm{dB\mu V})}{20}}}{B_{LTE}}. \tag{3}$$

Finally, the SLR ratio of L_{TV} and L_{LTE} can be expressed as:

$$SLR(-) = \frac{L_{LTE}}{L_{TV}}. \tag{4}$$

Based on the considered values of B_{TV} and B_{LTE} the SLR values will be between 0.042 and 1.555, respectively.

As mentioned earlier in this work, the interfering signal branch is generated by an LTE PHY downlink transmitter (TX) block, based on the TU Vienna LTE downlink link layer simulator (see Fig. 3). First of all, after adjusting the considered LTE system parameters, the generation of the LTE signal is started. At the point of Orthogonal Frequency Division Multiple Access (OFDMA) the signal processing is stopped and temporary results are saved. After that, the LTE signal is upconverted to carrier frequency $f_{c_{LTE}} = 810\,\mathrm{MHz}$. At this point the LTE signal is multiplied by the actual SLR value. Finally, the signals of DVB-T/T2 and LTE are simply added. For both systems we consider ideal channel conditions, so the only source of impairment is the inter-system interference. Hence, the channel model is represented using two signal adders (see Fig. 3). Finally, the impaired DVB-T/T2 signal is processed in the Rx PHY model and the parameters for evaluating the performance of DVB-T/T2 are calculated.

3.1 DVB-T/T2 and LTE Coexistence Measurement Setup

In order to verify the correctness of the proposed method and simulation results, we have executed a set of laboratory measurements. Hence, for the measurement of the interaction of the described coexistence scenarios between DVB-T/T2 and LTE services, a simple laboratory measurement testbed was established (see Fig. 4). The RF signal of DVB-T/T2

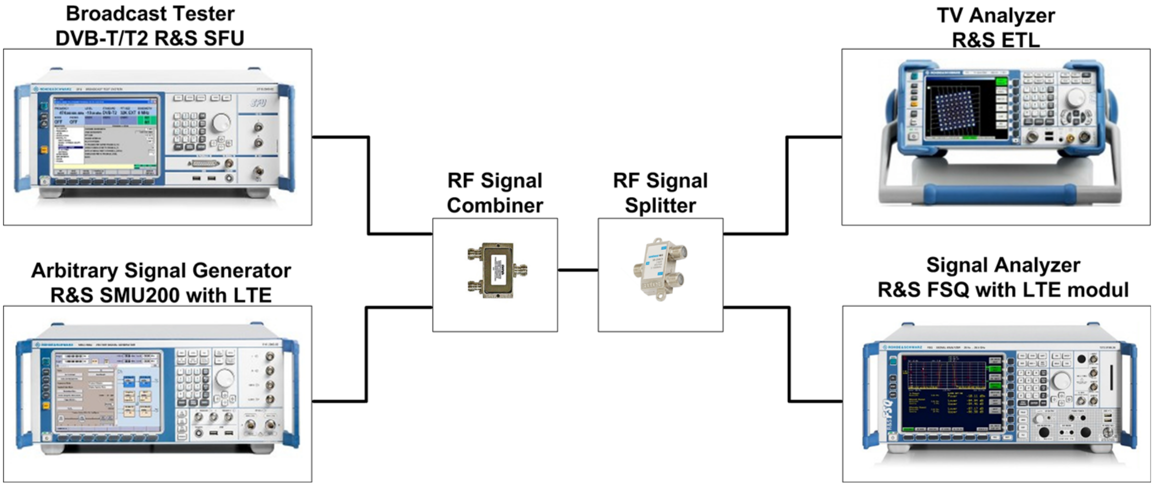


Fig. 4 Proposed measurement testbed for measuring interactions between DVB and LTE systems

(after its complete system parameter setting) is generated in a single frequency unit (SFU) at a center frequency of 810 MHz. The interfering LTE signals with different bandwidths are produced by equipment Rohde & Schwarz (R&S) SMU200A. The level of the LTE signal is set gradually. After generating both desired signals, they are combined and finally the impaired DVB-T/T2 signal is measured and analyzed with an appropriate measuring device (R&S ETL TV analyzer). Signal attenuation caused by combiner/splitter and the coaxial cables are considered. Once again, detailed system settings, which were used for our simulation and measurement, are summarized in Table 1.

4 DVB-T/T2 Performance Evaluation

Before presenting and discussing the obtained results, the most important parameters for evaluating the performance of DVB-T/T2 need to be defined.

In the area of DVB standards, for the assessment of a correctly received TV signal, the quasi-error-free (QEF) operation can be used. In general, QEF is represented by BER leading to no more than one perceivable error event in the decoded video per hour [3]. However, this threshold for DVB-T and DVB-T2 standards is defined differently. The limit for QEF operation in the DVB-T standard is defined as bit error rate (BER) equal to 2×10^{-4} after Viterbi decoding [4], while in DVB-T2 this value is equal to 1×10^{-7} after Low-Density Parity-Check (LDPC) decoding [6]. This difference is caused by different kinds of Forward Error Correction (FEC) encoding and decoding schemes used in DVB-T and DVB-T2 systems.

The LDPC FEC code, applied in DVB-T2, uses an iterative algorithm to decode a codeword. Consequently, the performance of LDPC decoding can be improved by increasing the number of decoding processes [5, 6]. Due to this the condition for QEF reception can be achieved at higher SLR ratios, compared to DVB-T. However, a higher number of decoding iterations has a larger impact on the power consumption of the user equipment and unwanted decoding latency is also possible. It is an important fact from the point of TV signal reception when mobile scenarios are considered. Hence, the dependences of the needed number of decoding processes on the SLR ratios in this study is investigated too.

Another important parameter to evaluate overall performance of DVB-T/T2 systems is the modulation error ratio (MER). The MER [3] parameter is an aggregate quantity which

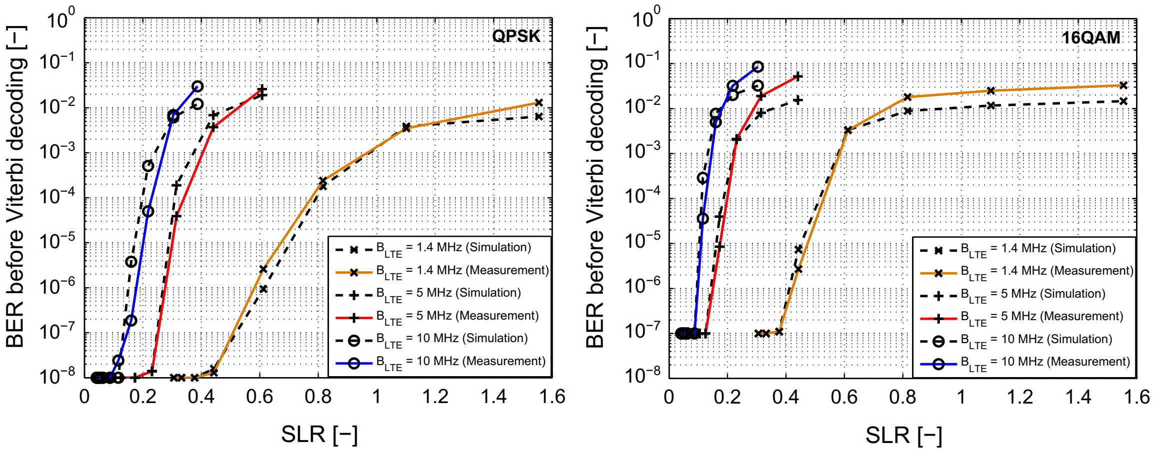


Fig. 5 Dependences of BER before Viterbi decoding on SLR in DVB-T when QPSK (*left*) and 16QAM (*right*) modulations are used

includes all possible individual errors and thus completely describes the performance of the transmission link. The values of MER in the area of DVB are in dB units. A higher value of MER means lower noise and less unwanted interferences in transmission.

Dependences of BER before Viterbi decoding on SLR ratios in the DVB-T standard are shown in Fig. 5. Results from simulations and measurements are plotted by dashed and smooth lines, respectively. As mentioned above, we consider interfering LTE services with three different bandwidths (B_{LTE}): 1.4, 5, 10 MHz. The robustness of mobile TV services, provided by the DVB-T standard using QPSK modulation (see Fig. 5 on the left), on the SLR ratios will be discussed first. The resistance of DVB-T services to unwanted interfering signals is the highest when the bandwidth of the interferer is the lowest (B_{LTE} = 1.4 MHz). When the SLR ratio is higher than 1, the BER values at the channel decoder input are still low enough (approximately 1×10^{-3}) to achieve the QEF reception condition after FEC decoding. At SLR higher than 1.55, the QEF conditions are not fulfilled because errors in the channel are high. The situation considering the LTE RF signal with higher B_{LTE} values is different. When the bandwidth of interfering LTE signals is 5 or 10 MHz, then with increasing SLR ratios, the decrease of DVB-T performance is quicker. Just for comparison, at SLR = 0.4 and 0.6 the channel errors for B_{LTE} = 1.4 MHz are low, but for B_{LTE} = 5 and 10 MHz the BER values at the input of the FEC decoder are very high and practically represent the limit for QEF reception. Secondly, the impact of the interfering LTE signal on DVB-T has been explored in the case of 16QAM modulation (see Fig. 5 on the right). The obtained curves have the same meaning and form as for QPSK modulation but now the DVB-T performance is slightly lower. The reason is that 16QAM modulation has lower resistance to interference noises. All obtained simulation results were verified by laboratory measurements. As can be seen, the results from simulations correlate well with measurement.

The whole simulation process was repeated, but this time TV services were provided by the DVB-T2 standard (see Fig. 6). Differences between the BER values before FEC decoding in DVB-T and DVB-T2 systems are minimal, but after deeper exploration it is visible that at some SLR ratios these values in the DVB-T2 system are slightly higher. These differences are probably caused by the different signal processing of the data in the T2 system block Bit Interleaved Coding and Modulation (BICM) [5]. Overall, the obtained results demonstrate that DVB-T2 performance before channel decoding has comparable performance with the DVB-T system.

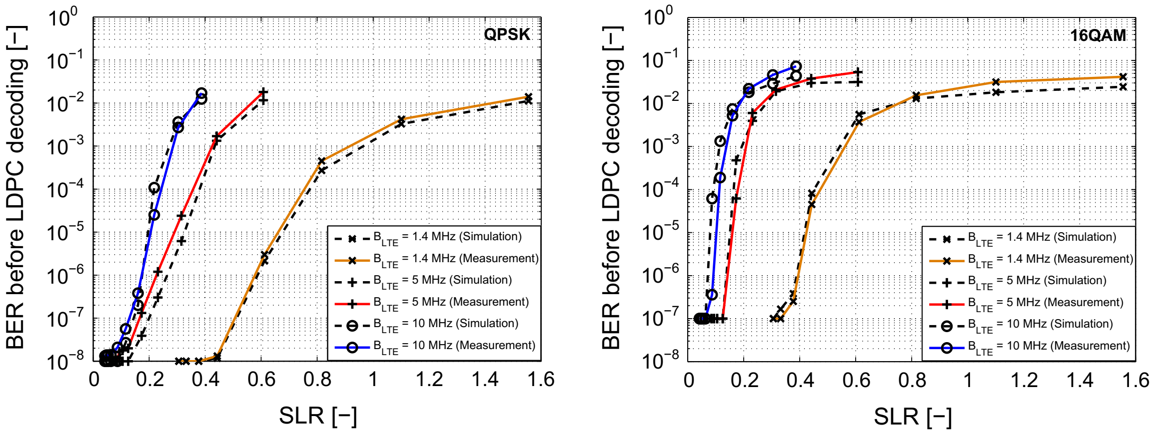


Fig. 6 Dependences of BER before LDPC decoding on SLR in DVB-T2 when QPSK (*left*) and 16QAM (*right*) modulations are used

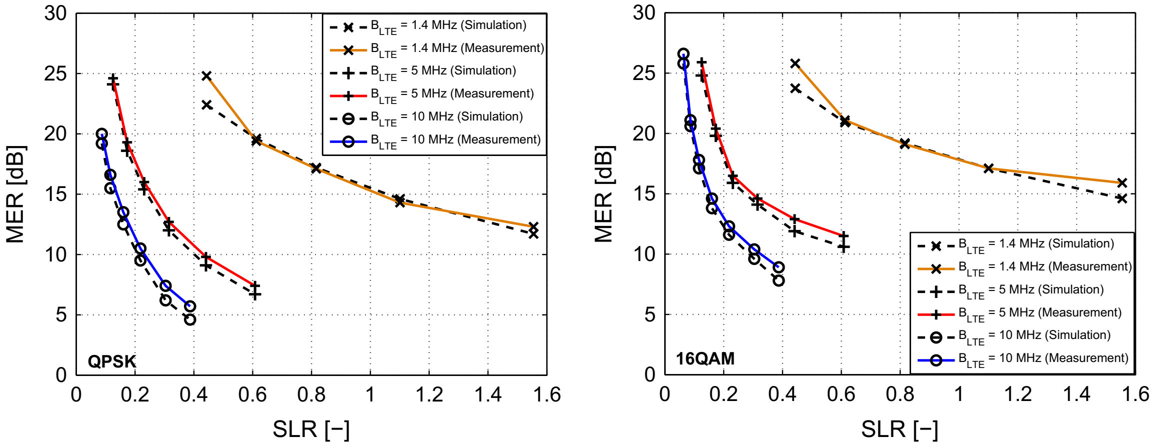


Fig. 7 Dependences of MER on SLR in DVB-T when QPSK (*left*) and 16QAM (*right*) modulations are used

Dependences of MER ratios on SLR in the DVB-T standard are graphically shown in Fig. 7. Once again, MER ratios for QPSK modulation (see Fig. 7 on the left) were obtained first. As can be seen, the obtained results correspond to previously investigated BER errors. To be more precise, at $B_{LTE} = 1.4$ MHz the decrease of MER ratio is the lowest while at $B_{LTE} = 10$ MHz is the highest. All obtained MER ratios from the simulation and measurement for 16QAM modulation are plotted in Fig. 7 (on the right). Influence of the SLR ratio on MER in the DVB-T2 system were investigated too (see Fig. 8). In general, all obtained curves have exponential features. Once again, simulation results (dashed lines) of MER values in DVB-T/T2 are verified by measurement (smooth lines). The maximum difference between the obtained results (simulation and measurement) is below 2 dB.

The performance of the LDPC decoder in DVB-T2, subject to interfering LTE services, is explored as the dependence of the needed number of iterations (repeated LDPC decoding) on the SLR ratios (see Fig. 9). As mentioned above, the LDPC decoding algorithm is an iterative process and its performance can be improved by increasing the number of decoding iterations to a certain boundary, beyond which the refinement is negligible. In our explorations (simulations and measurements) the number of required iterations [per Forward Error Correction Frames (FECFRAME)] at lower SLR ratios was

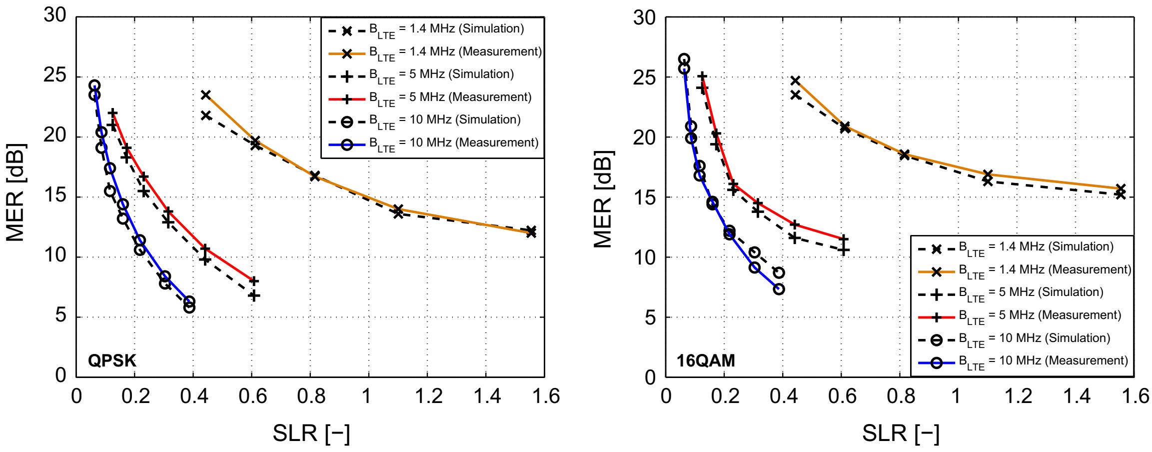


Fig. 8 Dependences of MER on SLR in DVB-T2 when QPSK (*left*) and 16QAM (*right*) modulations are used

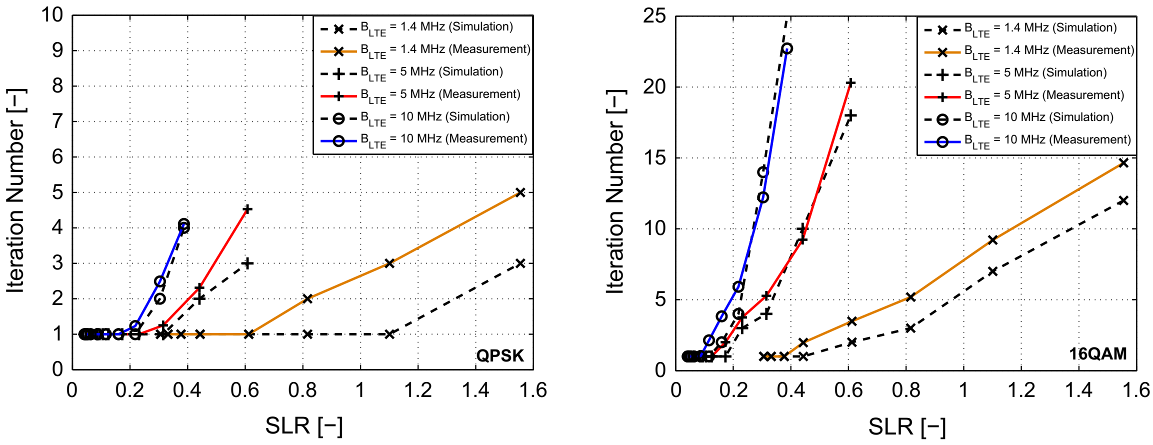


Fig. 9 Dependences of the amount (number of iterations) of repeated LDPC decoding on the SLR in DVB-T2 system

between 1 and 5 (when QPSK modulation is used) and at higher SLR ratios between 1 and 25 (when 16QAM modulation is used), respectively. This high difference in the needed number of iterations can be explained by the lower resistance of 16QAM modulation against interferences. It can be seen that the needed iteration process is the lowest at QPSK modulation when $B_{LTE} = 1.4$ MHz. As is visible, the dependences of needed iteration number are closely related to the results from MER versus SLR ratio (see Figs. 7, 8).

Table 2 clearly summarizes the limit values of SLR ratios at different bandwidths of the interfering signal where conditions of QEF reception in DVB-T/T2 standards are still fulfilled. As mentioned above, values corresponding to DVB-T2 are related to $\mathrm{BER} = 1 \times 10^{-7}$. This is the main reason for the differences of the presented results.

5 Conclusion and Future Work Plans

The risk of coexistence, causing shared or adjacent channel interferences between different kinds of wireless systems, can negatively affect the quality of their provided services. In this paper, the coexistence of the DVB-T/T2 and LTE downlink services in a common frequency band was investigated. To explore the impact of interfering LTE mobile services

Table 2 SLR ratios for different interfering signal bandwidths (B_{LTE}) where conditions for QEF in DVB-T/T2 are still fulfilled

Standard	Modulation	Interfering signal bandwidth (MHz)	Simulation SLR (–)	Measurement SLR (–)
DVB-T[a]	QPSK	1.4	1.56	1.57
		5	0.62	0.61
		10	0.39	0.37
DVB-T	16QAM	1.4	1.11	1.11
		5	0.37	0.39
		10	0.28	0.30
DVB-T2[b]	QPSK	1.4	1.57	1.56
		5	0.61	0.60
		10	0.39	0.38
DVB-T2	16QAM	1.4	1.10	1.09
		5	0.41	0.40
		10	0.30	0.30

[a] QEF operation with limit 2×10^{-4} (after Viterbi decoding)

[b] QEF operation with limit 1×10^{-7} (after LDPC decoding)

on broadcast TV reception at its PHY level, an appropriate simulation model was proposed. In our experiments we considered interfering LTE signals with different bandwidths. The correctness of this model was proved by laboratory measurements.

Simulation and measurement results proved that:

- At co-channel coexistence scenarios, unwanted narrowband interfering LTE signals have less impact on DVB-T/T2 performance than same level broadband.
- The impact of the LTE system on DVB-T/T2 system performance in a common frequency band highly depends on the level of their channels overlapping and on the power imbalance between RF signals.
- In DVB-T2 systems, the decodability of received broadcast TV signals at co-channel coexistence gradually decreases with higher SLR ratio. Different bandwidths of the LTE signal affect the DVB-T2 FEC decoder performance (from the point of needed iteration number) at the same SLR ratio differently.
- The requirements for QEF reception in DVB-T and DVB-T2 systems at the considered co-channel coexistences after FEC decoding are comparable.

Our future work plans can be divided into two directions. Firstly, we will continue with extending and optimizing the proposed simulation model (exploring DVB-T/T2/T2-Lite services' impact on LTE and vice versa). Moreover, we will extend our applications with different kinds of fading channel models [37, 39–43]. Secondly, we will explore how new additional features in the DVB-T2 system (e.g. depth of time interleaving, rotated constellation, type of pilot pattern) [3, 5, 6] can influence its overall resistance to the interfering LTE signals. These further studies will consider more kinds of different coexistence scenarios [35, 44–46].

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[7] POLAK, L., PLAISNER, D., KALLER, O., MILOS, J., KRATOCHVIL, T. Coexistence between DVB-T2-Lite and LTE Downlink Networks in Advanced Mobile Fading - Partial Overlapping RF Spectrum. In *Proceedings of the 39th International Conference on Telecommunications and Signal Processing (TSP 2016)*, Vienna (Austria), 2016. pp. 458–461. ISBN: 978-1-5090-1287-9. (70%)

Coexistence between DVB-T2-Lite and LTE Downlink Networks in Advanced Mobile Fading Channels - Partial Overlapping RF Spectrum

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***Abstract*—This paper presents results from the study of coexistence between second generation digital video broadcasting terrestrial-lite (DVB-T2-Lite) and Long-Term Evolution (LTE) downlink networks in a shared radio frequency (RF) band. Partial overlapping coexistence scenarios are considered. A laboratory measurement testbed is used to measure the impact of interfering LTE system on DVB-T2-Lite system. To emulate T2-Lite mobile scenario, Vehicular Urban (VU30) and Motorway Rural (MR100) advanced fading channel models are used. Experimental results show that the DVB-T2-Lite performance, measured as dependences of Bit and Modulation Error Ratios on the carrier-to-noise ratio, is highly depending not only on the proportion of RF channel overlapping and bandwidth of the LTE signal, but also on conditions in the transmission environment.**

***Keywords*—DVB-T2-Lite, LTE, fading channels, interference, coexistence, RF overlapping, BER, MER.**

I. INTRODUCTION

The second generation of digital video broadcasting terrestrial (DVB-T2) standard is a more complex and flexible system than its predecessor, the well-known DVB-T [1] - [3]. Moreover, there is defined a special system profile within the DVB-T2 main system, marked as DVB-T2-Lite [2]. It was proposed and designed in order to reduce the complexity of T2-Lite-only receivers so as to minimise the cost and power consumption of handheld devices. It is suitable to broadcast mobile and portable TV services. The T2-Lite content may be multiplexed together with a T2-base signal, with each signal being transmitted in the future extension frames (FEF) [4].

Based on current spectrum allocation, DVB-T2 system and the next generation mobile technology, the Long-Term Evolution (LTE) [5], may occupy the same UHF band [6]. Such unwanted interaction can cause significant performance degradation for both systems. Hence, users requirements on multimedia services in different quality [7], [8] can not be completely fulfilled.

In the last decade, many works have been focused on exploring of the coexistence between DVB-T/T2 and LTE systems [9] - [12]. In [13], authors examine the DVB-T and LTE compatibility in adjacent channels in the 700 MHz band. For this purpose the SEAMCAT software was used. Impact of LTE uplink signal on the DVB-T signal in different coexistence scenarios (non-overlapping, full and partial overlapping RF spectrum) is investigated in [14] and [15]. Critical coexistence issues between DVB-T2 and LTE networks in the 700 MHz and 800 MHz bands by measuring interference protection ratios in laboratory conditions are presented in [16]. In other work [17], authors explored the influence of interfering indoor LTE femtocell on the outdoor-to-indoor DVB-T2-Lite performance and vice versa in a shared frequency band. However, study of coexistence scenarios, especially partial overlapping radio frequency (RF) spectrum, between DVB-T2-Lite and LTE systems in advanced mobile TV fading channels is still missing. The aim of this paper is to investigate the influence of LTE downlink signal on T2-Lite system at different ratios of the RF spectrum overlap in advanced mobile fading channels.

The rest of this paper is organized as follows. A description of considered coexistence scenarios and physical layer (PHY) parameters of both systems, used in the measurement, are presented in Section II. The realized laboratory workplace and the measurement setup are outlined in Section III. Section IV contains the obtained results and their discussion. Finally, the paper concludes in Section V.

II. PARTIAL OVERLAPPING COEXISTENCE SCENARIO

In general, there are three different kinds of coexistence scenarios: non-overlapping (adjacent channel with no guard band), partial and full overlapping RF spectrum [12], [14]. In this work, only partial coexistence scenarios are considered. Partial overlapping coexistence scenario can occur when RF channels of the DVB-T/T2 and LTE signal partially overlap. The proportion of RF spectrum overlapping (in MHz) is

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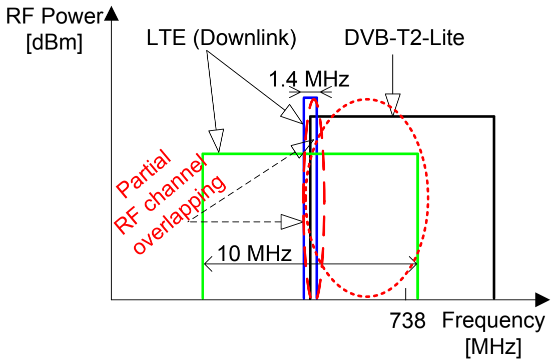

Fig. 1. Intersystem interference scenario between DVB-T2-Lite and LTE networks - partial overlapping scenario.

TABLE I. SETTINGS USED FOR EXPLORING THE COEXISTENCE SCENARIOS BETWEEN DVB-T2-LITE AND LTE DOWNLINK SERVICES

Settings	**DVB-T2-Lite**	**LTE (Downlink)**
FEC Scheme	LDPC+BCH (short length)	Turbo
Code Rate (CR)	2/3	1/3
Inner Modulation	16QAM	QPSK 16QAM 64QAM
Constellation Rotation	No	-
Transmission Mode	OFDM	OFDMA
Pilot Paatern (PP)	PP3	-
IFFT Size	2048	128 1024
Channel Bandwidth	8 MHz	1.4 MHz 10 MHz
Guard Interval (GI)	1/8 (28 μs)	4.7 μs
Channel Environment	AWGN VU30 MR100	AWGN

always less than the bandwidth of DVB-T/T2 signal (in this case 8 MHz). Such scenario is illustrated in Fig. 1.

The main system parameters of DVB-T2-Lite and LTE (downlink) networks, considered in this work, are clearly summarized in Table I. DVB-T2-Lite system configuration respects the features of considered mobile scenarios, emulated by Vehicular Urban (VU30) and Motorway Rural (MR100) fading channel models. Both channel models are based on real measurement data in real environment (urban and rural area). The speed of the receiver in VU30 and MR100 channel model is considered around 30 km/h and 100 km/h, respectively. More details can be found in [18].

Two bandwidths of the interfering LTE signal are assumed in this study: 1.4 MHz and 10 MHz. Furthermore, we consider Band 17 (from 734 MHz to 746 MHz) to provide LTE services, where LTE transmits (in the downlink) in frequency-division duplex (FDD) mode.

III. COEXISTENCE MEASUREMENT CAMPAIGN

Block diagram of the proposed general measurement testbed, based on our previous experience ([10], [14], [15], [17]), to measure the influence of RF coexistences on the DVB-T2-Lite system is shown in Fig. 2.

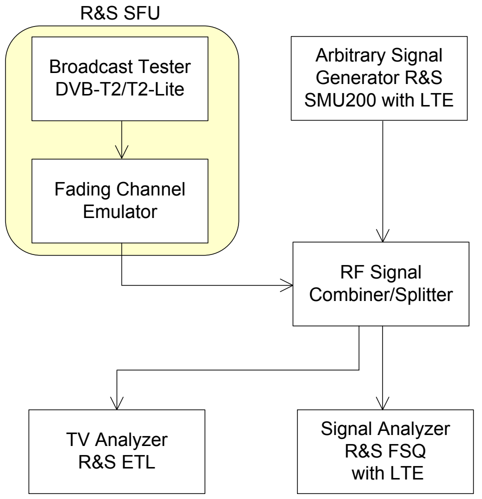

Fig. 2. Block diagram for measuring the interaction between DVB-T2-Lite and LTE (downlink) signals.

A single frequency unit (SFU) from Rohde&Schwarz (R&S) is used to generate a complete DVB-T2-Lite signal. After the set of all system parameters (see Table I), the T2-Lite signal, with a level of –50.4 dBm [14], is RF modulated. The carrier frequency is set to 738 MHz. During the measurement, the carrier-to-noise (C/N) ratio was changed between 10 dB and 40 dB. The SFU unit also contains a module to emulate different fading channel conditions. In this study, we consider VU30 and MR100 mobile fading channel models [18].

The complete LTE downlink RF signal, with defined system parameters (see Table I) is produced in an arbitrary signal generator R&S SMU200. In this study, we have generated two LTE downlink signals with bandwidths 1.4 MHz and 10 MHz, respectively. Ten sub-frames were generated where the used modulation types were equally used (3xQPKS; 4x16QAM and 3x64QAM). As a channel model only Additive White Gaussian Noise (AWGN) is assumed. The working frequency of the LTE RF signal is always depending on the considered channel overlap between T2-Lite and LTE RF signals. For example, at bandwidth 1.4 MHz, the carrier frequency is from 733.5 MHz to 734.5 MHz with step 200 kHz. It means that the influence of LTE interfering signal is measured at each RF channel overlap, increased by 200 kHz. This one is monitored with R&S FSQ signal analyzer.

Finally, both RF signals are combined (in combiner) and then Wilkinson splitter is used for dividing the interfered T2-Lite signal for the measurement of objective parameters by R&S ETL TV analyzer. The bit error ratio (BER) before and after Low-Density Paritiy-Check (LDPC) decoding and modulation error ratio (MER) [2], [17] are measured.

IV. EXPERIMENTAL RESULTS

Dependences of BER before LDPC decoding values on the C/N ratio for T2-Lite signal in AWGN channel at various channel overlap ratios with the LTE RF signal (bandwidth 1.4 MHz) are shown in Fig. 3. The reference BER curve in

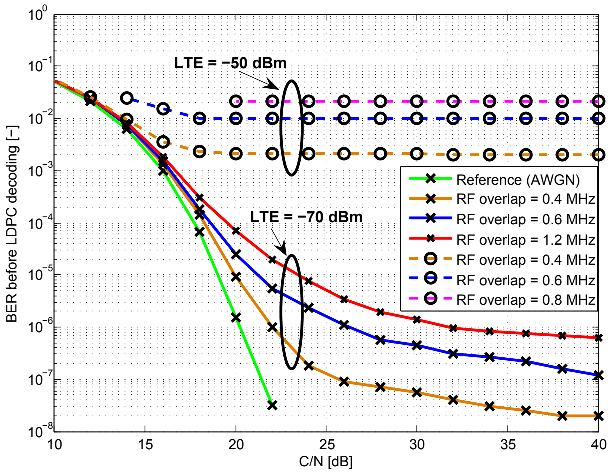

Fig. 3. BER versus C/N ratio in T2-Lite AWGN channel at different partial overlapping coexistence scenarios. LTE bandwidth 1.4 MHz.

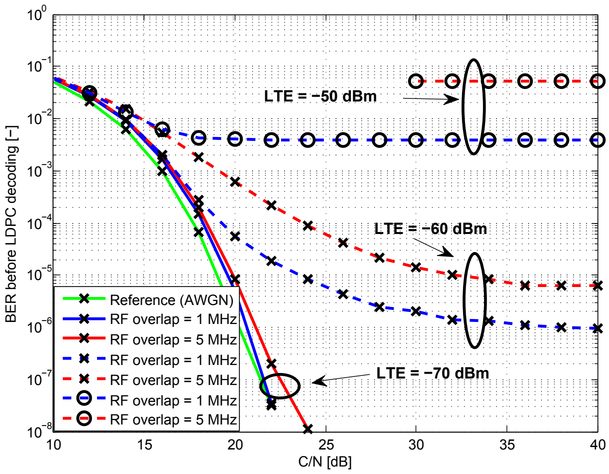

Fig. 6. BER versus C/N ratio in T2-Lite AWGN channel at different partial overlapping coexistence scenarios. LTE bandwidth 10 MHz.

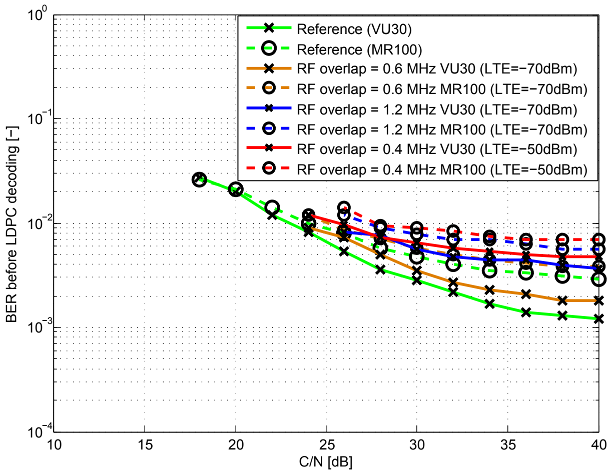

Fig. 4. BER versus C/N ratio in T2-Lite VU30 and MR100 channels at different partial overlapping coexistence scenarios. LTE bandwidth 1.4 MHz.

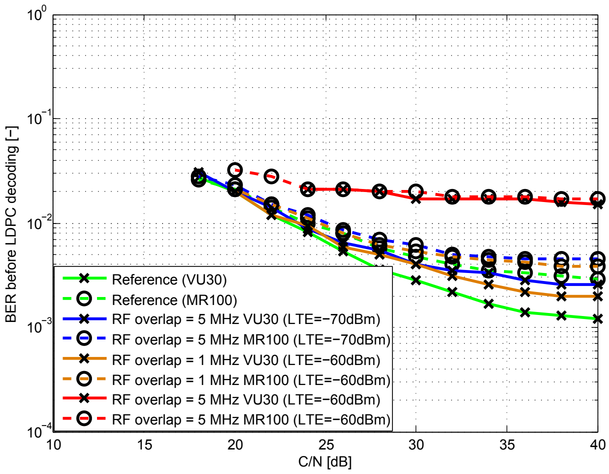

Fig. 7. BER versus C/N ratio in T2-Lite VU30 and MR100 channels at different partial overlapping coexistence scenarios. LTE bandwidth 10 MHz.

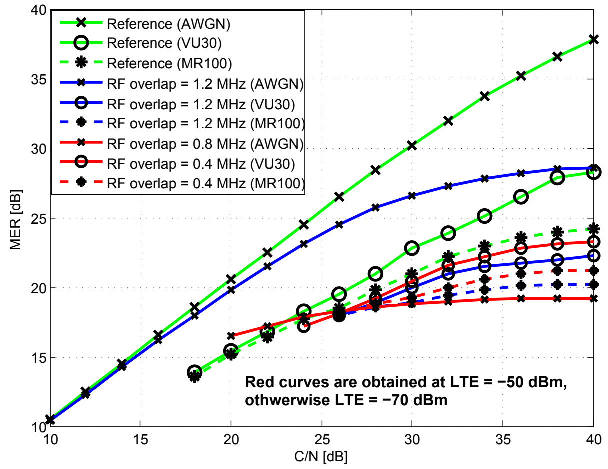

Fig. 5. MER versus C/N ratio in T2-Lite at different partial overlapping coexistence scenarios. LTE bandwidth 1.4 MHz.

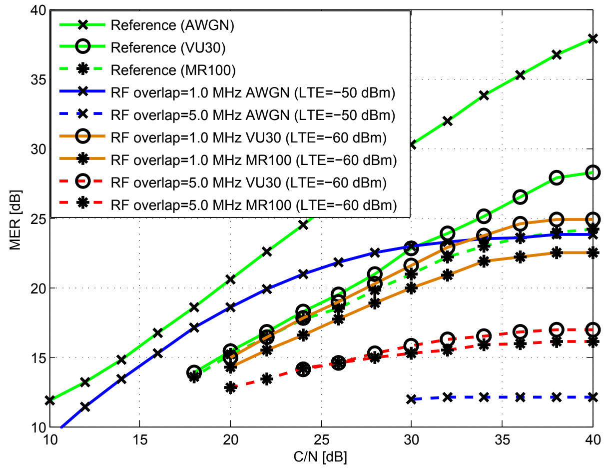

Fig. 8. MER versus C/N ratio in T2-Lite at different partial overlapping coexistence scenarios. LTE bandwidth 10 MHz.

the AWGN channel (no coexistence with LTE) is marked by a green solid line. With decreasing C/N ratio and increasing RF channel overlap at the same LTE signal level (–70 dBm) the performance of the DVB-T2-Lite is gradually decreasing. On the other hand, the minimal value of C/N ratio to fulfil Quasi-Error Free (QEF) condition [14] at all the considered RF overlap ratios is the same as in the reference AWGN channel (approx. 10.5 dB). The situation is different, when the level of the LTE signal is –50 dBm. In all the explored RF overlap scenarios, the BER values are very high (around 1.10^{-2}) and are practically constant from (C/N) 18 dB to 40 dB.

The same dependences but in VU30 and MR100 mobile fading channel models are plotted in Fig. 4. Firstly, reference curves in both channels have been obtained (solid and dashed green lines). It can be seen, that both curves are very similar because features of both channel models (Doppler shift and spectrum) are similar [18]. Thanks to this, the performance of T2-Lite coexistence with LTE is almost the same. However, the mentioned additional fading features and interferences from coexistence have higher influence on the T2-Lite performance. The QEF condition in VU30 channel is fulfilled from (C/N) 21 dB to 26 dB when LTE=–70 dBm. In MR100 channel at LTE=–50 dBm condition for QEF in T2-Lite is fulfilled only for RF overlap lower than 0.2 MHz (high BER in channel).

Figure 5 shows the MER versus C/N values for selected partial overlapping coexistence scenarios for two LTE signal levels (–70 dBm and –50 dBm). The MER parameter describes the overall performance of T2-Lite in the transmission link. The difference between the MER values at highest and lowest level of RF channel overlap is approx. 10 dB.

The whole measurement was repeated for LTE RF signal with bandwidth 10 MHz and the results are shown in Fig. 6 to Fig. 8. The shape of the curves, compared to the previous ones (LTE RF signal with bandwidth 1.4 MHz), is practically the same. However, wideband interfering LTE signal has higher impact on the T2-Lite performance. In the AWGN channel at LTE=–50 dBm and 5 MHz RF overlap the measured T2-Lite MER values are almost the same.

V. CONCLUSION

From the study, presented in this paper, it is evident that the robustness of DVB-T2-Lite to LTE in case of partial RF channel overlapping is highly dependent on three parameters, namely: the bandwidth of the LTE RF signal and its level, the C/N ratio of the T2-Lite signal and the considered channel overlap ratio of T2-Lite and LTE RF signals, related to the assumed channel conditions. Hence, further study of system parameters of DVB-T2 and LTE networks from the point of different coexistence scenarios of these systems is necessary.

This study will continue by exploring how additional features of the DVB-T2/T2-Lite system (e.g. constellation rotation, type of pilot pattern) can influence its performance subject to interfering LTE (and its advanced version LTE-A) signal at different coexistence scenarios and in different channel conditions [19] - [22].

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Influence of the LTE System using Cognitive Radio Technology on the DVB-T2 System using Diversity Technique

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UDK [621.397.23:654.165LTE]:621.391.8

Original scientific paper

In recent years, the development of advanced wireless communication systems has been rapidly progressing. In Europe, the 2nd Generation Terrestrial Digital Video Broadcasting (DVB-T2) and Long-Term Evolution (LTE) are the most promising techniques to provide multimedia services efficiently (in flexible quality and with high spectrum efficiency). The purpose of this work is to explore possible influences of the LTE uplink services, using cognitive radio (CR) technology, on the area which is covered by DVB-T2 services. In the case of DVB-T2, both single-input single-output (SISO) and multiple-input single-output (MISO) transmission techniques are considered. The defined coexistence scenarios are measured with an appropriate measurement testbed. The performance of the received TV signal is evaluated on its physical layer (PHY) level. The obtained results allow better understand the influence of LTE system on DVB-T2 which is using diversity technique in the same RF channel (co-channel coexistence). One of the main results is that there are the same requirements on the Forward Error Correction (FEC) decoding process in the DVB-T2 receiver, when power imbalances between TV transmitters (an both SISO and MISO modes) are considered at the interfering LTE signal. This finding was also proved by analysis of variance (ANOVA).

Key words: DVB-T2, LTE, cognitive radio, SFN, SISO/MISO, coexistence, interference, SDR, BER, MER

Utjecaj LTE sustava zasnovanog na kognitivnoj radio tehnologiji na DVB-T2 sustav zasnovan na metodi diverzifikacije. U posljednje vrijeme se znatno ubrzao razvoj naprednih bežičnih komunikacijskih sustava. U Europi metode prijenosa signala zasnovane na DVB-T2 (eng. 2nd Generation Terrestrial Digital Video Broadcasting) i LTE (eng. Long-Term Evolution) metodama najviše obećavaju u području učinkovitog pružanja multimedijalnih usluga (s prilagodivom kvalitetom i s visokom učinkovitosti spektra). U ovom radu je razmotrena mogućnost korištenja LTE signala uzlazne veze, uz korištenje kognitivne radio tehnologije, u području pokrivenom DVB-T2 signalom. Razmotrene su metode prijenosa DVB-T2 signala s jednim ulazom i jednim izlazom (eng. Single-Input Single-Output, SISO) te više ulaza i jednim izlazom (eng. Multiple-Input Single-Output, MISO). Definirani su scenariji koegzistencije i isti su izmjereni korištenjem prikladnog mjernog ispitnog stola. Kvaliteta primljenog TV signala je evaluirana na fizičkom sloju. Prikupljeni rezultati omogućuju bolje razumijevanje utjecaja LTE sustava na DVB-T2 koji koristi metodu diverzifikacije u istom radio-frekvencijskom kanalu (koegzistencija susjednog kanala). Jedan od glavnih rezultata je postojanje istih zahtjeva na proces dekodiranja s ispravljanjem pogrešaka u prijemniku (eng. Forward Error Correction) DVB-T2 prijemnika kada se neravnoteža snaga između TV predajnika (MISO i SISO režimi rada) uzima u obzir na interferirajućem LTE signalu. Navedeni rezultat potvrđen je analizom varijance.

Ključne riječi: DVB-T2, LTE, kognitivni radio, SFN, SISO/MISO, koegzistencija, interferencija, SDR, BER, MER

1 INTRODUCTION

Many people use different kinds of smart devices (phones, tablets and TVs). Depending on the type of communication standard, supported by the user's equipment, there are many ways to provide different wireless multimedia services offering different user experience. Requirements on modern multimedia services (image, audio and data content) in superb quality are common among the users. For the providers of these services the limited usage of radio frequency (RF) spectrum is the one of the biggest challenges. Hence, there is a great effort to optimize existing wireless infrastructures and develop new architectures which increase spectral efficiency [1,2]. Otherwise, the increasing amount of wireless services provided by different wireless techniques escalate the risk of unwanted coexistence scenarios [3–5].

The last decade in the development of advanced wireless communication standards was very intensive. In the near future, from the viewpoint of current technical requirements (advanced source coding, flexible system configuration and efficient spectrum usage), the Digital Video Broadcasting - 2nd Generation Terrestrial (DVB-T2) [6] and Long-Term Evolution (LTE) [7] systems will be deployed to provide all types of multimedia services in required quality, mainly in Europe. Due to its highly flexible system configuration [8, 9], the DVB-T2 system can provided digital TV (DTV) services in different transmission scenarios (mobile, portable and fixed). Furthermore, these services can be broadcasted by using multiple-input single-output (MISO) transmission technique, besides the traditional single-input single-output (SISO) transmission technique. The usage of modified Alamouti coding in the DVB-T2 system and two transmitting antennas which do not radiate the same transmitted signal can increase the signal robustness through transmit diversity [8, 9].

3GPP LTE [10] supports high data rates and flexible system configuration in order to adapt transmission parameters to the actual state of a radio link. This system can use flexible channel bandwidths, advanced signal processing and duplexing for downlink and uplink scenarios.

On the last World Radio Conference (WRC-2007), the International Telecommunication Union (ITU) has decided to harmonize the "700 and 800 MHz bands" for LTE technology. However, these RF bands are allocated to and used by DTV services, e.g., the DVB-T/T2 system. In Europe, several countries (e.g. Germany, Finland and United Kingdom) have already announced their intentions to allocate the 700 MHz band to mobile services. Consequently, there is a likely possibility for second digital dividend to effectively harmonize the usage of UHF bands "700 MHz" and "800 MHz" [11], [12].

Nowadays, significant attention is being dedicated to TV white spaces (TVWS) which can resolve the interference problem through cognitive radio (CR) technology in the coexistence scenarios [13, 14]. On the other hand, possible interferences may occur when narrowband systems (e.g. DTV) are operating under severe environmental conditions [15]. In this work, a possible negative impact of the LTE uplink signals, using CR technology (marked as LTE-CR), on DVB-T2 services (broadcasted by SISO/MISO techniques), received by fixed home receiver, is explored. For these purposes a special measurement testbed is used, based on [16, 17]. Attention is devoted to exploring the overall performance of DVB-T2 system, using SISO/MISO techniques, at co-channel coexistence with LTE-CR system.

The rest of this paper is organized as follows. After the Introduction, a brief state-of-the-art in the field of coexistence between DVB-T/T2 and LTE systems is presented in Section 2. This section also outlines the main contribution of our article. In Section 3, a description of the analyzed coexistence scenarios is presented. Section 4 contains a description of our proposed measurement workplace, including measuring method. Obtained results from measurements, their evaluation and discussion are presented in Section 5. Finally, the conclusion is given in Section 6.

2 RELEATED WORKS

Nowadays, exploring the possible coexistence scenario between the DVB-T/T2 and LTE/LTE-A standards and mitigation of interferences from these undesirable scenarios is still a hot topic [11]. This fact is also evidenced by many published studies available.

Guidotti et al., in [5], present the mutual co-channel interference problem between DVB-T and LTE mobile link. An analysis of the coexistence between the LTE downlink and DVB-T signals by simulation is outlined in [18]. Based on the achieved results, authors recommend several protection ratios (PRs) for DVB-T and minimum distances between LTE base station and DTV receivers. In [19], an impact of a small LTE cell on a large broadcast cell in the spectral overlap scenario between LTE and DVB-T technologies is explored. Results from simulations prove that the broadcast data rate is highly dependent on the separation distance between the DTV receiver and the LTE eNodeB. Influence of DVB-T system on the LTE system performance below 700 MHz at different distances between the two transmitters and different offset distances is investigated in [20, 21]. For the evaluation of the obtained results an adjacent channel interference ratio (ACIR) was used. Unwanted interference, generated by LTE services, to the DTV and its possible mitigation by using filters installed before the DTV receiver is presented in [22]. The common output of the mentioned studies is that these (spectrum) interferences can significantly decrease the capacity and the performance of the considered networks.

Authors in [12] deal with possible interferences from the coexistence between LTE uplink signal and DVB-T2 signal in the shared 700 MHz band. In this work, a fixed outdoor and portable indoor DTV reception is considered. Polak et. al. in [16] and [17] investigate possible coexistence scenarios between current and emerging mobile (from GSM to LTE) and TV broadcasting (DVB-T/T2) systems. Measurement results of mutual interactions between LTE and DVB-T2-Lite services under different coexistence scenarios were outlined in [23]. However, the influence of LTE uplink signal on DVB-T2 signal in fixed reception scenario, broadcasted by MISO technique, has not been explored yet. To be more precise, study of the impact of LTE uplink signal (based on CR technology) in the area covered by DVB-T2 using diversity technique is still an open topic. Therefore, based on the above presented works, the aim of this research article is as follows:

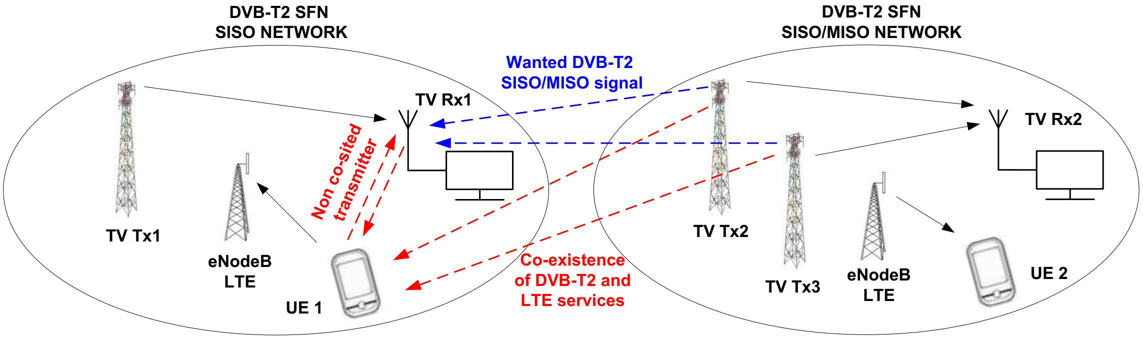

Fig. 1. Possible coexistence scenarios between mobile networks (LTE-CR) and DVB-T2 SISO/MISO SFN networks.

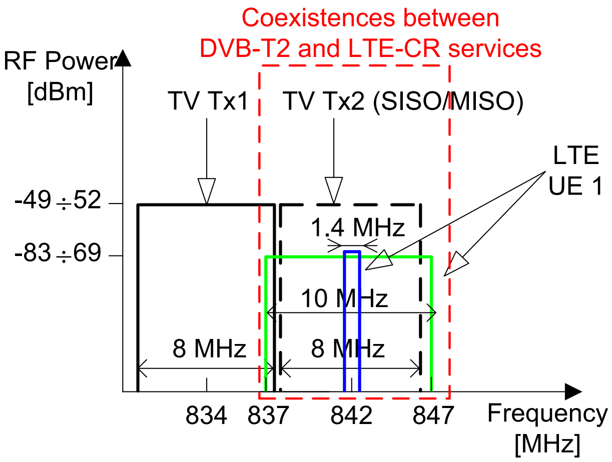

Fig. 2. The RF spectrum of analyzed coexistence scenarios (marked by red dashed rectangle) between DVB-T2 (8 MHz) and LTE-CR (1.4 MHz and 10 MHz) services.

1) Propose an appropriate measurement testbed, based on [16] and [24], to measure the coexistence between DVB-T2 (SISO/MISO) and LTE-CR (uplink) networks on their physical layer (PHY) level;

2) Explore the influence of the unwanted interferences from the co-channel coexistence between DVB-T2 SISO/MISO RF signal (consider different power imbalances) and LTE-CR uplink RF signal on the performance of DVB-T2 on its PHY level;

3) Evaluate the overall impact of the possible co-channel coexistence scenario (DVB-T2 vs LTE-CR (uplink)) networks on the DVB-T2 (SFN-SISO/MISO) performance.

3 COEXISTENCE SCENARIO AMONG DVB-T2 SISO/MISO AND LTE-CR SYSTEMS

It has been mentioned above, that in the TVWS band the CR technology can play a key role in the effective frequency band usage in the near future. Therefore, it can be expected that the features of CR technology in connection with TVWS will be mainly applied in LTE mobile networks. Nevertheless, when the spectrum sensing mechanism in CR is not able to accurately detect levels of other RF signals then possible coexistences scenarios can occur. The concrete coexistence scenario, investigated in this work, is plotted in Fig. 1.

The considered scenario is as follows. There are two single frequency networks (SFNs) in which DTV signals are broadcasted by TV towers. In the first SFN network, the SISO transmission mode is applied at a center frequency of 834 MHz while in the second SFN network, SISO or MISO techniques can be used at 842 MHz. Furthermore, in the first SFN network, an LTE base station (marked as eNodeB) is operated. It ensures LTE mobile network services for the user of smartphone, marked as UE1. The path of the data transmission is from the user to eNodeB (upload) and the LTE uplink system uses CR technology. Consequently, mutual interferences can not occur.

For the CR technology a transmit power control rule-based spectrum sharing technique is assumed [25–27]. Furthermore, for the LTE-CR system a special "worst case" scenario is considered when a limited number of RF channels are allocated to provide LTE services. Consequently, its move to the next “free” channel (in the case of detecting another RF signal) is difficult. Now a situation is assumed in which a user of TV set is receiving broadcasted TV signal from the second SFN network at the frequency 842 MHz. It means that the LTE mobile network, operating in the RF band (832÷862) MHz, can negatively affect this remote TV reception [28]. As a result, unwanted co-channel coexistence between DVB-T2 and LTE-CR systems can occur when the receiver of DTV services is located at the edge of cell coverage for LTE eNodeB [17]. It is assumed that both receiving equipments (TV and UE1) are stationary. For SFN-MISO network, we consider a 2x1 Alamouti MISO reception (diversity mode) [29, 30].

A graphical representation of the described RF coexistence scenario is clearly shown in Fig. 2. The bandwidth of LTE signal is 1.4 MHz and 10 MHz, respectively.

4 EXPERIMENTAL MEASUREMENT SCENARIO

For the measurement of the interactions between DVB-T2 and LTE-CR systems an extended version of an earlier presented testbed [16] was used. Its general block diagram is shown in Fig. 3.

Two single frequency units (SFUs) from Rohde&Schwarz (R&S) are used, where the first one is marked as a master (central unit) and the second one is marked as a slave transmitter. By using the internal T2-modulator interface (T2-MI) generator, the master SFU unit can provide a 10 MHz reference clock as well as other synchronization signals (T2-MI & 1pps) required for the slave SFU unit and not only for itself. In the master SFU unit, appropriate video transport streams (TSs) are generated for SISO and MISO transmission modes, respectively. To be more precise, two different streams are used, one each for the SISO and MISO modes. After that, in MISO mode, the TV input signal in the slave transmitter must be set as an external signal ("received" from the master SFU). From the point of correct synchronization and same system configurations (in both master and slave devices) this is extremely important. Otherwise, highly destructive spectral interferences can occur [24]. After its system parameter setting, the complete DVB-T2 signal is generated and RF modulated.

The generated LTE signals, which interact with DVB-T2 services, are produced in R&S SMU200A. The bandwidths of LTE signals are 1.4 MHz and 10 MHz, respectively. Ten sub-frames were generated, where only QPSK modulation was used. LTE transmits in the uplink, using frequency-division duplexing (FDD) duplex mode.

Finally, both RF signals are combined and then Wilkinson splitter is used for dividing signals for the further analysis and evaluation. During the measurement, the level of the LTE signal is set gradually. The Gaussian (AWGN) channel environment is assumed.

System parameters of both systems are summarized in Table 1. Different Pilot Pattern (PP) schemes are used for SISO (PP2) and MISO (PP1) techniques. The difference is caused by different system requirements of SISO/MISO mode settings [8, 9].

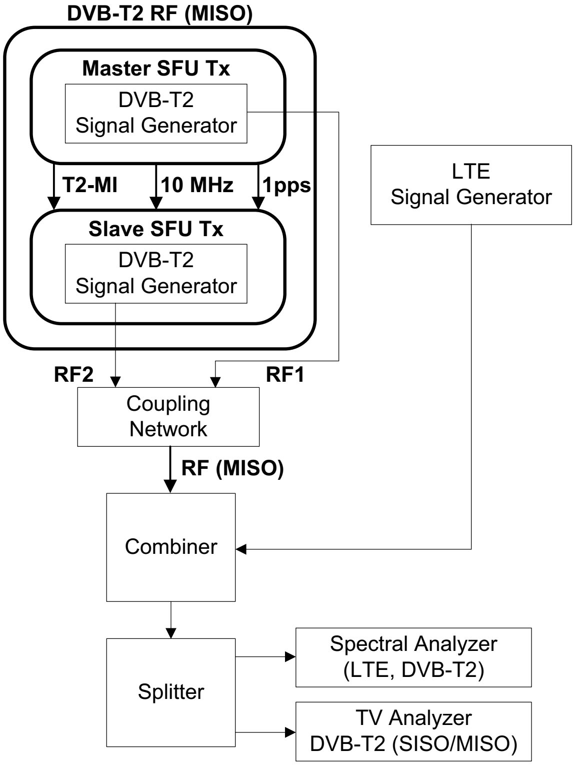

Fig. 3. General block diagram of workplace for measuring the interaction between DVB-T2 (SISO/MISO configuration) and LTE-CR networks

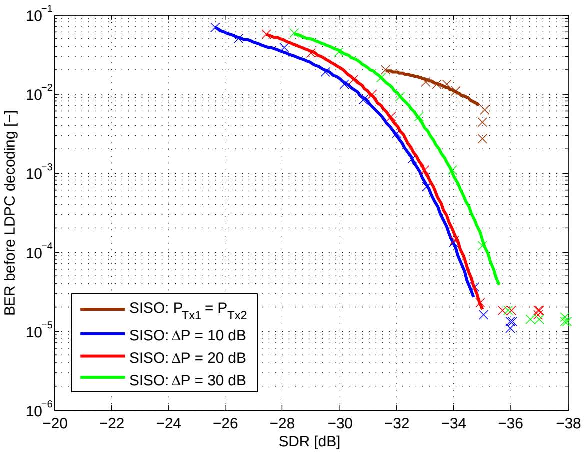

Fig. 4. Dependences of BER at the input of FEC decoder in DVB-T2 on the SDR ratio when DVB-T2 SISO and LTE-CR services coexisting. Power levels DVB-T2 RF signals from TV transmitters are either equal (brown curve) or different (other curves). LTE-CR bandwidth 10 MHz.

5 EVALUATION OF THE OBTAINED RESULTS

Before the discussion of the obtained results the most important parameters for the evaluation of the DVB-T2 performance are briefly outlined at the beginning of this section. In order to evaluate the influence of inter-

Table 1. Settings of DVB-T2 and LTE-CR main system parameters, used for exploring the described coexistence scenarios

Settings	**DVB-T2**	**LTE-CR**
FEC code rate	$2/3$(BCH+LDPC)	$1/3$ (Turbo)
Type of modulation	256QAM	QPSK
Constellation rotation	No	-
Spectrum access method	OFDM	SC-FDMA (FDD)
FFT size	16384 (16K)	128 and 1024
Channel bandwidth	8 MHz	1.4 MHz and 10 MHz
Type of PP pattern	PP2 (SISO) PP1 (MISO)	- -
Cyclic prefix duration	266μs ($19/128$)	4.7μs (short)
Transmission mode	SISO/MISO	SISO
Scenario (reception)	Fixed	Mobile
Channel frequency	834 MHz (SFN1) 842 MHz (SFN2)	(832÷862) MHz
RF power	(-52÷-49) dBm	(-83÷-69) dBm
Channel environment	AWGN	AWGN
FEC decoding	1D LLR (soft)	Max Log-Map

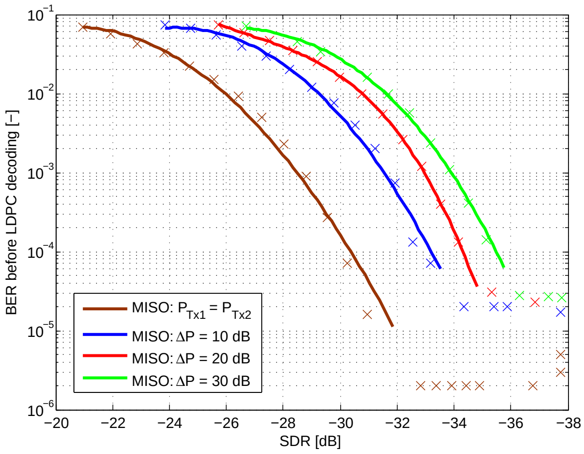

Fig. 5. Dependences of BER at the input of FEC decoder in DVB-T2 on the SDR ratio when DVB-T2 MISO and LTE-CR services coexisting. Power levels of DVB-T2 RF signals from TV transmitters are either equal (brown curve) or different (other curves). LTE-CR bandwidth 10 MHz.

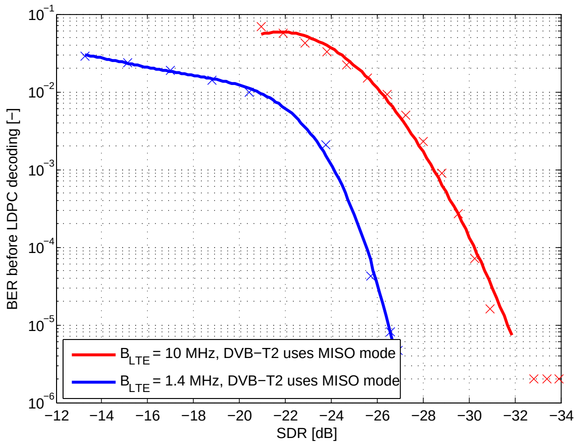

Fig. 6. Dependence of BER at the input of FEC decoder on the SDR ratio when DVB-T2 (using MISO technique and both TV transmitters have the same transmit power) and LTE-CR services coexisting. LTE-CR bandwidth 1.4 MHz and 10 MHz.

fering LTE signals on the performance of the DVB-T2 SISO/MISO system on its PHY level, bit error rate (BER) at the FEC decoder input and output, and the modulation error rate (MER) at the receiver input are measured.

The BER values before forward error correction (FEC) represent raw errors which occur during the broadcasting between transmitter and receiver. The measure of the BER values after Low-Density Parity-Check (LDPC) decoding are monitored for the assessment of a correctly received DTV signal. For the assessment of a correctly received DVB-T2 signal, the quasi-error-free (QEF) operation is used. The QEF requires less than one uncorrected error event occurring per hour, corresponding to a BER after LDPC decoding lower than or equal to 10^{-7} [8, 9].

To evaluate the overall performance of the DVB-T2 system in the considered transmission modes and channel environments, the modulation error ratio (MER) was used [8, 9].

Obtained results were analyzed as a dependence on the spectral density ratio (SDR). The SDR is defined as the power ratio between T2 and LTE signal per unit of the used

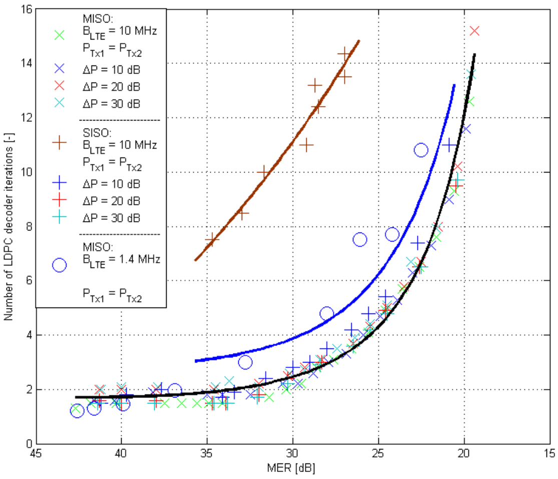

Fig. 7. Dependence of the amount of repeated (number of iterations) LDPC decoding on MER, at which the BER after FEC decoding is less or equal to 10^{-7} (limit for QEF reception). LTE-CR bandwidth 1.4 MHz and 10 MHz.

bandwidth. Such value is calculated as follows [23]:

$$\begin{aligned} \mathrm{SDR} &= \mathrm{P_{LTE}} - 10\mathrm{log}(\mathrm{B_{LTE}}) + \\ &= -((P_{\mathrm{TV1}} + P_{\mathrm{TV2}}) - 10log(B_{\mathrm{TV}})), \end{aligned} \tag{1}$$

where $\mathrm{P_{LTE}}$ is the power level of the LTE signal, $\mathrm{B_{LTE}}$ expresses the bandwidth of the used LTE channel, $\mathrm{P_{TV1}}$ and $\mathrm{P_{TV2}}$ are the power levels of DVB-T2 signals from the considered Tx1 and Tx2 transmitters respectively and B_{TV} represents the bandwidth of the used TV channel. There are considered zero (72 and 72 dBμV) and non-zero power imbalances (72 and 62 dBμV; 72 and 52 dBμV; 72 and 42 dBμV) of TV towers, marked as ΔP. From (1) it can be clearly seen that the spectral density of the TV level is higher than the level of LTE-CR with negative SDR values.

Figure 4 shows the BER versus SDR values at the DVB-T2 channel decoder input when the SISO technique is used. In the case of equal power levels of TV signals the BER values are high, independent of the SDR values. This is caused by the SISO-SFN configuration which results in an overlay of more-or-less identical signals in the receiver. Such scenario is known as 0-dB echo [9] and represents the situation when two TV towers broadcast TV signal in the same SISO-SFN network. This can lead to significant destructive spectral interference. Performances of DVB-T2 SISO configuration at considered non-zero power imbalances are comparable. Convincing results are achieved at ΔP = 10 dB.

Figure 5 shows the BER dependences on the SDR at the DVB-T2 channel decoder input when MISO technique is used. DVB-T2 MISO performances at the same TV signal levels, compared to SISO, are much better. This is caused by applying the modified Alamouti coding technique [9]. Interestingly, in the remaining cases (non-zero power imbalances) the DVB-T2 MISO performances are comparable with SISO ones. To be more precise, for large power imbalances the MISO gain, compared to SISO one, is decreasing. All in all, there is assumed a perfect channel estimation and synchronization at the receiver. Hence, as described in [31], the influence of the relative delay on the MISO gain can be neglected.

Table 2. SDR ratios where conditions for QEF in DVB-T2 are fulfilled

Scenario	**DVB-T2 SISO mode**	**DVB-T2 MISO mode**
ΔP = 0 dB; B_{LTE} = 10 MHz	at any SDR	-20.9 dB
ΔP = 10 dB B_{LTE} = 10 MHz	-25.6 dB	-23.9 dB
ΔP = 20 dB B_{LTE} = 10 MHz	-27.5 dB	-25.7 dB
ΔP = 30 dB B_{LTE} = 10 MHz	-28.2 dB	-26.7 dB
ΔP = 0 dB B_{LTE} = 1.4 MHz	at any SDR	-13.8 dB

In previous scenarios we considered $\mathrm{B_{LTE}}$ = 10 MHz. Curves, channel BER versus SDR for DVB-T2 MISO (in the case $\Delta\mathrm{P_{TV}}$ = 0 dB) at interfering LTE-CR with $\mathrm{B_{LTE}}$ = 1.4 and 10 MHz are plotted in Fig. 6. Obtained results proved that narrowband interfering LTE-CR signal has lower impact on DVB-T2 MISO performance than same level wideband interference.

The overall performance of the DVB-T2 TV signal distributed by the SISO/MISO technique, coexisting with the LTE-CR signal, was investigated too. For this purpose, dependences of the number of LDPC decoding repetitions (needed for successful decoding of FEC frames) on MER were measured. The obtained results are shown in Fig. 7. To prove that at power imbalances higher than 10 dB the DVB-T2 SISO and MISO FEC performances at interfering LTE signal are the same, the results were subject to analysis of variance (ANOVA). From the distribution of measured values in R^2 (MER, Number of LDPC decoder iterations) it is assumed that the distributions of measured values are independent of the transmitters' power difference in the case of the SISO and MISO techniques. A null hypothesis was tested where the values of square errors are the same for all power difference (Δ) clusters:

$$\begin{aligned} H_0 : \mu_{\Delta\mathrm{iterations}^2}(\Delta_0) &= \mu_{\Delta\mathrm{iterations}^2}(\Delta_1) \\ &= \mu_{\Delta\mathrm{iterations}^2}(\Delta_2) = \mu_{\Delta\mathrm{iterations}^2}(\Delta_3), \end{aligned} \tag{2}$$

where Δ_0, Δ_1, Δ_2, Δ_3 denote values of power imbalances (0, 10 20 and 30) dB, respectively. One-way ANOVA confirmed the assumption, because p-level (p = 0.6986) is higher than the chosen significant level α = 0.05. In case of the DVB-T2 SISO/MISO system at ΔP $\geq$ 10 dB and at the same RF channel conditions, power imbalance has no effect on the broadcasted TV signal from TV towers. This leads to the same DVB-T2 FEC decoder performance at interfering LTE-CR signals. The black curve in Fig. 6 is the minimum mean square error (MMSE) interpolation for all measured MER values in DVB-T2 SISO and MISO mode. Lastly, the dependence of iteration number = f (MER) on B_{LTE} = 1.4 MHz was measured (see Fig. 9 values marked by blue "o").

Table 2 summarizes the maximum SDR values at considered scenarios of interfering signal where conditions of QEF reception in DVB-T2 are still fulfilled. Its threshold is related to BER after LDPC decoding equal to 10^{-7} [9]. The results have also been proved subjectively, as in [18]. Once again, these results were obtained in the Gaussian reference channel. For more relevant transmission scenarios it is necessary to increase the SDR values. For fixed outdoor reception the SDR values should be increased by 1 dB for Rice channel (RC20) and by 5-6 dB for Rayleigh channel [11], [12]. In this study, the influence of multipath phenomenon at fixed transmission scenario (RC20 and RL20 channel models) [9], related to the influence of coexistence, can be considered as an additive noise.

Finally, we have studied compatibility of DVB-T2 with LTE. To be more precise, we present the required minimal protection distance (no interference) between the UE and DTV station. This calculation is based on a method which has been presented in [21]. We consider a scenario for DVB-T2 SFN-SISO mode (see Table 2): ΔP = 10 dB, B_{LTE} = 10 MHz and *SDR* = -25.6 dB.

To ensure the QEF reception in the area covered by DVB-T2 signal, we consider field strength between 47 dBμV/m (E_{TVmin}) and 60 dBμV/m (E_{TVmax}) . The RF power for UE can be considered in the interval from 0.02 to 0.2 W (13 to 23 dBm) [10]. The antenna gain (G_{UE}) can be in the interval from 0 to 3 dBi. The maximal field strength ($E_{UE|max}$) at UE antenna far region, based on [32], can be calculated as follows:

$$E_{UE|max} = \sqrt{\frac{480P_{UE}}{G}}\,\frac{\pi f}{c}, \tag{3}$$

where *G* is the gain of an antenna, *f* [Hz] is the working frequency (at the coexistence) and *c* [m/s] is the speed of light. For P_{UE} = 0.02 W and *G* = 1, the $E_{UE|max}$ will be 27.32 V/m which is 148.73 dBμV/m. The equivalent maximal field strength $E_{UE|TVmax}$, where QEF for DVB-T2 is fulfilled, can be calculated as:

$$\begin{aligned} E_{UE|TVmax} = SDR + 20log(B_{LTE}) + \\ - 10log(B_{TV}) + E_{TVmax}. \end{aligned} \tag{4}$$

Hence, the $E_{UE|TVmax}$ will be 28.29 dBμV/m. The isolation loss is then converted into a separation distance using the free-space attenuation $L_{(loss)}$. The $L_{(loss)}$ is calculated as ($E_{UE|max}$-$E_{UE|TVmax}$). In our case it is equal to 120.44 dB. Finally, the required protection distance (in km) between the mobile station and the DTT receiver is [21]:

$$d = 10^{\frac{L_{(loss)} - 32.4 - 20log(f)}{20}}. \tag{5}$$

Considering the values above, the minimal distance between the mobile station and DTT receiver should be 29.97 km.

6 CONCLUSIONS AND FUTURE WORK

In this paper, coexistence of the DVB-T2 and LTE services in the same frequency band was explored and measured. More precisely, we explored possible influences of the LTE system, using cognitive radio technology (for uplink), on the area covered by DVB-T2 SISO (the case when two TV towers operating in the same SISO SFN network) and/or MISO services. For this purpose, an appropriate measurement testbed was realized.

The results show that the overall performance of the DVB-T2 MISO technique against co-channel interferences, compared to the SISO one, is better. Connection between spectral density ratio and measured objective quality indicators of DVB-T2 services was also found. From the obtained results in the explored coexistence scenario it is observed that:

- The impact of LTE-CR system performance on the DVB-T2 system performance in their co-channel coexistence scenario in a shared frequency band highly depends on the bandwidth of the LTE signal, on the used DVB-T2 transmission technique and on the power imbalance between RF signals;
- The DVB-T2 MISO gain against interferences from LTE-CR system at power imbalances higher than ΔP = 10 dB is gradually decreasing. In the considered coexistence scenarios, the overall performance of the DVB-T2 FEC decoder for SISO and MISO transmission mode at ΔP $\geq$ 10 dB is almost the same;
- Different bandwidths of LTE-CR uplink RF signal affect the DVB-T2 RF signal (broadcasted by SISO and MISO technique) in a different way.

All in all, it was proved that overall resistance of DVB-T2, broadcasted by MISO technique at considered zero and lower non-zero power imbalances of TV tower signal strengths, to unwanted interfering LTE signal is evident and promising successful implementation and real operation without any disturbances.

Our future work will continue by finishing and improving the proposed methods for measuring interactions between DVB-T2 and LTE services. Moreover, we are also considering extending our research with fading channel models with Doppler shift [33–35]. Field trial measurements are also considered [36].

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Measurement Setup for Evaluation the Coexistence between LTE Downlink and WLAN Networks

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Abstract—**Measuring the performance of wireless communication systems, especially on the physical layer level, is essential for their development and usage in the real world. With the upcoming 5G technology, various wireless technologies will be used at the same place and at the same time. Consequently, measuring and evaluating their influence on each other is important. In this paper, we present a simple measurement setup to monitor and evaluate the coexistence between LTE (downlink) and WLAN (IEEE 802.11). The setup allows to measure the performance of LTE physical downlink control channels (PDCCH), influenced by IEEE 802.11n, as the dependence of raw bit error ratio (BER) on the carrier-to-interference-and-noise ratio (CINR). The proposed solution is universal because it allows to measure the coexistence of WLAN (uses different technologies) and LTE in the same or adjacent radio frequency (RF) band. The comparison of the results from simulations and measurements validates the correctness of the proposed measurement setup.**

Index Terms—**LTE, WLAN, Wi-Fi, 5G, RF measurement, automatized measurement, coexistence.**

I. INTRODUCTION

The upcoming 5G networks will try to join the spectrum and technologies, such as Long Term Evolution (LTE) and Wireless-Fidelity (Wi-Fi), together to increase high-rate coverage [1], [2]. However, such solution can cause unwanted interaction of these technologies in a shared radio frequency (RF) band. Hence, possible performance degradation of communication systems should be quantified in an appropriate way.

Presently, measuring the interaction (coexistence) of different wireless communication systems in the same or adjacent RF band is very important. In the last decade, several studies were published on this topic. An automated setup for measuring and evaluating the network performance of Wireless Local Area Network (WLAN) Access Point (AP)s was presented in [3]. Authors in [4] proposed an universal measurement setup to monitor and evaluate coexistence scenarios between Digital Video Broadcasting-Terrestrial (DVB-T/T2) and LTE. The measurement workplace for measuring coexistence interferences with focus on Quality of Services (QoS) in mobile networks (e.g. HSPA/WCDMA) was described in [5]. Exploring the coexistence between LTE and WLAN networks with measurement testbeds, enabling to measure mainly throughput degradation in such networks, were presented in [6] - [9]. Such measurement testbeds are realized either in anechoic chambers/laboratory environments or simulators, connected with Software-defined radio (SDR), are used for emulating LTE/Wi-Fi network. However, an appropriate measurement method and setup to measure the influence of WLAN networks on LTE physical downlink control channels (PDCCH) in the 2.4 GHz band has not been proposed so far.

In this paper universal measurement setup for monitoring and evaluating the coexistence between LTE (downlink) and WLAN (IEEE 802.11n) at their physical layer (PHY) level is presented. The main attention is focused on measuring the performance of LTE PDCCH channels.

The paper is organized as follows. The possible coexistence of LTE and WLAN networks is briefly described in Section II. The proposed coexistence measurement setup is presented in detail in Section III. Section IV contains the measurement results and their comparison with simulation results. Conclusion remarks are outlined in Section V.

II. LTE AND WLAN COEXISTENCE

The emerging Internet-of-Things (IoT), which is closely related to the upcoming 5G networks, will need advanced wireless communication systems. Such systems should be able to provide wireless services within the wide range of the RF spectrum and allow reliable traffic offload, i.e. rerouting of mobile data traffic to WLAN networks [1]. From this point of view, LTE and WLAN networks can fulfil these requirements. WLAN networks are mainly utilized in industrial, scientific and medical (ISM) bands (2.4 GHz and 5 GHz) whereas LTE based cellular networks lie outside these RF bands. On the other hand, there are several RF bands allocated for LTE around the ISM band. Moreover, there is serious consideration about the utilization of a part of the ISM band for LTE [10]. As a result, possible coexistence scenarios between WLAN and LTE can occur. In this work, we assume co-channel coexistence scenario (worst case). We consider a scenario when LTE and Wi-Fi services are provided in the same area and the user equipment (UE) of LTE is located at the edge of cell coverage for Wi-Fi AP.

III. COEXISTENCE MEASUREMENT METHODOLOGY

Measuring LTE/WLAN coexistence in real conditions and real devices gives the best insight into the issue. Only this type of measurement provides decisive information about the possibility of using LTE in the 2.4 GHz ISM band. Three LTE

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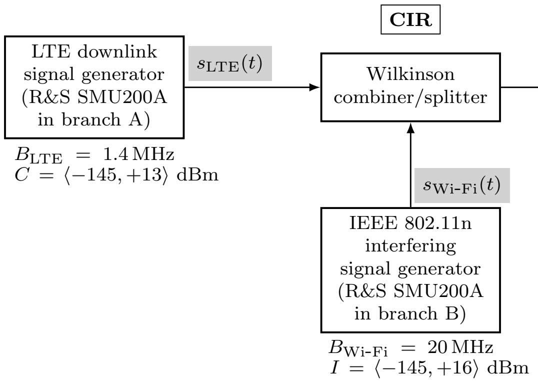

Fig. 1: Block diagram of proposed workplace for measuring the performance of LTE and WLAN.

network providers (in various stages of testing or coverage of an area) are in the Czech Republic – T-Mobile, O2 and Vodafone. Unfortunately, in present days, there is no possibility of performing measurements on their devices. Therefore, in this section, we present a measurement testbed to measure and evaluate possible coexistence between LTE and WLAN in the 2.4 GHz band. The laboratory workplace for the proposed measurement testbed was realized in the Mobile Communications of the Department of Radio Electronics (DREL), Brno University of Technology (BUT) and the measurement equipment was supported by the SIX research center.

A block diagram of the measurement setup is depicted in Fig. 1. A two-channel signal generator, Rohde & Schwarz (R&S) SMU200A, creates a useful LTE signal $s_{\mathrm{LTE}}(t)$ with a defined bandwidth and power level C as well as an interfering Wi-Fi (IEEE 802.11n) signal $s_{\text{Wi-Fi}}(t)$ with 20 MHz bandwidth and power level I. The useful LTE signal is generated in branch A and the interfering signal is generated in branch B. The carrier frequency in both branches is set to 2.412 GHz. The maximal output signal power level of an LTE base station (eNodeB) depends on the base station class according to the cell size [11], [12]. The maximal defined output signal power level in LTE Pico eNodeB for one transmitting port (1 Tx) is 24 dBm.

Both signals lead to a Wilkinson splitter (designed for the 2.4 GHz ISM band). Signals $s_{\mathrm{LTE}}(t)$ and $s_{\text{Wi-Fi}}(t)$ are split keeping the power ratio $C - I$ to signal $r_{\mathrm{LTE}}^{'}(t) = s_{\mathrm{LTE}}(t) + s_{\text{Wi-Fi}}(t)$. Signal attenuation caused by the Wilkinson splitter and coaxial cables is considered. The split signal $r_{\mathrm{LTE}}^{'}(t)$ is led to the R&S FSW26 signal analyzer using a coaxial cable. The power level of the thermal noise $n(t)$ superimposed to the input of the analyzer is defined as follows:

$$N = N_0 + 10 \log_{10} \left(B_{\mathrm{LTE}} \right). \tag{1}$$

where B_{LTE} is the bandwidth of the LTE signal (in this work 1.4 MHz). The noise power spectral density N_0 is calculated as $N_0 = 10 \log_{10} (kT) + 30$, where k is the Boltzmann's constant and T is the absolute temperature of the receiver input in Kelvin (in this work $T = 290\,K$). Hence, N_0 and N are equal to $-173.98\,\mathrm{dBm/Hz}$ and $-112.52\,\mathrm{dBm}$, respectively. The received signal $r_{\mathrm{LTE}}(t)$ enters to analyzer with power ratio $C - (I + N)$ corresponding to the carrier-to-interference and noise ratio (CINR). We consider ideal channel conditions, so the only source of impairment is the inter-system interference.

The R&S FSW26 signal analyzer supports measuring of raw BER depending on the allocation of resource elements (RE) using an Allocation summary feature. Raw BER is measured for all LTE control channels in downlink and it is an evaluation parameter of the measurement. LTE control channels are used for signaling and transfer of system information from the base station to individual user equipment (e.g. HARQ processing, user equipment power level settings, type of precoding) [13]. The Allocation summary feature allows to measure Error Vector Magnitude (EVM), depending on the allocation of physical channels [14]. The value of EVM is always normalized, using reference signal constellation, which is known in both measuring devices. EVM is evaluated as:

$$\mathrm{EVM}_{\mathrm{RMS}} = \sqrt{\frac{\frac{1}{N}\sum\limits_{k=1}^{N}\left[(X_k - \bar{X}_k)^2 + (Y_k - \bar{Y}_k)^2\right]}{\frac{1}{N}\sum\limits_{k=1}^{N}\left(X_k^2 + Y_k^2\right)}}, \tag{2}$$

where N is the number of considered modulation symbols, k is the index of modulation symbol ($k = 1, 2, \ldots, N$). Reference IQ values are defined as transmitted modulation symbols from the signal generator $(X + \mathrm{j}Y)$ (sampled in ideal sampling time) and measured IQ values are defined as received modulation symbols $\left(\bar{X} + \mathrm{j}\bar{Y}\right)$. Measured EVM values are converted to error bit probability P_b for better comparison of simulation and measurement results. The association between EVM and PSK bit error probability is defined as follows [15],

$$P_{\mathrm{b}} \approx \frac{1}{2}\mathrm{erfc}\left(\sqrt{\frac{1}{{\mathrm{EVM}_{\mathrm{RMS}}}^2}}\right). \tag{3}$$

The minimal reference sensitivity of the LTE downlink receiver is not specified in the 2.4 GHz ISM band. Due to this circumstance, it is necessary to estimate the reference sensitivity value for the QPSK modulation $P_{\mathrm{REFSENS}}^{\mathrm{QPSK}}$. The sensitivity

TABLE I: LTE system parameters

Parameters	Description
Frame structure	FDD
Number of transmitted subframes	500
System bandwidth	1.4 MHz
Cyclic prefix length	normal
Subcarrier spacing	15 kHz
Channel model	AWGN
Channel estimation	no estimation needed
Modulation scheme	QPSK
Antenna configuration $[N_{TX} \times N_{RX}]$	1×1 (SISO only)
Carrier frequency	2.412 GHz
Evaluation type	BER and raw BER

TABLE II: WLAN (IEEE 802.11n) system parameters

Parameters	Description
System bandwidth	20 MHz
Subcarrier spacing	312.5 kHz
FFT length	64
Number of data subcarriers	52
Number of pilot subcarriers	4
Modulation scheme	64QAM
Antenna configuration $[N_{TX} \times N_{RX}]$	1×1 (SISO only)
Used unlicensed band	2.4 GHz
Carrier frequency	2.412 GHz

value $P_{\text{REFSENS}}^{\text{QPSK}}$, defined for LTE-FDD and with 1.4 MHz bandwidth, is equal to -104.7 dBm (in Channel 23) [15], [16]. This $P_{\text{REFSENS}}^{\text{QPSK}}$ value is above the noise level on the signal analyzer input ($N = -112.52$ dBm). The dynamic range of the input signal is greater than 100 dB. The maximal input power level of the signal analyzer is 30 dBm.

The R&S devices have common measuring profiles defined for LTE-FDD in downlink direction [14]. These profiles are used in generator and analyzer, hence, it is not necessary to use synchronization. Finally, both R&S devices are connected via USB interface to a PC equipped with MATLAB software and parameters of both systems are set by a custom written application. Furthermore, this application allows to evaluate and save the measured results continuously. Detailed LTE and IEEE 802.11n system settings, used in this work, are summarized in Tab. I and Tab. II, respectively.

IV. EXPERIMENTAL RESULTS

To verify the correctness of the proposed measurement setup, measurement results were compared with simulation results. For this purpose the LTE downlink level simulator [17] developed at TU Vienna was used. LTE PDCCH channels were added to the simulator together with upconverting and downconverting blocks [15].

Figure 2 presents BER results of the co-channel inter-system interference in Physical Control Format Indicator Channel (PCFICH), Physical Downlink Control Channel (PDCCH) and Physical Hybrid ARQ Control Channel (PHICH) for single-input single-output (SISO) antenna mode from a simulation. A 21-bit length PDCCH format 0 is transmitted, a 2-bit length Control format indicator (CFI) message in the PCFICH channel is transmitted and a single bit length Hybrid-ARQ indicator (HI) message ($n_{\text{PHICH}} = 1$) within a single PHICH group is transmitted in the PHICH channel. A BER reference level 10^{-3} is reached for a CINR value equaling -23.2 dB for the PDCCH channel. This reference level was determined according to the required target quality for LTE control information reception [15]. The BER reference level is reached for CINR -28.8 dB and -27.6 dB for the PCFICH channel and PHICH channels, respectively. The presented value of CINR in which BER reaches the reference level indicates very good resistance to interference and the ability to use an LTE system in the ISM band as a Supplemental Downlink (SDL) pipeline.

Co-channel inter-system interference in the PCFICH channel, depending on CINR, is shown in Fig. 3. The simulated PCFICH raw BER values are calculated from 32-bit length CFI codewords at the beginning and at the end of the transmission chain (16 resource elements, QPSK modulation). The simulated PCFICH CINR reference value equals -19.3 dB. The measured PCFICH CINR reference value is -15.8 dB. The difference between the simulated and measured CINR reference values is 3.5 dB and it is a result of the necessary PCFICH power offset in the measurement.

The same exploration was repeated in a single PHICH ($n_{\text{PHICH}} = 1$) channel as well and the results are plotted in Fig. 4. The simulated PHICH raw BER values are calculated from 12-bit length HI codewords at the beginning and at the end of the transmission chain (12 resource elements, BPSK modulation). The simulated PHICH CINR reference value equals -21.45 dB. The measured PHICH CINR reference value equals -19.8 dB. The difference between the simulated and measured CINR reference values is 1.7 dB.

Finally, co-channel inter-system interference in PDCCH is shown in Fig. 5. Simulated raw BER values are calculated from 184-bit length DCI codewords at the beginning and at the end of the transmission chain (72 resource elements, QPSK modulation). The simulated PDCCH CINR reference value equals -18.1 dB whereas the measured one equals -17.2 dB. The difference between the simulated and measured CINR reference values is 0.9 dB.

V. CONCLUSION

Measuring the performance of wireless communication systems is important to better understand its behavior in real-world scenarios. We have proposed a measurement methodology to explore LTE and Wi-Fi co-channel inter-system interference in the 2.4 GHz ISM band. Co-channel inter-system interference measurements in the 2.4 GHz ISM band is provided for CINR values from -30 to -5 dB. Synchronization failure occurs when CINR values are lower than -8 dB (non-detection of primary and secondary synchronization signals). This fact has minimum impact on the measurement. Results from simulations and measurements correspond in the range from 0.9 dB to 3.5 dB. In the future, we will extend our measurements for different coexistence scenarios [4] in different fading channel models [13] .

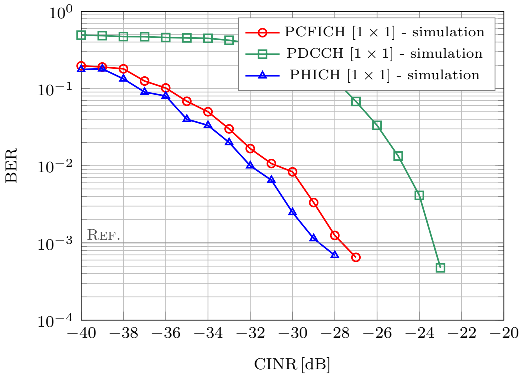

Fig. 2: Dependence of BER on the co-channel inter-system interference in PCFICH, PDCCH and PHICH.

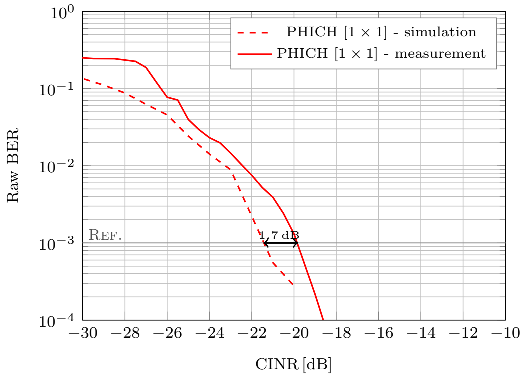

Fig. 4: Dependence of raw BER on the co-channel inter-system interference in the PHICH LTE control channel.

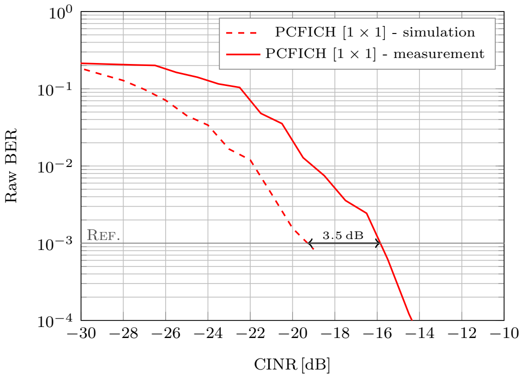

Fig. 3: Dependence of raw BER on the co-channel inter-system interference in the PCFICH LTE control channel.

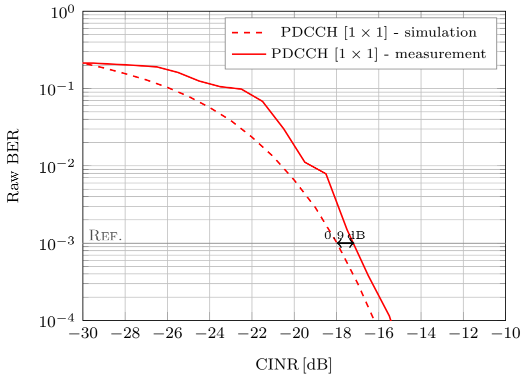

Fig. 5: Dependence of raw BER on the co-channel inter-system interference in the PDCCH LTE control channel.

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Wi-Fi Influence on LTE Downlink Data and Control Channel Performance in Shared Frequency Bands

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Abstract. *Nowadays, providers of wireless services try to find appropriate ways to increase user data throughput mainly for future 5G cellular networks. Utilizing the unlicensed spectrum (ISM bands) for such purpose is a promising solution: unlicensed frequency bands can be used as a complementary data pipeline for UMTS LTE (Universal Mobile Telecommunication System - Long Term Evolution) and its advanced version LTE-Advanced, especially in pico- or femtocells. However, coexisting LTE and WLAN services in shared ISM bands at the same time can suffer unwanted performance degradation. This paper focuses predominantly on co-channel coexistence issues (worst case) between LTE and WLAN (IEEE 802.11n) services in the ISM band. From the viewpoint of novelty, the main outcomes of this article are follows. Firstly, an appropriate signal processing approach for coexisting signals with different features in the baseband is proposed. It is applied in advanced link-layer simulators and its correctness is verified by various simulations. Secondly, the influence of IEEE 802.11n on LTE data and control channel performance is explored. Performance evaluation is based on error rate curves, depending on Signal-to-Interference ratio (SIR). Presented results allow for better understanding the influence of IEEE 802.11n on the LTE downlink physical control channels (PCCH) and are valuable for mobile infrastructure vendors and operators to optimize system parameters.*

Keywords

LTE, WLAN, LTE physical channels, coexistence, interference, ISM band, 5G

1. Introduction

The increasing demand high mobile data rates and the growing number of user equipments (e.g. Internet-of-Things services) brings forth the question of how to improve the performance or extend the functionality of existing 3G/4G cellular networks, mainly in small cells. The licensed spectrum is the first choice for mobile operators thanks to its predictable behavior ensuring Quality of Service (QoS), mobility and system control. Naturally, the amount of available licensed spectrum is limited. Some former television bands have been sold to mobile operators in vendue. These frequency bands are almost fully occupied, especially in Europe [1–3]. Thus, there is a need for further expansion or a different solution.

Currently, the companies Qualcomm and Huawei are driving innovation to transfer Long Term Evolution (LTE) technology and its advanced version (LTE-A) to Industry-Science-Medical (ISM) unlicensed bands [4–6]. This concept is also called LTE-Unlicensed (LTE-U). Such innovation has been planned as a complementary or supporting data pipeline in small cells where demands on user data are higher. Both above mentioned companies have utilized the 2.4 GHz and 5 GHz ISM bands for LTE/LTE-A and take advantage of respective signal propagation possibilities. The considered frequency bands are used especially for Wireless and Personal Local Area Network (WLAN and WPAN). Some mobile operators are building picocells and utilizing Wireless-Fidelity (Wi-Fi) networks in the 2.4 and 5 GHz radio frequency (RF) bands as a supporting data pipeline in city centers or places with high density of user equipments [7], [8]. These Wi-Fi networks are controlled centrally by mobile operators. Locally, they have the potential to provide higher data throughput than 3G/4G small cells.

Several recent papers deal with the study of coexistence of LTE and WLAN/WPAN networks in ISM bands [9]. Abinader et al. in [10] presented average user throughput results for coexisting LTE and Wi-Fi in indoor environment in the 5.8 GHz unlicensed band and introduced a generalized collaborative coexistence algorithm. The presented results show that the average LTE user throughput value is similar to the case of non-coexistence scenarios and contrasts with degraded Wi-Fi average user throughput (for high Access Point (AP) density). Cavalcante in [11] provided a coexistence analysis of LTE and Wi-Fi in the 900 MHz RF band under TGah indoor environment for an LTE system with system bandwidth of 20 MHz. Other studies [12–15] explored possible LTE average user throughput and performance decreasing under different LTE and Wi-Fi coexistence scenarios, mainly in 5 GHz unlicensed bands. Appropriate simulation tools and methods for study of LTE and WLAN coexistence play a key role. A simulation-based study of the effect of LTE interference on an IEEE 802.11a system has been briefly discussed

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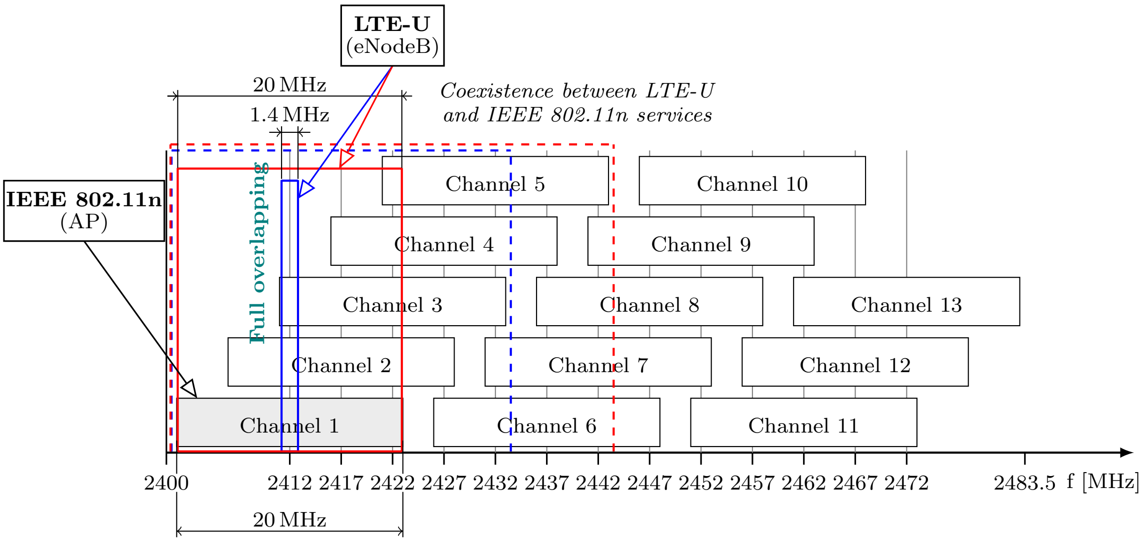

Fig. 1. Graphical representation of LTE-Unlicensed (1.4 and 20 MHz system bandwidth marked by blue and red color, respectively) and Wi-Fi (IEEE 802.11n, system bandwidth 20 MHz) services in frequency domain, full overlapping in ISM 2.4 GHz band.

in [16]. Comprehensive evaluation of the Licensed-Assisted Access (LAA) LTE and IEEE 802.11 coexistence scenarios based on system-level simulations were presented in [17]. In [18] the discrete-event Established Network Simulator (ns-3) has been extended to study LTE and Wi-Fi coexistence in 5 GHz band.

From this state-of-the-art review is evident that performance degradation of LTE and Wi-Fi communication systems caused by their coexistence on link-level has not been investigated in details. Hence, in this work we present an approach to analyse LTE including LTE downlink physical control channel (PCCH) performance at the link level influenced by Wi-Fi (based on IEEE 802.11n) in the same ISM frequency bands. To the best of our knowledge, no similar exploration in this form has been presented yet. The proposed methodology is appropriate especially for worst-case coexistence scenarios.

The main contributions of the article are follows:

1) An appropriate approach to emulate and evaluate coexistence between LTE (downlink) and Wi-Fi (IEEE 802.11n) at the link-level in ISM bands is proposed.
2) Based on LTE and Wi-Fi co-channel coexistence evaluation, general conclusions for non-critical and critical coexistence scenarios are formulated.

The remaining part of this paper is composed as follows. The considered co-channel coexistence scenario between LTE and Wi-Fi is outlined in Section 2. Furthermore, Section 2 presents the proposed signal processing of coexisting LTE and Wi-Fi signals and its implementation to simulators. Section 3 states and discusses the simulated performance results of LTE (downlink) under the presented coexistence scenario. Finally, the main outputs of the work are clearly summarized in Conclusion.

2. Coexistence Scenario

Integration with the licensed spectrum, minimum changes in LTE air-interface and ensuring coexistence in unlicensed bands [19] are general design principles and prerequisites for LTE-U. Aggregation of licensed and unlicensed carriers brings better network performance, longer range and increasing capacity. Furthermore, unification of the LTE network with common authentication, security and management is an advantage. There are two main approaches for LTE-U. First one is supplemental downlink (SDL) which increases throughput only in downlink (main option for LTE Frequency Division Duplex (FDD)) whereas second one is carrier aggregation (CA) which increases throughput in both downlink and uplink (an option for LTE Time Division Duplex (TDD)). According to Huawei and its concept for unlicensed secondary carrier design for FDD [19], the following option is adopted: the primary cell (Pcell) FDD in downlink (user data+control information) is transmitted in the licensed band and the secondary cell (Scell) FDD in downlink (user data+control information) is transmitted in the unlicensed band. In this work, we only consider SDL due to the major use of LTE-FDD in the European region.

Currently, the 2.4 GHz and 5 GHz ISM bands are utilized by WLAN (Wi-Fi) and WPAN (e.g. Bluetooth, ZigBee) technologies. Wi-Fi, built on IEEE 802.11n and IEEE 802.11ac standards, is the dominant system in the 2.4 GHz and 5 GHz ISM bands, respectively [20]. Hence, modeling, measurement and suppression of interferences from mutual coexistence between WLAN/WPAN and LTE in ISM bands is becoming a key issue in future 5G networks. In Fig. 1, we can see the graphical representation of LTE-U and Wi-Fi services overlapping in the 2.4 GHz ISM band. All possible WLAN channels with system bandwidth $BW_{\text{sys}}^{\text{Wi-Fi}} = 20\,\text{MHz}$ are depicted with marked central frequencies.

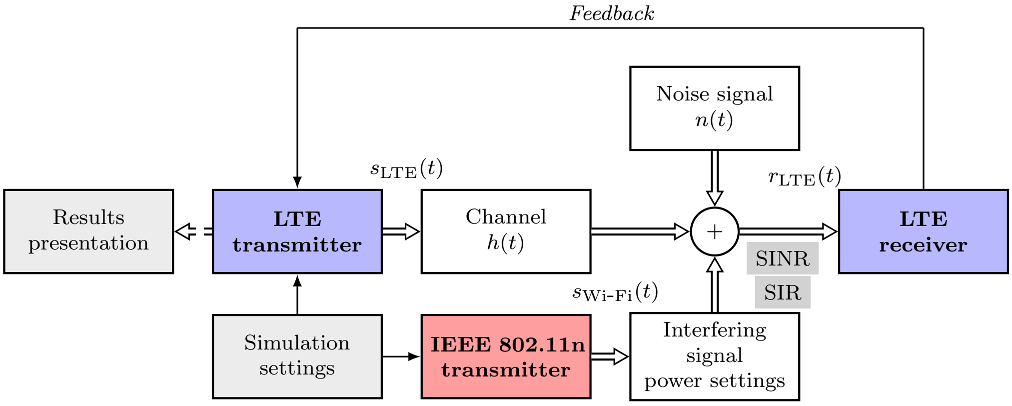

Fig. 2. Block diagram of the proposed LTE vs. IEEE 802.11n coexistence link-level simulator.

Band [GHz]	**Frequency range** [MHz]	**Bandwidth** [MHz]
2.4	2400–2483.5	83.5
5.1	5150–5350	200
5.3	5350–5470	120
5.4	5470–5825	355
5.8	5725–5875	150
5.9	5850–5925	75

Tab. 1. Summary of worldwide available 2.4 GHz and 5 GHz ISM frequency bands.

We consider that LTE services are provided on the first channel central frequency (f_{c} = 2412 MHz). LTE with $BW_{\mathrm{sys}}^{\mathrm{LTE}}$ = 1.4 MHz is fully overlapped by Wi-Fi channels 1, 2 and 3 whereas, LTE with $BW_{\mathrm{sys}}^{\mathrm{LTE}}$ = 20 MHz is fully overlapping with Wi-Fi channel 1 and partially overlapping with channels 2, 3, 4 and 5 (see Fig. 1). According to the described scenario, we consider only co-channel inter-system coexistence (CIC) which represents the worst-case scenario. In such scenario the RF spectrum of one communication system is completely overlapping with the RF spectrum of other communication system (central frequencies of both systems are the same). Consequently, mutual interference of the systems is the greatest. It is equivalent to overlapping of the baseband signals [25]. A list of available unlicensed frequency bands is summarized in Tab. 1.

2.1 Coexistence Link Level Simulator

A block diagram of the proposed LTE-U/WLAN link level coexistence analysis model in downlink direction is depicted in Fig. 2. The LTE downlink link level simulator, developed at TU Vienna, was adopted as the basic simulation tool [26], [27]. We extended this MATLAB-based simulator by adding physical downlink control channel models. Thus, the impact of interferences from coexsitence between LTE and Wi-Fi is explored for all LTE downlink physical control channels, namely: Physical Control Format Indicator Channel (PCFICH), Physical Downlink Control Channel (PDCCH) and Physical Hybrid ARQ Control Channel (PHICH) [28].

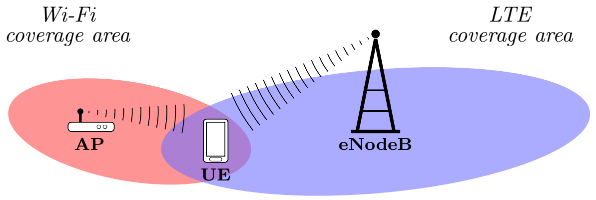

Fig. 3. Graphical representation of the LTE and Wi-Fi coexistence scenario in the same geographical area.

LTE control channels are used for signaling and transferring system information from the base station to individual user equipment (e.g. HARQ processing, user equipment power level settings, type of precoding) [29]. For emulation of the interfering Wi-Fi signal, we have proposed a universal WLAN link-level simulator supporting IEEE 802.11n technology. More details about this simulator can be found in [30].

Transceiver blocks in LTE downlink are marked with blue color and the interfering IEEE 802.11n system is marked with red color. The simulator was adjusted for simulations of inter-system coexistence. Motivated by processing time constraints, the simulator is implemented in baseband only, working with a complex envelope of the signal $s(t) = s_{\mathrm{I}}(t) + \mathrm{j}s_{\mathrm{Q}}(t)$, where s_{I} and s_{Q} are in-phase and quadrature components, respectively [31]. In this case, baseband signals in the frequency domain have a frequency spectra concentrated near zero frequency, which fits for the presented co-channel coexistence scenario. A simple graphical representation of the investigated LTE-U and Wi-Fi collision scenario in the same geographical area is shown in Fig. 3.

Coexistence Channel Model

The presented LTE vs. IEEE 802.11n coexistence analysis model is based on general coexistence model described in time domain by the following equation:

$$r_0(t) = \underbrace{s_0(t) * h_0(t)}_{\text{useful signal}} + \underbrace{n_0(t)}_{\text{noise}} + \underbrace{\sum_{k=1}^{N_{\mathrm{I}}} \left(s_k(t) * h_k(t)\right)}_{\text{interfering transmitters}} \quad (1)$$

where $r_0(t)$ is the received useful signal, $s_0(t)$ is the transmitted useful signal, $h_0(t)$ is the impulse response of the useful channel (LTE branch), $*$ represents discrete convolution and $n_0(t)$ is an additive white Gaussian noise added to the investigated receiver input. Interfering branch $s_k(t)$ is modeled as a sum of the signals from N_I interfering transmitters. Each interfering signal is led through a fading channel described by channel impulse response.

According to the presented coexistence scenario (see Fig. 2), the number of interferers $N_\mathrm{I} = 1$ (IEEE 802.11n) and $h_1(t) = \delta(t)$ (delta function, no fading channel in the interfering branch). Thus we can rewrite (1) to

$$r_\mathrm{LTE}(t) = \underbrace{s_\mathrm{LTE}(t) * h(t)}_{\text{LTE signal}} + \underbrace{n(t)}_{\text{noise}} + \underbrace{s_\text{Wi-Fi}(t)}_{\text{Wi-Fi signal}} \tag{2}$$

where $r_\mathrm{LTE}(t)$ is the received LTE signal, $s_\mathrm{LTE}(t)$ is the transmitted LTE signal and $s_\text{Wi-Fi}(t)$ is the interfering Wi-Fi signal. The channel block adjusts the LTE output signal $s_\mathrm{LTE}(t)$ in accordance with the used channel model and its impulse response $h(t)$. In this paper, no fading channel model is considered, thus $h(t) = \delta(t)$. Hence, (2) could be simplified to

$$r_\mathrm{LTE}(t) = s_\mathrm{LTE}(t) + n(t) + s_\text{Wi-Fi}(t). \tag{3}$$

The output signal ($s_\mathrm{LTE}(t)$) from the LTE transmitter block (*victim*), is an OFDMA-based baseband signal in time domain with average power per symbol $\sigma^2_{s_\mathrm{LTE}(t)} = 1$. The output signal from IEEE 802.11n (Wi-Fi, *interferer*) transmitter is an OFDM-based baseband signal in time domain $s_\text{Wi-Fi}(t)$ with average power per symbol $\sigma^2_{s_\text{Wi-Fi}(t)} = 1$. After that, the $s_\mathrm{LTE}(t)$ signal passes through the channel model block, it enters the signal adder (see Fig. 2). Here, a random noise vector $n(t)$ and the interfering signal $s_\text{Wi-Fi}(t)$ are added to the useful signal $s_\mathrm{LTE}(t)$ according to the defined Signal-to-Interference plus Noise Ratio (SINR) and Signal-to-Interference Ratio (SIR), respectively. In the presented scenario, SINR for each sample is defined as

$$\mathrm{SINR} = \frac{P_\mathrm{tx}^{(\mathrm{LTE})}}{\sigma_n^2 + P_\mathrm{tx}^{(\text{Wi-Fi})}} \tag{4}$$

where σ_n^2 is the average power of the noise signal $n(t)$ which is modeled as a vector of normally-distributed random values with zero mean $\mu_{n(t)} = 0$, $P_\mathrm{tx}^{(\mathrm{LTE})}$ is the power of LTE signal at the transmitter output and $P_\mathrm{tx}^{(\text{Wi-Fi})}$ is the power of Wi-Fi signal in transmitter output. In the coexistence scenario considered, $\sigma_n^2 = 0$; hence, the SINR from (4) simply leads to SIR

$$\mathrm{SIR} = \frac{P_\mathrm{tx}^{(\mathrm{LTE})}}{P_\mathrm{tx}^{(\text{Wi-Fi})}}. \tag{5}$$

Both SINR and SIR are defined as the post-FFT ratio at the receiving antenna (after FFT operation in the LTE receiver) [26]. Each sample of the received signal r_LTE influenced by interfering singal is calculated as

$$r_\mathrm{LTE} = s_\mathrm{LTE} + \frac{1}{\sqrt{2}} \frac{N_\mathrm{FFT}}{N_\mathrm{tot}} s_\text{Wi-Fi} 10^{\left(\frac{-\mathrm{SIR}_{(\mathrm{dB})}}{20}\right)} \tag{6}$$

where N_FFT is the FFT size used in LTE transmitter/receiver and N_tot is the total number of subcarriers in a single LTE OFDMA symbol. In case of non-zero noise signal average power σ_n^2, the received signal r_LTE definition is obtained by adding noise sample to (6), i.e.,

$$r_\mathrm{LTE} = s_\mathrm{LTE} + \frac{1}{\sqrt{2}} \frac{N_\mathrm{FFT}}{N_\mathrm{tot}} \left[s_\text{Wi-Fi}\, 10^{\left(\frac{-\mathrm{SIR}_\mathrm{dB}}{20}\right)} + n\, 10^{\left(\frac{-\mathrm{SNR}_{\mathrm{ch}\,(\mathrm{dB})}}{20}\right)} \right] \tag{7}$$

where SNR_ch is the SNR in considered AWGN channel model ($\mathrm{SNR}_\mathrm{ch} = P_\mathrm{tx}^{(\mathrm{LTE})}/\sigma_n^2$) with constant value in whole simulation. In case of added AWGN (7), SINR defined in (4) is an independent value in the coexistence model and numerically SINR $\approx$ SIR. As mentioned above, two baseband signals (LTE and Wi-Fi) are added due to the property of linearity considered for this scenario. Interpolation is not used since it has negligible influence to performance results [35].

The interfered LTE signal $r_\mathrm{LTE}(t)$ with additive noise enters the LTE receiver, where inverse OFDMA operations are performed. According to the used SISO transmission mode, the multi-antenna decoding process is not necessary. Due to using the AWGN channel model, an estimation of used transmission channel is not provided here, thus the LTE receiver has perfect knowledge of the channel. Furthermore, Soft-Sphere Decision (SSD) is used as the demodulation algorithm [26]. We also assume a static transmission scenario (no movement of LTE receiver).

In the presented LTE downlink simulator, the physical control channel (PCFICH, PHICH and PDCCH) signal processing at the receiving side is performed separately from the physical downlink shared channel (PDSCH) which carries user data [29]. Channel decoding and evaluation of the received information is performed. The received user data, control information, data acknowledgement information and Channel Quality Indicator (CQI) are reported to the LTE transmitter block. Of course, the influenced signal $r(t)$ could also lead to the IEEE 802.11n receiver where inverse OFDM operations are performed and the obtained results are evaluated [30].

Physical Downlink Shared Channel

Quality of reception of user data in LTE downlink transmitted via PDSCH depends mainly on quality of the respective transmission channel, used modulation and channel coding, the use of Hybrid-ARQ (HARQ) retransmissions and link adaptation algorithms and user data scheduling. The modulation and channel coding scheme used in PDSCH is determined from CQI parameter. The list of these parameters is presented in Tab. 2. The CQI index [26] defines the corresponding modulation type and code rate, including channel coding efficiency. Due to only having a single user in the simulation scenario, there is no demand for user data scheduling (user data occupies all available resource elements (REs)). In the presented simulations, CQI is always defined as fixed.

CQI index	Modulation	Code rate × 1024	Efficiency
1	QPSK	78	0.1523
2		120	0.2344
3		193	0.3770
4		308	0.6016
5		449	0.8770
6		602	1.1758
7	16-QAM	378	1.4766
8		490	1.9141
9		616	2.4063
10	64-QAM	466	2.7305
11		567	3.3223
12		666	3.9023
13		772	4.5234
14		873	5.1152
15		948	5.5547

Tab. 2. The list of LTE Channel Quality Indicator (CQI) parameters [26].

Physical Control Format Indicator Channel

The Control Format Indicator (CFI) parameter is transmitted via PCFICH. CFI contains two-bit value which defines mapping of PDCCH in LTE downlink subframe [28]. PCFICH uses block channel coding with code rate 1/16. PCFICH is always placed in the first OFDM symbol in downlink subframe. In the frequency domain, PCFICH is spread into four parts (additional frequency diversity) and its position is also given by cell identification number $N_{\text{cell}}^{\text{ID}}$.

Physical Downlink Control Channel

PDCCH is the most important control channel in LTE downlink since it carries system information aboout scheduling grants, MIMO settings, modulation and channel coding (CQI) etc. PDCCH symbols are located at the beginning of each subframe while the number of OFDM symbols for PDCCH is defined by CFI value [28]. PDCCH uses convolutional coding with code rate 1/3. At the receiver, the PDCCH is processed via combination of Blind and Viterbi decoding process.

Physical Hybrid-ARQ Indicator Channel

PHICH transmits the Hybrid-ARQ Indicator (HI) which contains acknowledge or non-acknowldge message of previous user data sent in uplink [29]. PHICH uses simple repetition channel coding with code rate 1/3. Repeated symbols are spread using up to 8 orthogonal sequences. Number of PHICH transmitted in single subframe depends mainly on system bandwidth and PHICH scaling factor N_{g} which defines number of PHICH groups in single subframe. PHICH is situated either in the first or the first and second OFDM symbol. Each PHICH group is also spread into three parts. Their position is given by $N_{\text{cell}}^{\text{ID}}$ as well [29].

3. Coexistence Analysis

LTE and Wi-Fi (IEEE 802.11n) general system parameters considered in the presented simulation scenario are sumarized in Tab. 3. For LTE we consider two extreme system bandwidths $BW_{\text{sys}}^{\text{LTE}} = 1.4\,\text{MHz}$ (narrowest) and 20 MHz (widest) and subcarrier spacing $\Delta_{\text{f}}^{\text{LTE}} = 15\,\text{kHz}$. The Wi-Fi system model is considered for system $BW_{\text{sys}}^{\text{Wi-Fi}} = 20\,\text{MHz}$ only and $\Delta_{\text{f}}^{\text{Wi-Fi}} = 312.5\,\text{kHz}$. Extended Wi-Fi system bandwidth of 40 MHz is not modeled.

System parameter			LTE		Wi-Fi
System bandwidth	BW_{sys}	[MHz]	1.4	20	20
Number of occupied subcarriers	N_{sc}	[-]	72	1200	56
IFFT/FFT size	N_{FFT}	[-]	128	2048	64
Subcarrier space	Δ_{f}	[kHz]	15	15	312.5

Tab. 3. General physical layer parameters of the LTE and Wi-Fi link-level models.

Simulation parameter		Value
Signal-to-Interference ratio (SIR) range		$\langle -30, 30\rangle$ dB
Number of transmitted subframes		2000
Channel Quality Indicator range		$\langle 1, 15\rangle$
PDSCH:	Number of allocated users	1
	Scheduling algorithm	static and fixed
PHICH:	Group scaling factor	$N_{\text{g}} = \{1/6, 1/2, 1, 2\}$
	HI (users) per group	1
PCFICH:	CFI message range	$\langle 1, 4\rangle$ or $\langle 0, 3\rangle$
PDCCH:	Transmitted DCI format	F0

Tab. 4. Simulation parameters used in the presented link-level coexistence scenario.

The number of occupied subcarriers equals to 56 according to the definition of the Greenfield Wi-Fi mode [20]. We consider single-user SISO (SU-SISO) transmission mode for both systems. For LTE it means a single base station (eNodeB) and a single user equipment (UE).

Before the coexistence simulation starts, it is necessary to define simulation parameters. Parameters common to the LTE/Wi-Fi trnansmitter and LTE receiver are listed in Tab. 4. The independent SIR variable should be set together with the number of transmitted LTE subframes ($N_{\text{subf}} = 2000$). The PDSCH performance is simulated for CQI in range from 1 to 15 (see Tab. 2) as a fixed value. PHICH error rate performance is simulated for all available scaling factor N_{g} values with single user per PHICH group. The performance results (BER, BLER, throughput) in all physical channels are computed by averaging over all their allocated resource elements.

3.1 Simulation Results

In this section, results of the LTE vs. Wi-Fi coexistence analysis are presented and discussed. The LTE PDSCH link performance represented as a dependence of Block Error Rate (BLER) on SIR is shown in Fig. 4. Results were obtained for various CQI values and system bandwidths of 1.4 and 20 MHz. As we can see from presented BLER results, LTE receiver with CQI value set in the range from 13 to 15 is unable to reach the required 10 % BLER and thus, these CQI are unusable for user data transmission under presented LTE/WLAN coexistence scenario. The BLER reference level $10^{-1} = 10\,\%$ BLER was determined according to the required target quality for LTE shared physical channel user data reception [21].

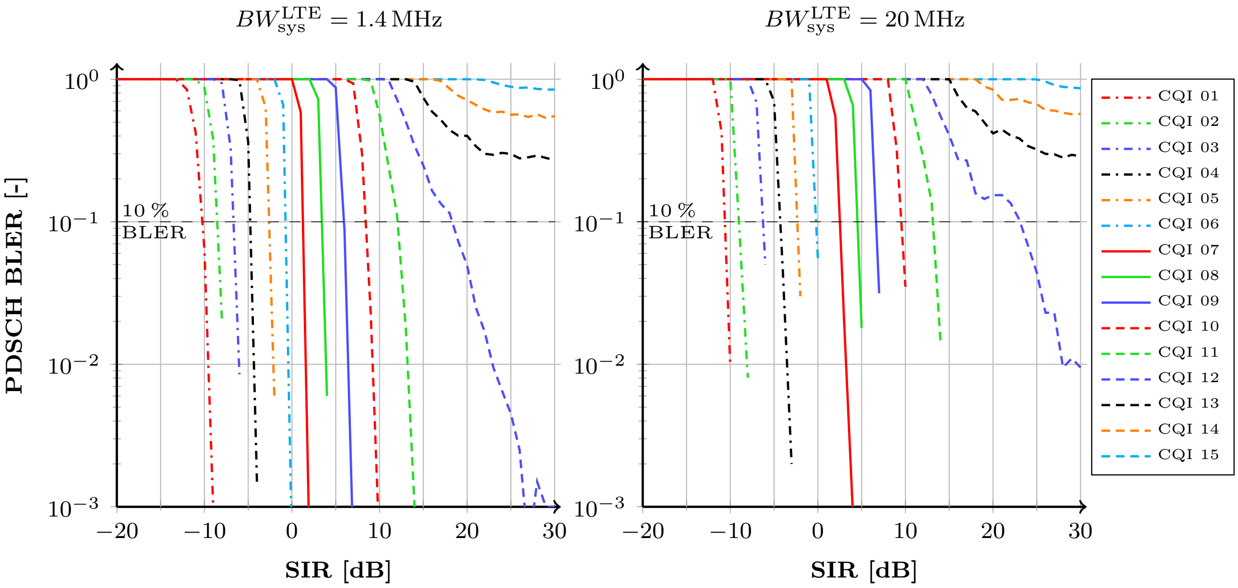

Fig. 4. LTE PDSCH Block error rate link performance for various CQI's under the Wi-Fi co-channel coexistence scenario ($BW_{\text{sys}}^{\text{LTE}}$ = 1.4 MHz and 20 MHz, $BW_{\text{sys}}^{\text{Wi-Fi}}$ = 20 MHz).

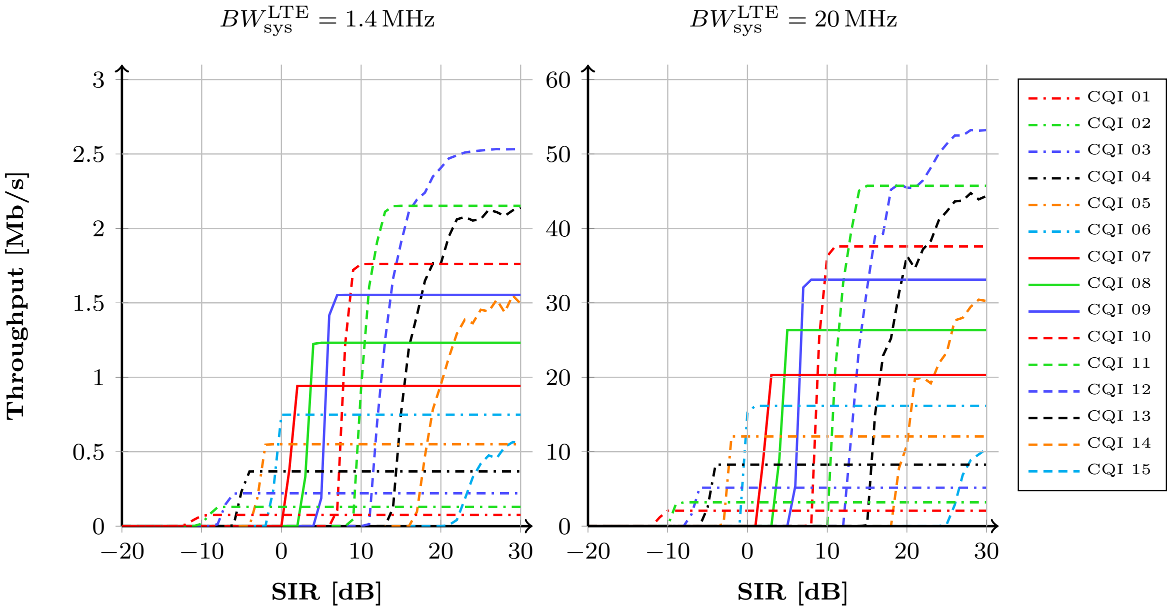

Fig. 5. LTE PDSCH user data throughput for various CQI's under the Wi-Fi co-channel coexistence scenario ($BW_{\text{sys}}^{\text{LTE}}$ = 1.4 MHz on the left, $BW_{\text{sys}}^{\text{LTE}}$ = 20 MHz on the right), N_{subf} = 2000, $BW_{\text{sys}}^{\text{Wi-Fi}}$ = 20 MHz.

LTE PDSCH throughput curves versus SIR for $BW_{\text{sys}}^{\text{LTE}}$ = 1.4 MHz and 20 MHz are shown in Fig. 5. From the results it is seen that LTE throughput is measurable for SIR higher than −12 dB, independently of the considered LTE system bandwidth. Using of CQI = 13, 14 and 15 could bring unpredictable behavior. Using of CQI = 12 is possible but the throughput is slightly decreased compared to non-coexistence scenario results [27].

The LTE PDSCH to SIR mapping for 10 % BLER is shown in Fig. 6. These mapping curves are very important for modeling and simulation methodology. This mapping is termed effective SINR/SIR mapping (ESM). It serves as the basis for physical layer abstraction for link-to-system level mapping, including MIMO technology [22], [23]. The concept is also used in Vienna LTE System-level simulator for LTE intra-system interference evaluation [24]. The CQI to SIR or SINR mapping is approximately linear in non-coexistence scenarios due to equidistant points of intersection [24]. Here, the equidistance is not obtained for CQI using 64QAM (10, 11 and 12). As we can see from the figure, CQI = 13, 14 and 15 are not mapped to SIR (these curves do not reach 10 % BLER).

Figure 7 presents the BER performance results of the co-channel inter-system interference, depending on SIR, in the PCFICH and PDCCH physical control channel. PCFICH missdetection could bring packet loss and even short-term loss of connection. Hence, exploring of its performance is important. One percent PCFICH bit error rate (see Fig. 7 on the left) is reached for SIR = −14.1 dB ($BW_{\text{sys}}^{\text{LTE}}$ = 1.4 MHz) and −12.8 dB ($BW_{\text{sys}}^{\text{LTE}}$ = 20 MHz). PDCCH information is transmitted with one percent bit error at SIR = 0 dB (see Fig. 7 on the right). Evaluated results reveal the fact that the LTE system bandwidth used has negligible effect on the LTE PDCCH physical downlink control channel performance at its co-channel coexistence with IEEE 802.11n.

Finally, LTE PHICH control channel performances affected by co-channel Wi-Fi interferences was investigated and the obtained results described as BER vs. SIR dependence are shown in Fig. 8. The purpose PHICH channel in the downlink is to carry HARQ acknowledgements for uplink data transfers. PHICH performance requirements are defined by 3GPP [33]. PHICH BER (acknowledge to non-acknowledge error and vice versa) should be within the range from 10^{-3} to 10^{-4} (see gray filled area in Fig. 8). Firstly, PHICH performances were obtained for various scaling factors (N_{g}) at $BW_{\text{sys}}^{\text{LTE}}$ = 1.4 MHz. In such case (see blue curves in Fig. 8), parameter (N_{g}) has no influence on PHICH performance.

Mapping of LTE downlink physical control channels depends mainly on cell identification number ($N_{\text{cell}}^{\text{ID}}$), system bandwidth $BW_{\text{sys}}^{\text{LTE}}$, PHICH scaling factor N_{g} and amount of system information to transmit (PDCCH). Example of the LTE downlink physical control channels mapping (symbols 1 and 2) for the highest system bandwidth $BW_{\text{sys}}^{\text{LTE}}$ = 20 MHz, $N_{\text{cell}}^{\text{ID}} = 0$ is depicted in Fig. 9. Here, the LTE spectrum is fully overlapping with Wi-Fi spectrum (IEEE 802.11n, $BW_{\text{sys}}^{\text{Wi-Fi}}$ = 20 MHz). The part of bandwidth used for user data and control information transmitting (BW_{used}) is usually less than the system bandwidth in OFDM-based systems. LTE with system bandwidth 20 MHz uses 1200 subcarriers in frequency domain and 1 DC subcarrier. Due to $\Delta_{\text{f}}^{\text{LTE}}$ = 15 kHz distance between subcarriers, the used bandwidth $BW_{\text{used}}^{\text{LTE}} = (1200 + 1) \times 15\,\text{kHz} = 18.015\,\text{MHz}$.

The Wi-Fi (IEEE 802.11n) with the same system bandwidth uses only 56 subcarriers and 1 DC subcarrier. The distance between subcarriers in Wi-Fi system is much higher ($\Delta_{\text{f}}^{\text{Wi-Fi}}$ = 312.5 kHz), thus $BW_{\text{used}}^{\text{Wi-Fi}} = (56+1) \times 312.5\,\text{kHz} = 17.8125\,\text{MHz}$. There is 98.88 % overlap in LTE spectrum. As we can see from Fig. 9, amount of PHICH influenced by Wi-Fi interference also depends on scaling factor N_{g}, where a specific part of PHICH is not fully overlapped by Wi-Fi spectrum (see magnified image).

The same dependences were investigated for $BW_{\text{sys}}^{\text{LTE}}$ = 20 MHz. At the widest LTE system bandwidth, there is a significant difference of PHICH performance for various N_{g} values. When $N_{\text{g}} = 1/6$ is considered then to fulfil BER range from 10^{-3} to 10^{-4} the coding gain for $BW_{\text{sys}}^{\text{LTE}}$ = 20 MHz is approximately 11 dB less in comparison with $BW_{\text{sys}}^{\text{LTE}}$ = 1.4 MHz. Such behaviour is given by different PHICH mapping and different amounts of interfered resource elements in the resource grid (see gray filled areas in Fig. 9).

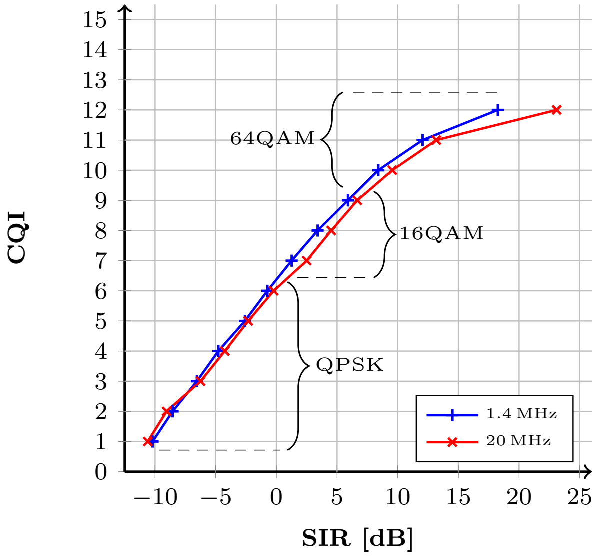

Fig. 6. LTE PDSCH CQI to SIR ESM mapping under the Wi-Fi co-channel coexistence scenario.

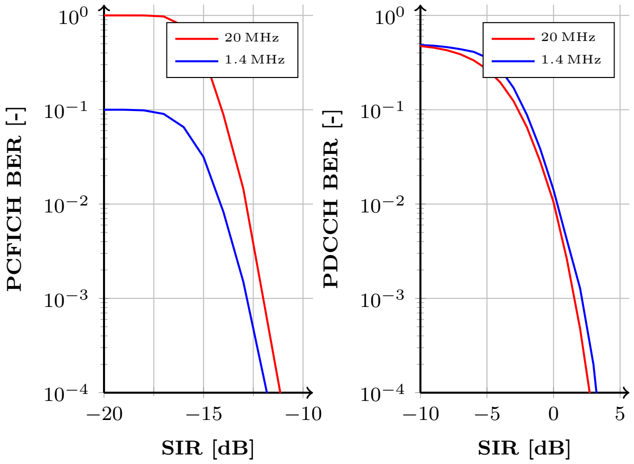

Fig. 7. LTE PCFICH and PDCCH control channel performance under the Wi-Fi co-channel coexistence scenario (PCFICH on the left, PDCCH on the right).

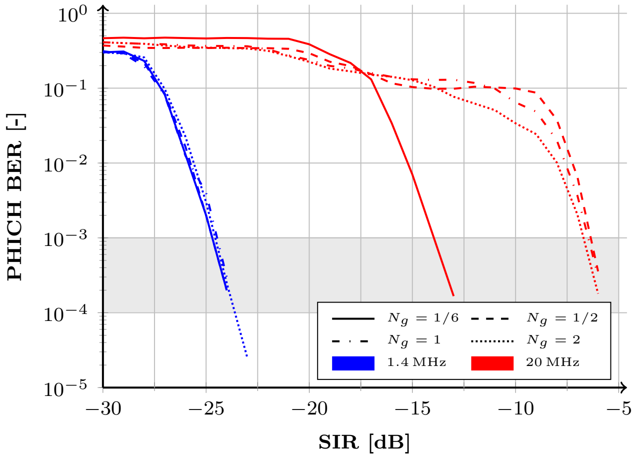

Fig. 8. LTE PHICH control channel performance for various scaling factors N_{g} under the Wi-Fi co-channel coexistence scenario ($BW_{\text{sys}}^{\text{LTE}}$ = 1.4 MHz blue, $BW_{\text{sys}}^{\text{LTE}}$ = 20 MHz red).

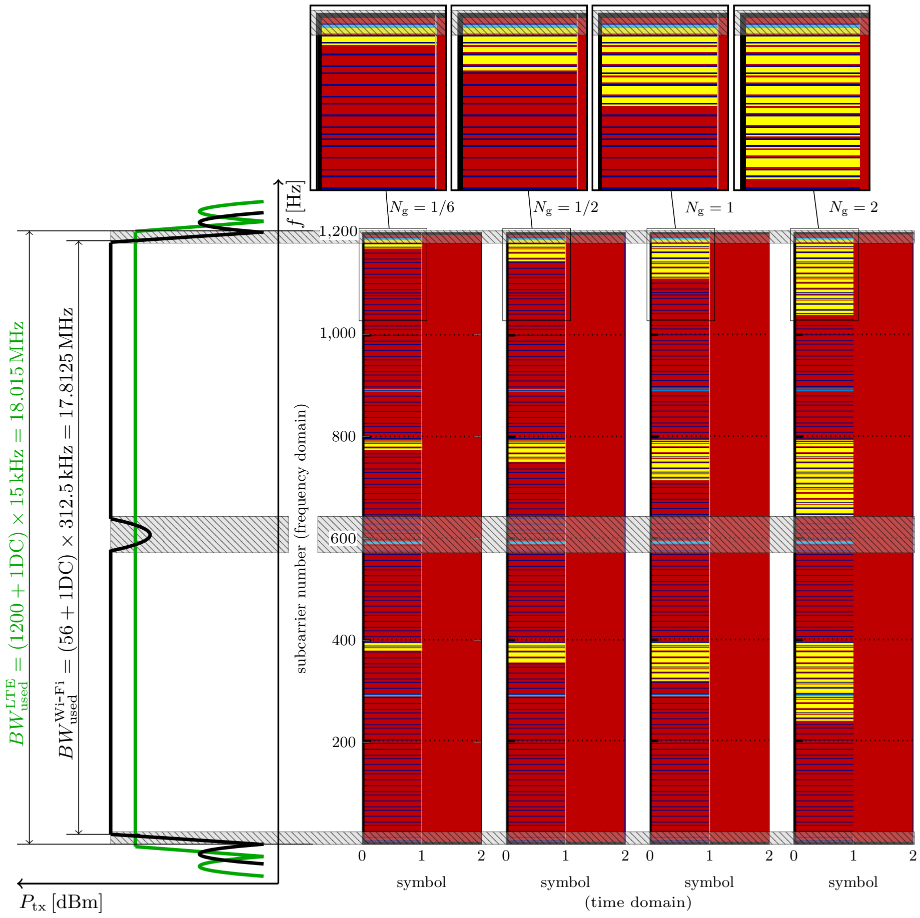

Fig. 9. LTE physical control channel mapping in resource grid $BW_{sys}^{LTE} = 20\,MHz$, $N_{cell}^{ID} = 0$ (example case) and scaling factor N_g (red = PDCCH, blue = PCFICH, yellow = PHICH) and LTE spectrum (green) fully overlapped by a Wi-Fi spectrum (black, IEEE 802.11n, $BW_{sys}^{Wi\text{-}Fi} = 20\,MHz$) in frequency domain (on the left). Magnified part of the physical control channels mapping is on the top.

Overall, BER PHICH curves reach the reference value 10^{-3} at SIR = −24.6 dB for $BW_{sys}^{LTE} = 1.4\,MHz$, SIR = −14 dB for $BW_{sys}^{LTE} = 20\,MHz$, $N_g = 1/6$ and SIR = −6.6 dB for $BW_{sys}^{LTE} = 20\,MHz$, $N_g \neq 1/6$. From these values (lower SIR) is evident that LTE PHICH downlink channel has good resistance features against interferences from coexistence with Wi-Fi.

4. Conclusion

This paper introduces a novel approach in analysing LTE link-level coexistence issues in shared frequency bands. It presents the results of LTE data and control channel performance under co-channel inter-system coexistence with WLAN (Wi-Fi) services. For the analysis, the LTE-U vs. Wi-Fi coexistence link level simulator was created. The presented simulator could provide a basic tool for research in the field of controlled heterogenous networks and cooperative algorithms. The analysis of the obtained results from the presented co-channel coexistence scenario leads to the following general conclusions:

1. LTE transmission is robust and resistant against interference from Wi-Fi services (IEEE 802.11n) in shared frequency bands.
2. User data transmitted via LTE PDSCH are well protected for the link with lower CQI index (from 1 to 11). PDSCH link with CQI = 12 operates properly for SIR greater than 15 dB. Using the PDSCH link with CQI higher than 12 is not suitable for LTE vs. Wi-Fi (IEEE 802.11n) co-channel coexistence scenarios.
3. LTE PDSCH CQI to SIR ESM mapping is linear in the range of CQI from 1 to 9 and non-linear in the range of CQI from 10 to 12 (CQI = 13, 14 and 15 are unusable for transmission in the LTE vs. WLAN coexistence scenario).
4. Scalable bandwidth in LTE has inconsiderable impact on the PDCCH physical control channel performance (convolutional channel coding with code rate 1/3). The performance of PCFICH is more influenced by scalable bandwidth, where ΔSIR ≈ 1.8 dB at PCFICH BER equaling to 10^{-2} (block channel coding with code rate 1/16).
5. For the presented scenario, the scaling factor N_g highly affects PHICH control channel performance mainly for LTE system bandwidth 20 MHz. The PHICH BER results for $N_g = 1/6$ show a gain 7 dB (at PHICH BER 10^{-3}) comparing to other N_g values.

Coexistence methodology and results presented in this paper enable to better understand the LTE performance and reliability at the same frequency bands and location area with WLAN. This paper defines conditions and preliminary recommendations for LTE and Wi-Fi operation of uncontrolled LTE-U networks. The results could be valuable for developers, vendors and mobile operators to optimize system parameters.

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