VĚDECKÉ SPISY VYSOKÉHO UČENÍ TECHNICKÉHO V BRNĚ

Edice Habilitační a inaugurační spisy, sv. 598

ISSN 1213-418X

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COEXISTENCE BETWEEN ADVANCED WIRELESS COMMUNICATION SYSTEMS IN SHARED RADIO FREQUENCY BANDS

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COEXISTENCE BETWEEN ADVANCED WIRELESS COMMUNICATION SYSTEMS IN SHARED RADIO FREQUENCY BANDS

KOEXISTENCE POKROČILÝCH BEZDRÁTOVÝCH KOMUNIKAČNÍCH SYSTÉMŮ VE SDÍLENÝCH FREKVENČNÍCH PÁSMECH

SHORT VERSION OF HABILITATION THESIS

FIELD: ELECTRONICS AND COMMUNICATION
OBOR: ELEKTRONIKA A SDĚLOVACÍ TECHNIKA

VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ NAKLADATELSTVÍ VUTIUM

BRNO 2018

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

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

THE THESIS IS AVAILABLE AT:

Brno University of Technology, Dept. of Radio Electronics, Technická 3082/12, 616 00 Brno, Czech Republic

ISBN 978-80-214-5640-2
ISSN 1213-418X

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About the Author

Ladislav Polák was born in 1984, in Šúrovo, Slovak Republic. He received his Bc. (in 2007), M.Sc. (in 2009) and Ph.D. (in 2013) degrees in the field of Electronics and Communication from the Brno University of Technology (BUT), Czech Republic. Currently, he is a research worker (junior scientist at the SIX research center) at the Department of Radio Electronics (DREL) of the Faculty of Electrical Engineering and Communication (FEEC), BUT. In February 2012, he was a visiting researcher with MADS Group, University of A Coruna, CITIC-research building, A Coruna, Spain. His research interests are Digital Video Broadcasting (DVB), mobile and wireless communications, modeling of communication systems on PHY level and RF measurement. He also deals with video image quality evaluation, design of subjective video quality methodologies and signal processing.

From 2014 to 2016, he was a member committee (MC) in the international Cooperation in Science and Technology (COST) action 3D-ConTourNet. Between 2015 and 2016, he led the national COST CZ project *Quality Optimized Coding and Transmission of Stereoscopic Sequences (QOCIES)*, focused on the research of efficient techniques for 3D video coding and its QoE-QoS evaluation in modern multimedia systems. Since 2016, he has been an MC member in the international COST action IRACON. From 2009 to 2017, he was a member of a team in several projects of fundamental research supported by GAČR, COST CZ and EUREKA.

He is an author or co-author of 13 research articles published in SCI-E international journals, 4 articles in other journals, 37 papers published in proceedings of international conferences and 1 university textbook. Until February 1, 2018, in accordance to Web of Science (WoS), his articles received 101 citations (without autocitation), and his h-index is 9. Since 2014, he has been an Associate Editor of the *Radioengineering* journal.

His pedagogical activities are focused on practical education (laboratory exercises in the courses *Digital Television and Radio Systems* and *Low-Frequency and Audio Electronics*). In 2011, he received an innovation project from the Council of Higher Education Institutions (FRVŠ). He serves as a lecturer of selected topics in the course *Digital Television and Radio Systems*. He is an author or co-author of several software/hardware products and educational materials (laboratory works, presentations). He supervised 6 bachelor and 5 master theses and 5 contributions of students at the Electrical Engineering, Information and Communication Technologies (EEICT) conference.

Between 2010 and 2012, he twice received the 1^{st} place and once 2^{nd} place at the national EEICT student conference, in the category *Electronics, Communications and Microelectronics (Doctoral 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, monitoring and suppressing of various 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. 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. A brief conclusion closes this habilitation thesis in Section 5.

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

The LDPC FEC scheme, applied in DVB-T2, 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. 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], [16], [17].

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 (≈ 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). Next, 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 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. 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. 2.

The non-overlapping coexistence scenario with a GB band (see ① in Fig. 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. 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. Both of these scenarios can be also called adjacent channel coexistence. The partial overlapping coexistence scenario (see ③ in Fig. 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. 2), also called co-channel coexistence, it means that one RF signal is completely overlapped with another RF signal [5].

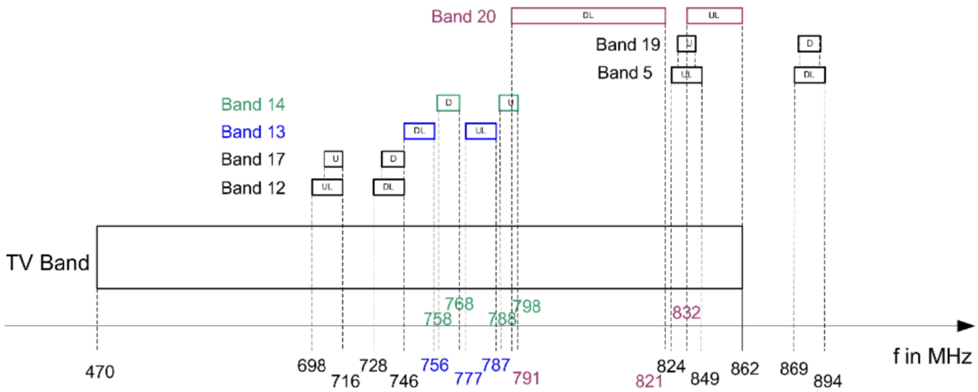

Figure 1: Coexistence scenarios between DVB-T/T2 and LTE in the UHF band [28].

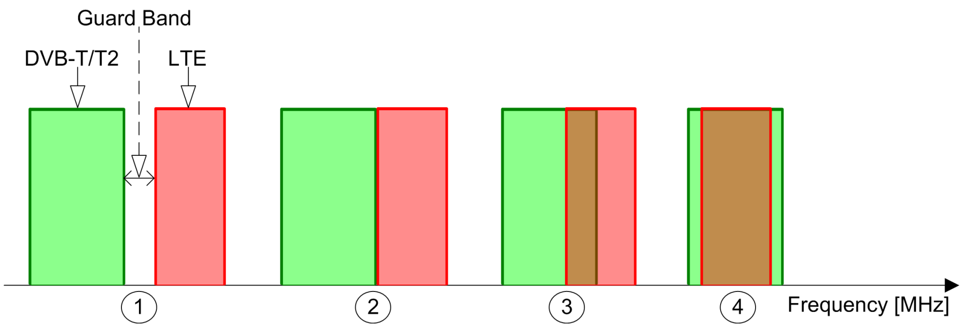

Figure 2: Graphical illustration of possible coexistence scenarios between DVB-T/T2 and LTE systems: ① non-overlapping with GB>0 MHz, ② non-overlapping with GB=0 MHz, ③ partial overlapping, and ④ full overlapping RF spectrum.

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].

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. It is clearly seen that between LTE and WLAN systems adjacent coexistence scenarios can occur.

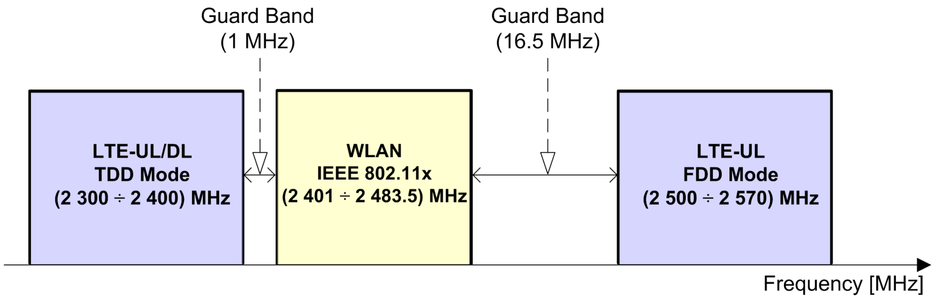

Figure 3: Assumed utilization of the 2.4 GHz ISM band by the LTE system.

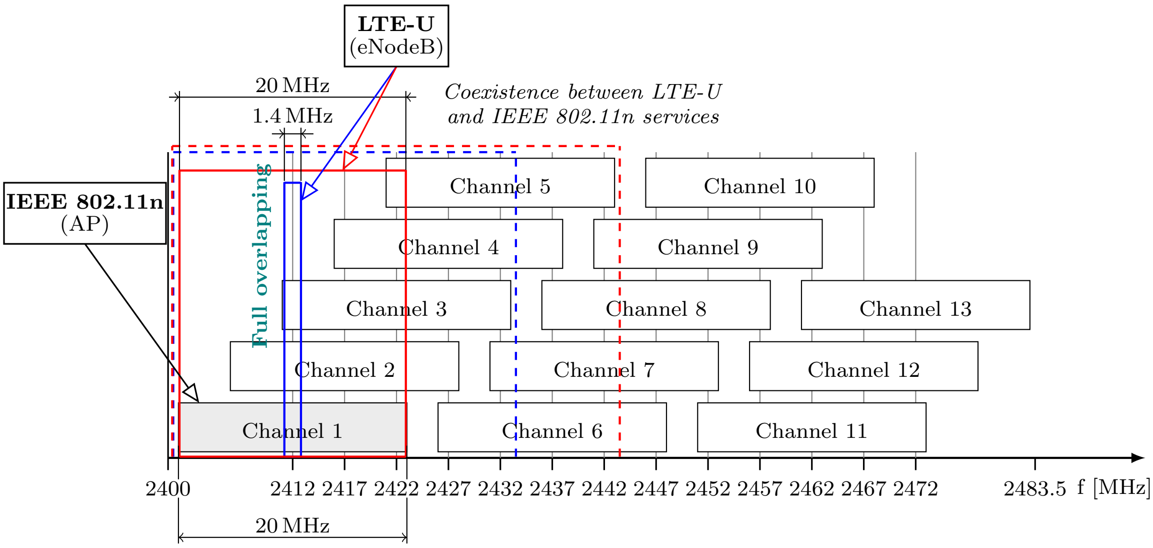

Figure 4: Graphical representation of the LTE-Unlicensed (1.4 MHz and 20 MHz system bandwidth marked by blue and red color, respectively) and WLAN services in ISM 2.4 GHz band - full overlapping coexistence scenarios [10].

Furthermore, thanks to higher density of wireless networks, co-channel coexistence scenarios are possible too. Such situations are shown in Fig. 4.

Undesirable interactions between similar or different kinds of wireless communication systems, operating in 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 are as follows:

1) to define uses cases (UC) and related coexistence scenarios between DVB-T/T2 and LTE systems and between LTE and WLAN systems in shared RF bands;

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 Coexistence between DVB-T/T2 and LTE

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.

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.

4.1.1 DVB-T/T2 and LTE Coexistence Measurement Testbed

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 (see Fig. 5). 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/T2) 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 Section 3) between different wireless communication systems. Its functionality has been also verified and demonstrated in [1] and [2]. Illustrative snapshots of RF spectrum captured at reference conditions (any coexistence) and at the coexistence of DVB-T2-Lite and LTE signals are shown in Fig. 6.

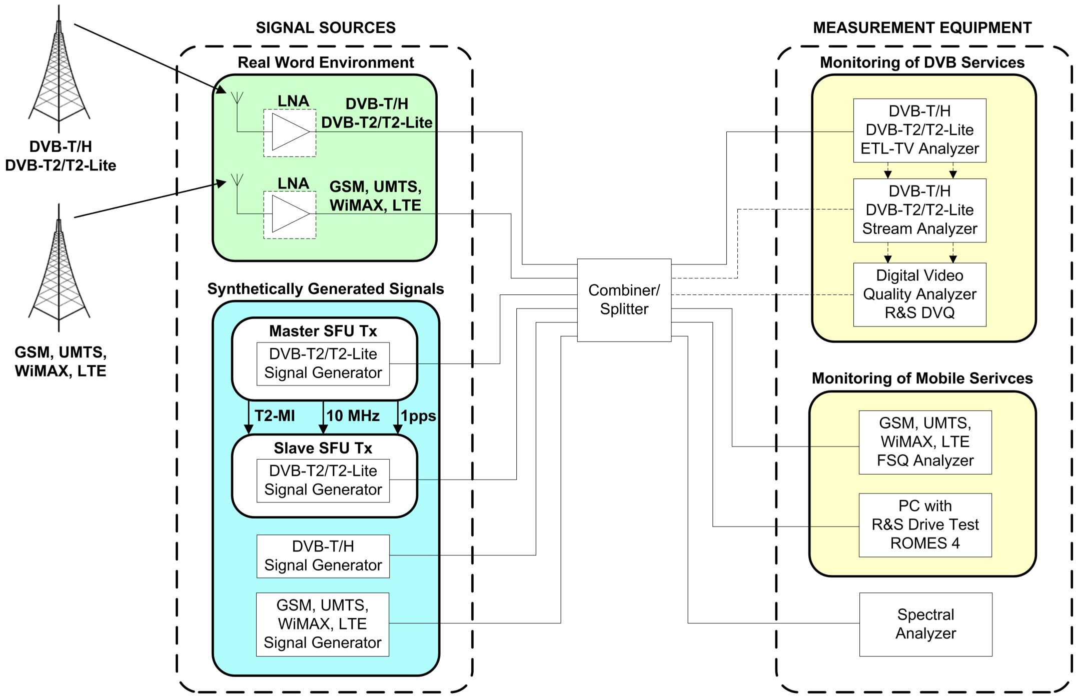

Figure 5: Block diagram of the proposed measurement testbed for measuring interactions between different wireless communication systems [1].

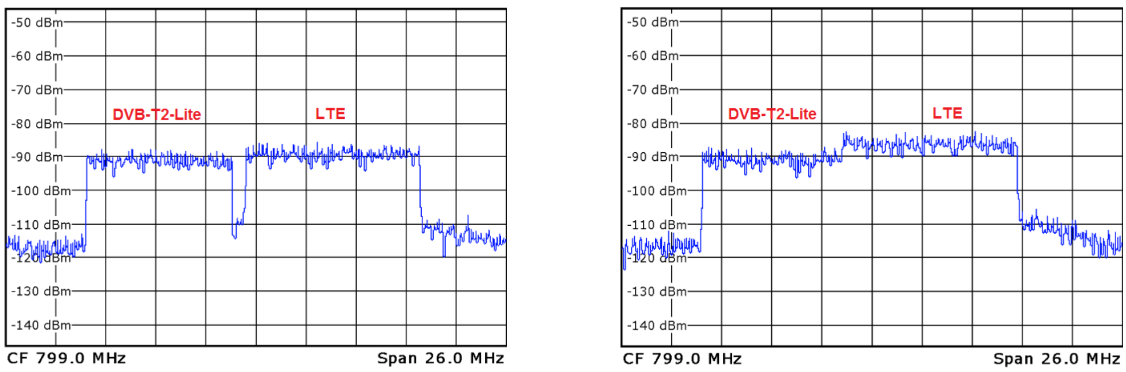

Figure 6: [left] RF spectrum of DVB-T2-Lite and LTE signals without any coexistence; [right] RF spectrum of coexisting DVB-T2-Lite and LTE signals [2].

4.1.2 DVB-T2-Lite and LTE Coexistence in Real 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.

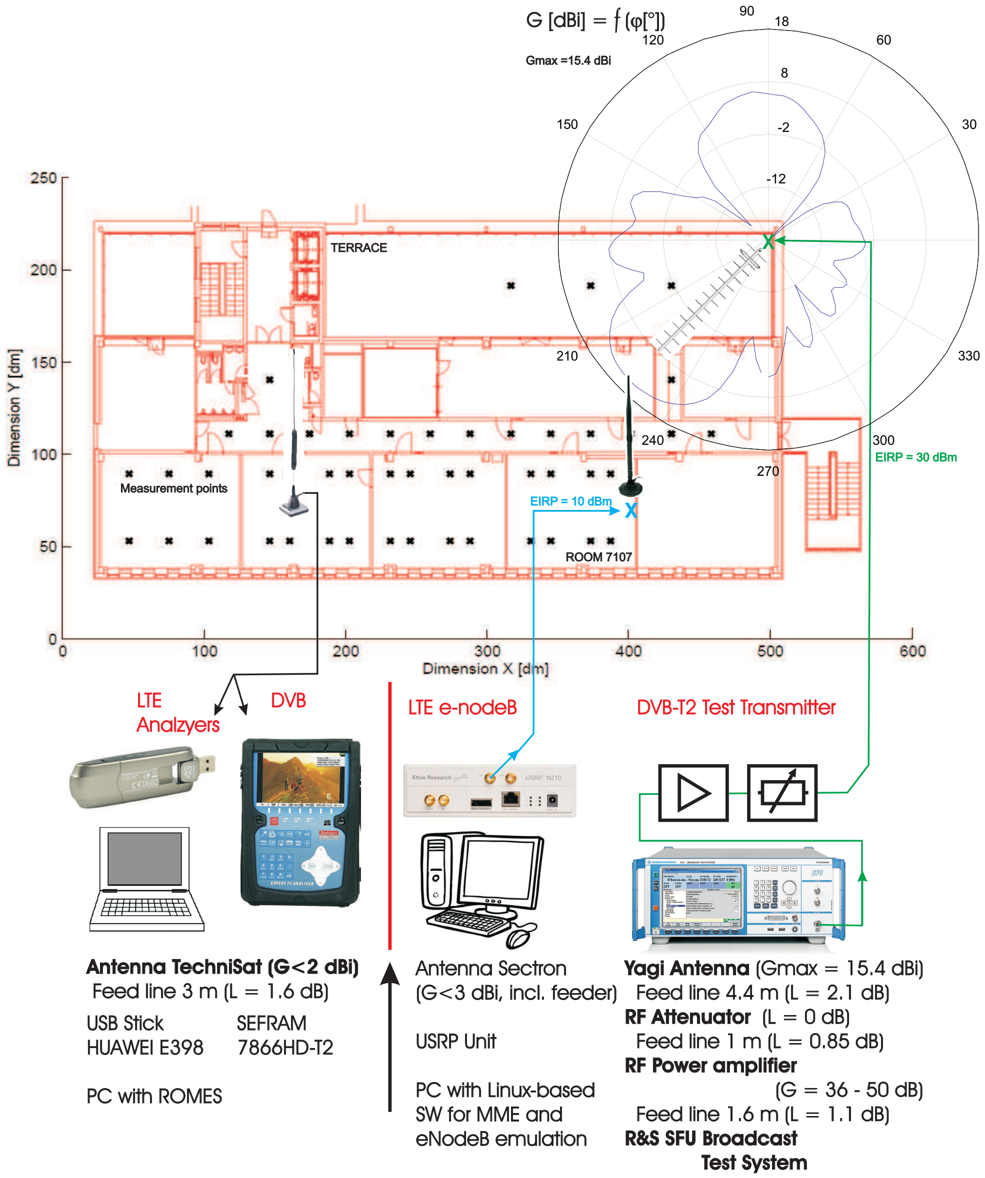

Figure 7: Floor plan of the 7^{th} floor in the building of BUT FEEC, DREL and general block diagram of the measurement testbed [3].

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 (see Fig. 7). 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≤2 dBi).

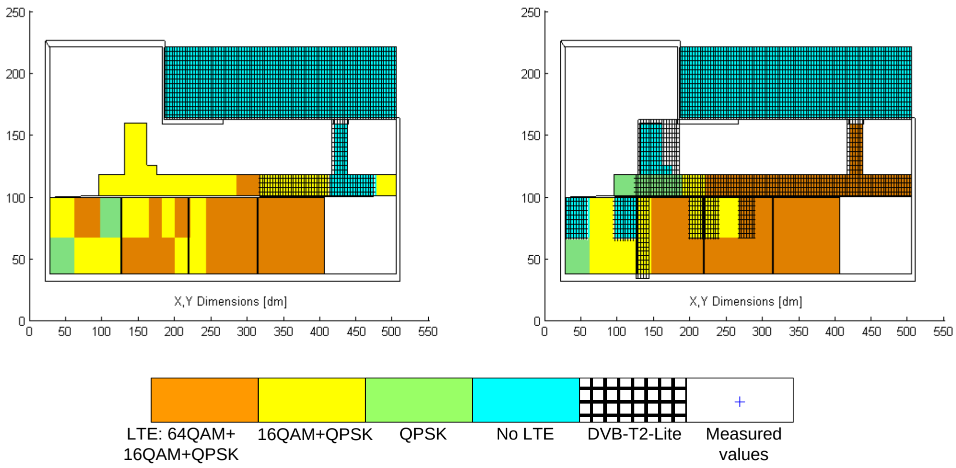

Figure 8: The map representation of QoS states of coexisting systems: [left] B_{LTE}=10 MHz, B_{TV}=8 MHz, ΔP=0 dB and channel overlap=800 kHz, [right] B_{LTE}=20 MHz, B_{TV}=8 MHz, ΔP=-10 dB and channel overlap=1600 kHz [3].

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 (see Fig. 8). 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 ($\Delta P = EIRP_{\mathrm{LTE}} - EIRP_{\mathrm{TV}}$) 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].

4.1.3 Study of DVB-T/T2 and LTE Coexistence under Laboratory Conditions

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].

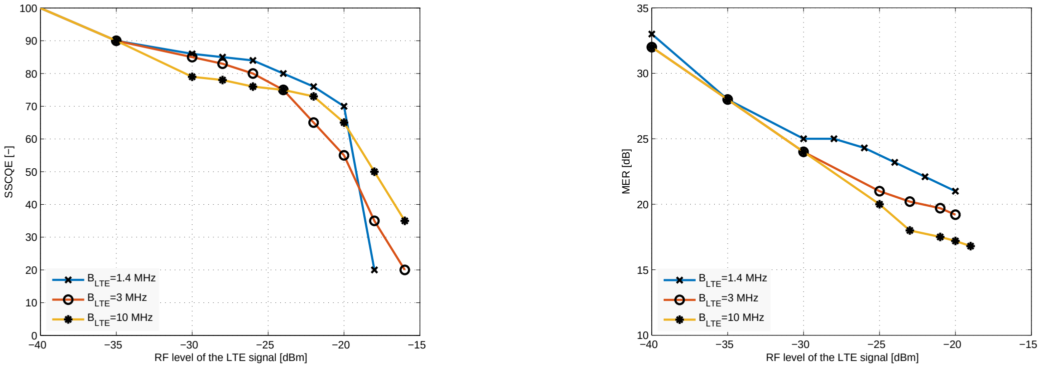

Figure 9: Co-channel coexistence between DVB-T/H and LTE systems [4]: [left] SSCQE vs. RF level of the LTE signal; [right] MER vs. RF level of the LTE signal (© 2015 IEEE).

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 (see Fig. 9). 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. Curves MER versus RF level of the LTE signal (see Fig. 9 [right]) show slightly different performance of DVB-T/H against interfering LTE signal with different B_{LTE}, but only for higher level of the LTE signal.

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 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.

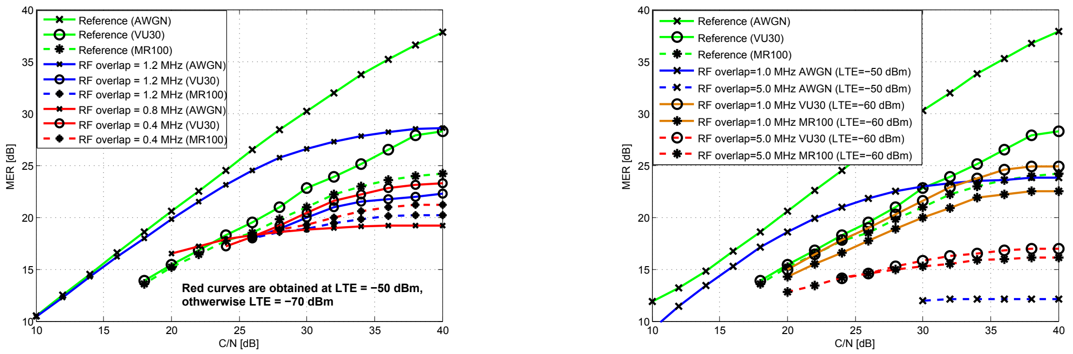

Figure 10: MER vs. C/N for T2-Lite in different channel models at different partial RF overlapping coexistence scenarios [7]: B_{LTE}=1.4 MHz [left] and 10 MHz [right] (© 2016 IEEE).

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 (see Fig. 10). 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 [1] 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 RF signals (P_{TV_1} and P_{TV_2} DVB-T2 RF signals from the master and slave unit, respectively). Here, it is marked as ΔP_{TV}. The established DVB-T2 objective parameters (BER before/after FEC decoding and MER) on the spectral density ratio (SDR) were analyzed.

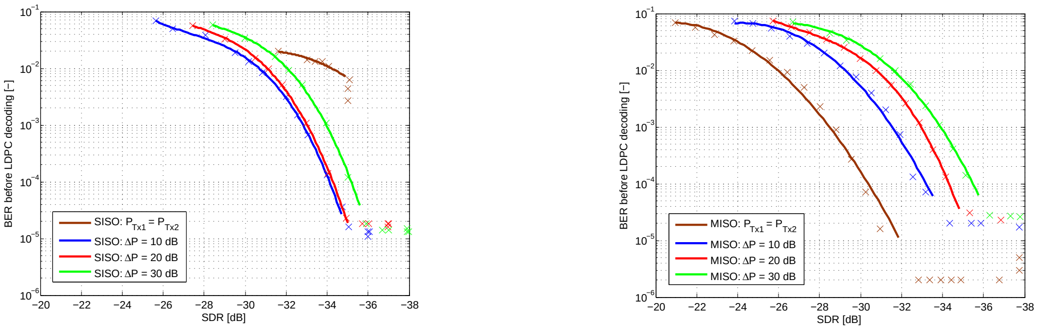

Figure 11: Dependences of BER at the input of FEC decoder in DVB-T2 on the SDR ratio when DVB-T2 SISO [left], DVB-T2 MISO [right] and LTE-UL services coexisting. Power levels of DVB-T2 RF signals from TV transmitters are either equal (brown curve) or different (other curves). In both cases B_{LTE}=10 MHz [8].

SDR is defined as the power ratio between LTE and DVB-T2 RF signals per unit of the used bandwidth. Its value is calculated as follows:

$$\mathrm{SDR} = \mathrm{P_{LTE}} - 10\log(\mathrm{B_{LTE}}) - ((\mathrm{P_{TV_1}} + \mathrm{P_{TV_2}}) - 10\log(\mathrm{B_{TV}})), \tag{1}$$

where $\mathrm{P_{LTE}}$ is the power level of the LTE signal, $\mathrm{B_{LTE}}$ expresses the bandwidth of the used LTE channel, $\mathrm{P_{TV_1}}$ and $\mathrm{P_{TV_2}}$ are the power levels of DVB-T2 signals from the considered $T\mathrm{X}_1$ and $T\mathrm{X}_2$ transmitters respectively and B_{TV} represents the bandwidth of the used TV channel. There are considered zero (0 dB) and non-zero power imbalances (10 dB; 20 dB and 30 dB) between $T\mathrm{X}_1$ and $T\mathrm{X}_2$ 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-UL with negative SDR values.

Figure 11 [left] 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 a scenario is known as 0-dB echo [17] 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.

Figure 11 [right] 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 [17]. Interestingly, in the remaining cases (non-zero power imbalances) the DVB-T2 MISO performances are comparable with SISO ones. The DVB-T2 MISO signal has the highest robustness against interferences, but only for $\Delta\mathrm{P}_{TV} \in$ <0,10> dB. All in all, there is assumed a perfect channel estimation and synchronization at the receiver. Hence, the influence of the relative delay on the MISO gain can be neglected.

In general, the obtained results revealed that the impact of LTE-UL system on the DVB-T2 system 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 DVB-T2 RF signals. Different bandwidths of LTE-UL RF signal affect the DVB-T2 RF signal (broadcasted by SISO and MISO technique) in a different way.

4.2 Coexistence between LTE and WLAN

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.

4.2.1 LTE and WLAN Coexistence Measurement Testbed

A universal laboratory measurement setup (see Fig. 12) 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 generate LTE-DL and Wi-Fi (according to the IEEE 802.11n Tx block) RF 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 (see Fig. 13 and Fig. 14).

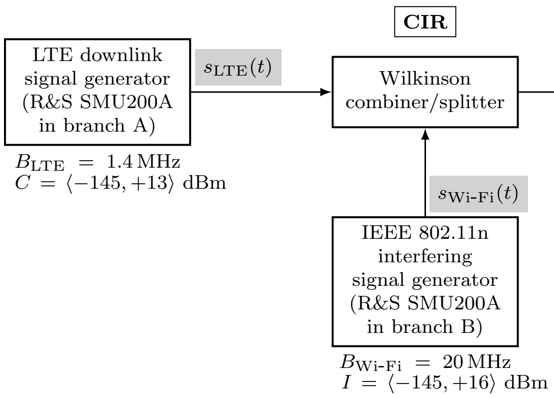

Figure 12: Block diagram of the workplace to measure LTE/Wi-Fi signals [9] (© 2016 IEEE).

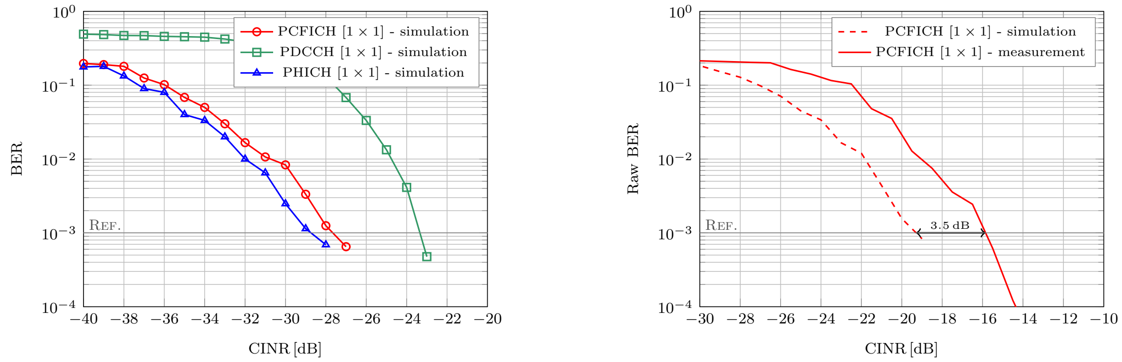

Figure 13: BER versus CINR for PCFICH, PDCCH and PHICH; [right] raw BER versus CINR for PCFICH [9] (© 2016 IEEE).

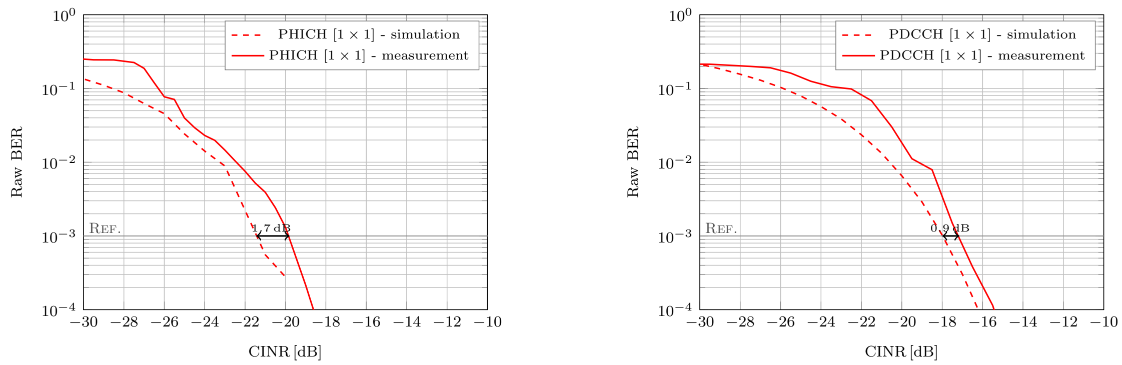

Figure 14: Dependence of raw BER on the co-channel inter-system interference in the PHICH LTE [left] and in the PDCCH LTE control channels [right] [9] (© 2016 IEEE).

4.2.2 LTE/WLAN Coexistence Link Level Simulator

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. 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. Its block diagram is shown in Fig. 15.

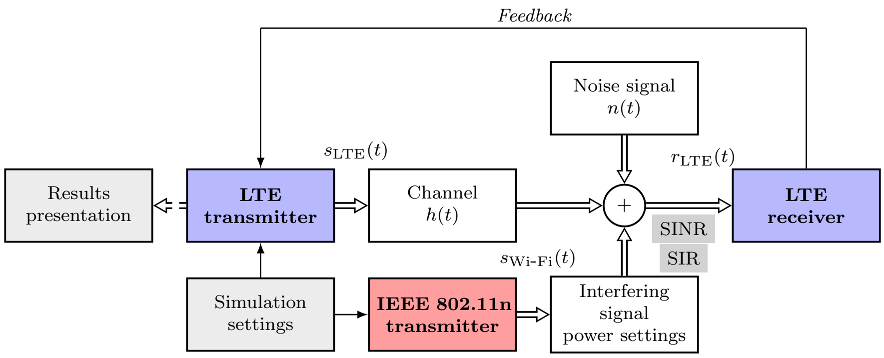

Figure 15: Block diagram of the LTE vs. IEEE 802.11n coexistence link-level simulator [10].

For this purpose, the LTE downlink link level simulator, developed at TU Vienna [33], [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. Mathematically it as follows:

$$r_0(t) = \underbrace{s_0(t) * h_0(t)}_{\text{useful signal}} + \underbrace{n_0(t)}_{\text{noise}} + \underbrace{\sum_{k=1}^{N_I} (s_k(t) * h_k(t))}_{\text{interfering transmitters}} \ , \tag{2}$$

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), $*$ signs 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 fading channel described by its impulse response.

According to assumed co-channel coexistence scenario, the number of interferers $N_I = 1$ (IEEE 802.11n) and $h_1(t) = \delta(t)$ (delta function, no fading channel in the interfering branch). Thus we can rewrite (2) to:

$$r_{LTE}(t) = \underbrace{s_{LTE}(t) * h(t)}_{\text{LTE signal}} + \underbrace{n(t)}_{\text{noise}} + \underbrace{s_{Wi\text{-}Fi}(t)}_{\text{Wi-Fi signal}} \ , \tag{3}$$

where $r_{LTE}(t)$ is the received LTE signal, $s_{LTE}(t)$ is the transmitted LTE signal and $s_{Wi\text{-}Fi}(t)$ is the interfering Wi-Fi signal. The channel block adjusts the LTE output signal $s_{LTE}(t)$ 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, (3) could be simplified to:

$$r_{LTE}(t) = s_{LTE}(t) + n(t) + s_{Wi\text{-}Fi}(t). \tag{4}$$

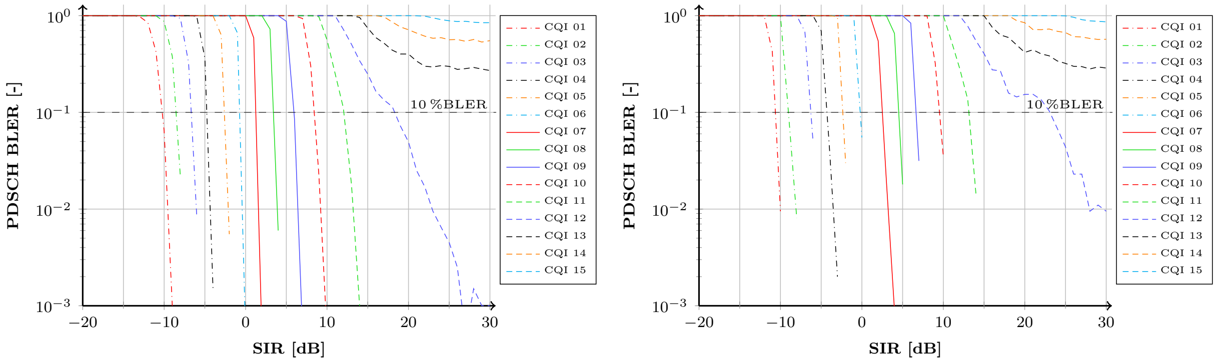

Figure 16: LTE PDSCH Block error rate link performance for various CQI's under the Wi-Fi co-channel coexistence scenario ([left] B_{LTE}=1.4 MHz and [right] B_{LTE}=20 MHz) [10].

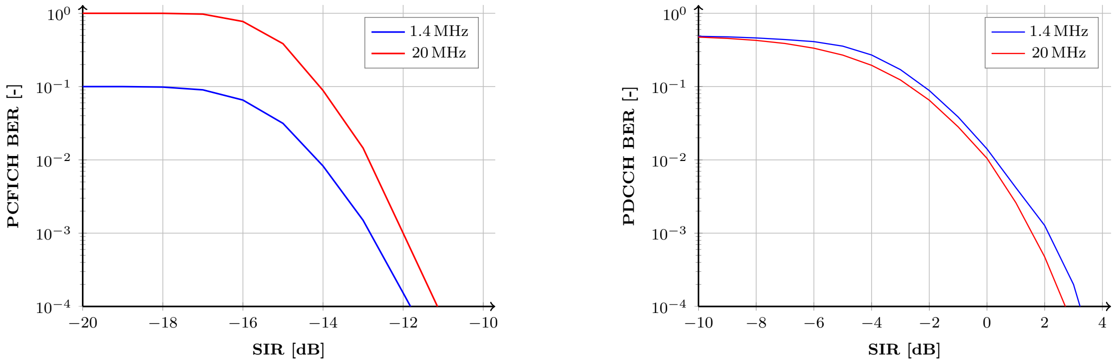

Figure 17: [left] LTE PCFICH and [right] PDCCH control channel performance under the Wi-Fi co-channel coexistence scenario [10].

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. Parameter SIR is calculated as:

$$SIR\ [dB] = P_{Tx}^{LTE}\ [dBm] - P_{Tx}^{Wi\text{-}Fi}\ [dBm], \tag{5}$$

where P_{Tx}^{LTE} is the power of LTE signal at the LTE transmitter output and $P_{Tx}^{Wi\text{-}Fi}$ is the power of Wi-Fi signal at the Wi-Fi transmitter output. Parameter SIR is defined as the post-FFT ratio at the receiving antenna (after FFT operation in the LTE receiver).

Simulation results the 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 scenario 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 (see Fig. 16). User data transmitted via LTE PDSCH are well protected for the link with lower CQI index (from 1 to 11). Using the PDSCH link with CQI higher than 12 is not suitable for LTE vs. Wi-Fi (IEEE 802.11n) co-channel coexistence scenarios. Scalable bandwidth in LTE has inconsiderable impact on the PDCCH physical control channel performance (see Fig. 17).

5 Conclusion

This short version of the habilitation thesis briefly summarized research activities of the applicant in the last 5 years (2013-2017) at DREL, BUT. Firstly, the results from exploring of the coexistence between DVB-T/T2 and LTE broadband networks were presented and discussed. Secondly, the results from the analysis of the co-channel coexistence between LTE and WLAN systems were summarized.

In Chapter 4.1, according to the main goals of this habilitation thesis (see Chapter 3), possible coexistence scenarios between DVB-T/H/T2/T2-Lite and LTE-DL/UL systems were defined, described and analyzed. 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 papers [1]-[8].

In Chapter 4.2, according to the main goals of this habilitation thesis (see Chapter 3), possible co-channel coexistence scenarios between LTE-DL and WLAN systems were defined, described and anaylzed. 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 papers [9] and [10].

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Acknowledgments

I would like to express my sincerest thanks to *prof. Ing. Tomáš Kratochvíl, Ph.D.*, for guiding me since my doctoral thesis, from the beginning of my scientific and also pedagogic career at the Department of Radio Electronics (DREL). He has supported and inspired me throughout my academic and scientific career with his patience and knowledge.

Special thanks goes to my colleagues *Ing. Ondřej Kaller*, *Ing. Jiří Miloš, Ph.D.*, *Ing. Lukáš Klozar*, *Ing. Libor Boleček, Ph.D.* and *doc. Ing. Jiří Šebesta, Ph.D.*, and other colleagues from the department DREL for close collaboration, and fruitful discussions made during recent years. I really appreciate their huge help in solving many tasks in several research projects. Published journal papers and presented results at international conferences, which are the main core of this habilitation thesis, would have never been completed without their support.

I would like to thank *Ing. Philip Bělohlávek* and *doc. Ing. Martin Slanina, Ph.D.* for their help in improving the English grammar of published journals and conference papers.

I greatly appreciate working with bachelor and master students. I would also like to thank my students *Ing. Adam Strouhal*, *Ing. Peter Hrach*, *Ing. Denis Plaisner*, and *Bc. Michal Mikláš*. They achieved excellent results in their bachelor and masters works, which I was able to use in solving fundamental research projects.

Cardinal thanks belongs to my parents *Katarína Poláková* and *Ladislav Polák*, for their constant and unlimited love, understanding, support, encouragement and belief in me. Without their help and patience, it would not have been possible to complete this habilitation thesis. You are always there for me.

Abstract

In this short version of the habilitation thesis research activities in the field of coexistence between wireless communication systems are presented. A basic description of the considered advanced communication systems, namely first and second generation Digital Video Broadcasting-Terrestrial (DVB-T and DVB-T2), Long Term Evolution (LTE) and Wireless Local Area Networks (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. Coexistence scenarios between DVB-T/T2 and LTE systems and between LTE and WLAN systems are defined. Next, appropriate measurements methods are proposed to explore the impact of coexistence scenarios on the robustness of DVB-T/T2 and LTE systems. Finally, the influence of unwanted interferences from coexistence scenarios on the performances of DVB-T/T2 and LTE systems are evaluated and briefly discussed.

Abstrakt

Tato habilitační práce popisuje výzkumné aktivity v oblasti koexistence bezdrátových komunikačních systémů. Základní popis uvažovaných pokročilých 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. V této části jsou definovány koexistenční scénáře mezi systémy DVB-T/T2 a LTE a mezi systémy LTE a WLAN. Dále jsou navrženy měřící metody pro zkoumání vlivu jednotlivých koexistenčních scénářů na robustnost systémů DVB-T/T2 a LTE. Na závěr je vyhodnocen a stručně diskutován vliv něžádoucích interferencí z dříve definovaných koexistenčních scénářů na robustnost systémů DVB-T/T2 a LTE.