Mobile Heterogeneous Telecommunications Networks Coexistence in Unlicensed Bands

(*Invited paper*)

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Abstract— **Mobile communication networks are constantly evolving and each new generation provides considerably higher data transmission capabilities. Having in mind predictions of high cellular data traffic growth over the next few years, it is clear that the licensed band communications would have problems to support such a high bandwidth demand. One of the possible solutions to this problem is to adaptively use some additional spectrum out of the dedicated licensed band, such as some of the unlicensed bands. LTE-A standard introduced a new mechanism, named Carrier Aggregation, which provides the possibility to simultaneously use multiple frequency bands, such as the licensed and unlicensed bands. In order to work in an unlicensed band, LTE has to employ some new procedures that provide shared access with other systems using the same frequency band, such as WiFi. These procedures include spectrum sensing, dynamic frequency selection, as well as the coordination of the shared access. Performance measurements and the analysis of the procedures will be shown in this paper.**

Keywords-WiFi; LTE; 5G; heterogenous newtworks; unlicensed band; coexistence

I. INTRODUCTION

The data transmission in mobile communications was gaining its importance over time. The offered capacity increased as the demands for the mobile data traffic raised. The first generation of cellular wireless systems were characterized by their analog modulation schemes and were designed primarily for delivering voice services.

After the first generation mobile systems, which were analog and voice transmission oriented, the improved technology, with more powerful and more efficient processors, paved the way for the second generation (2G) mobile communication systems [1]. 2G systems used digital modulation, but like its predecessors also were voice oriented. Digital modulation brought some improvements in the user experience and system performance. For example, system capacity was improved through the implementation of several different technologies. Time Division Multiple Access (TDMA) allowed multiple users to utilize the same frequency channel. Better bit error rate of the digital modulation, more powerful coding techniques, and better channel equalization techniques provided a tight frequency re-use, meaning that the same set of frequencies could be used in the cells that are closer to each other. Finally, the system capacity was further improved by the use of spectrally efficient digital speech codecs. New digital speech codec also improved the voice quality. Besides the better voice quality, the user experience in 2G mobile communication systems was enriched by some new applications. The most interesting application was the Short Messaging Service (SMS). Other significant improvement was the support for low (from today's point of view) data rate mobile applications. The first 2G systems supported circuit switched data transfer at 9600 bps. Later, packet data transmission was introduced, as well. Compared with modern systems, 2G mobile data services provided rather limited amount and type of information from the Internet, such as weather, stock quotes, news, travel direction, etc. Besides the limitation in data rate, there was a limitation in the performance of the mobile devices. Namely, 2G mobile devices had limited processing power, memory and display capacity. Therefore, some specialized technologies, such as the Wireless Access Protocol (WAP), were developed to adapt and provide the Internet content to mobile devices. By the mid-1990s, the European Telecommunications Standards Institute (ETSI) introduced the GSM Packet Radio Systems (GPRS), often referred to as 2.5G, as an evolutionary step for GSM systems toward higher data rates. GPRS opened in 2000. as a packet-switched data service embedded to the channel-switched cellular radio network GSM. GPRS extended the reach of the fixed Internet by connecting mobile terminals worldwide. GPRS and GSM systems share the same frequency bands, time slots, and signaling links. GPRS was designed to support different data throughputs per slot, from 8 kbps to 20 kbps, by using different channel coding schemes. There are eight slots in TDMA frame, allowing a maximum theoretical data rate of 160 kbps, if all slots are used for the data transmission and if channel condition are good enough to support the channel coding with the smallest redundancy and therefore 20 kbps bitrate per slot. However, the obtained practical data rates were up to 80 kbps, because depending on the network capacity as well as the number of active users in the cell, the number of time slots that are allocated was on average up to four. The GSM standard mobile data transfer speed was further improved with the introduction of Enhanced Data Rate for GSM Evolution standard, known as EDGE (2.75G), in the early part of 1997. The first implementation of EDGE on a GSM network was in the beginning of 2003. EDGE added support for 8PSK

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modulation to boost the data rate three times over GPRS. The theoretical data transfer speed was up to 384 kbps, and practical data rates were up to 120 kbps, on average.

A revolutionary step in the development of the mobile communication systems was made with the introduction of the third generation (3G) systems. Compared to 2G systems, 3G systems provided much higher data rates and highly increased voice capacity. Also, 3G system systems presented the support for advanced services and applications, including multimedia. More powerful mobile devices followed this improvement. Universal Mobile Telephone Service (UMTS) was originally developed by ETSI as the 3G system based on the evolution of GSM. UMTS includes a core network (CN) that provides switching, routing, and subscriber management; the UMTS Terrestrial Radio Access Network (UTRAN); and the User Equipment (UE). The basic architecture is based on the GSM/GPRS architecture. 3G systems are backward compatible with previous mobile systems, with each element enhanced for 3G capabilities. The biggest change was in the radio or air interface. While UMTS retained the basic architecture of GSM/GPRS networks, the 3G radio interface called Wide-band CDMA (W-CDMA) is a radical departure from the 2G air interface. It is a Direct Sequence Spread Spectrum (DS-SS) CDMA system where user data is multiplied with pseudo-random codes that provide channelization, synchronization, and scrambling. Pseudo-random code has the bitrate of 4.096 Mbps. The system operates on a larger 5 MHz bandwidth, providing peak data rates from 384 to 2 Mbps. Also, the system implements the power control, i.e. the output power of the transmitter is controlled by itself at the frequency of 1500 Hz. High-Speed Packet Access, or HSPA, is the term used to refer to the combination of two key enhancements by 3rd Generation Partnership Project (3GPP) to UMTS-WCDMA: High-Speed Downlink Packet Access (HSDPA) introduced in Release 5 [2] in 2002 and High-Speed Uplink Packet Access (HSUPA) introduced in Release 6 [3] in 2004. HSDPA defined a new downlink transport channel capable of providing up to 14.4 Mbps peak theoretical throughput, using QPSK and 16QAM modulation scheme. HSUPA is capable of supporting up to 5.8 Mbps peak uplink throughput, using dual BPSK modulation. 3GPP Release 7 published in June 2007 had substantial enhancements included as a further evolution of HSPA. Release 7 [4] HSPA, sometimes referred to as HSPA+, contains a number of additional features that improve the system capacity (including voice capacity), end-user throughput, and latency. Compared to HSPA, HSPA+ increased the downlink speed through the introduction of 64QAM modulation scheme. On the uplink, support for 16QAM is included. Due to usage of 64QAM and 16QAM, maximum downlink and uplink data rates are reached 21.1 Mbps and 11.5 Mbps, respectively. HSPA+ also defined the use for up to two transmit antennas in the base station and two receive antennas in the mobile terminal for MIMO (multiple input multiple output) transmission. The use of 2 × 2 MIMO spatial multiplexing increases the peak downlink theoretical rate to 28 Mbps, because the simultaneous use of 64QAM and MIMO is not allowed. Mentioned combination of 64QAM and MIMO is introduced in 3GPP Release 8, and therefore the maximum downlink data rate is increased to 42 Mbps. As with other wireless and mobile systems, the maximum theoretical rates are rarely achieved in practice.

Due to the continually growing need for higher data speeds for mobile users, new and more efficient methods of utilizing the scarce resources of the RF spectrum is required. 3GPP is an ever-evolving standard for accommodating these needs and Long Term Evolution (LTE), or 4G, is yet another step towards higher data speeds, making sure that this new technology is compatible and can co-exist with 2G/3G. LTE was first defined in 3GPP Release 8 [5]. Via the use of wide bandwidths, advanced modulation (Orthogonal Frequency Division Multiplexing (OFDM)) and MIMO antenna schemes, LTE is able to provide data speeds in excess of 1000 Mbps on the DL and 500 Mbps on the Uplink. With regard to the spectrum efficiency, 4G/LTE is about three to four times better than 3G/HSDPA on the downlink and two to three times better than 3G/HSUPA on the uplink. This makes 4G/LTE a very attractive tool for network operators for better spectrum utilization.

Currently, the mobile data transfer was almost completely based on the usage of the licensed spectrum. Having in mind predictions of 12 times cellular data traffic growth over the next few years, Fig. 1 [6], it is clear that the licensed band communications would have problems to support such a high bandwidth demand. One of the possible solutions to this problem is to adaptively use some additional spectrum out of the dedicated licensed band. The unlicensed bands are particularly suitable for the bandwidth extension.

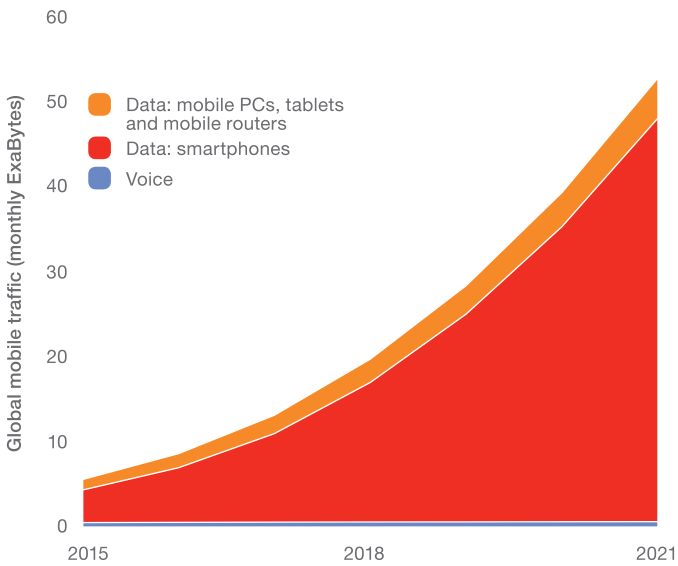

Figure. 1. Mobile data growth

In the 3GPP Release 10 [7], LTE was improved to fulfil the requirements of 4G mobile networks and it was named LTE–Advanced (LTE-A). The most important advancement of the LTE-A is the possibility of simultaneous use of multiple frequency bands by the means of the Carrier Aggregation (CA) technology. CA is the key technology that enables the unlicensed spectrum usage by the LTE devices.

Although the unlicensed band may be freely used by the communication systems, there are some regulations that have to be followed, such as Dynamic Frequency Selection (DFS) and listen-before-talking (LBT), which may use different technologies, such as carrier sense multiple access or spectrum sensing [8]. These coordination mechanisms, which are variants of dynamic spectrum access (DSA), are essential for achieving efficient coexistence between different systems that are operating in unlicensed spectrum. As the 5GHz band is primarily used by IEEE 802.11ac WiFi networks, the focus should be on the coordination between the LTE and WiFi. The main problem lies in the fact that the LTE was designed to operate in a dedicated, licensed band. Therefore, it does not have shared access mechanisms, like WiFi does. Papers [9] and [10] provide respectively simulation and theoretical results on the coexistence of LTE and WiFi networks and show the need for some sort of coordination between these two networks. Experimental analysis of the 2.4 GHz band WiFi communication influenced by LTE is given in [11]. The LTE is represented only by the base station, without any mobile stations. In this case, LTE eNB (evolved Node B) waits for the UE and transmits mainly control signals.

There are two possible solutions to the problem of WiFi and LTE networks coexistence. The first approach is to modify the LTE standard and adapt it to work in frequency shared environment. LTE-U (LTE-Unlicensed), proposed by LTE-U forum [12], uses a LTE version with duty cycle i.e. with pauses in the transmission. In this way, WiFi has the opportunity to transmit its data during the silent periods of the LTE-U. Besides, LTE-U access point listens to WiFi transmissions, tries to predict the usage patterns and to adapt to them. Licensed Assisted Access (LAA) will be a part of the future 3GPP LTE Release-13 standard [13], [14], and includes Listen Before Talk (LBT) mechanism to transmit when the channel is free. Standardization progress and the summary of the LAA is given in [15]. Also, an operator level system performance is analyzed for indoor hotspot, indoor office, and outdoor small cell scenarios. The analysis showed that a significant LTE capacity increase may be obtained by using LAA and LBT. Paper [16] considers the design of LBT for the LAA system and analyzes the influence of LAA clear channel assessment threshold on the performance of both LTE and WiFi networks. The paper shows that the proposed LBT algorithm is able to improve LAA and to keep low interference to WiFi. However, both LTE-U and LAA require significant modifications of the LTE standard and will not be available in near future.

The second approach is to introduce a coordinated access to the shared channel. There are two general approaches to spectrum coordination as follows [17]: reactive spectrum coordination and proactive spectrum coordination. The most straightforward reactive spectrum coordination concept is so called agile wideband radio scheme [18]. In this scheme, transmitter analyzes the spectrum and chooses its frequency band and modulation scheme, having in mind the highest allowed interference level. There is no higher-level coordination with the neighboring nodes. This coordination scheme is very simple, but has one serious possible problem with the hidden nodes, i.e. with the nodes that may not be visible to the station, but may interfere with it. Another simple coordination scheme is reactive control [19]. All the radio stations in a network control its transmit power, rate, or frequency band in a way to optimize channel quality and interference levels. The name reactive comes from the fact that the station change its parameters as a reaction to the changes in the wireless environment. Although these schemes are simple, with low software and hardware complexity, their application is limited to some simple scenarios. Proactive spectrum coordination schemes are slightly more complex than the reactive ones. An example of proactive schemes is the spectrum etiquette protocol [20]. This scheme employs a distributed coordination by the means of either Internet services or a separate coordination radio channel reserved for this purpose within the frequency band common to all participating radio nodes. These schemes enable radio nodes, using different radio access technologies, to coordinate its activities and adjust transmit parameters for successful joint operation. The etiquette approach is capable of operating in more complex scenarios than the reactive schemes. The Common Spectrum Coordination Channel (CSCC) variant of the etiquette approach is given in [20], [21] together with the demonstration of proof-of-concept experiments for coexisting IEEE 802.11b/g and Bluetooth networks in the shared 2.4 GHz unlicensed band. Paper [22] proposes an internetwork spectrum coordination across Wi-Fi and LTE systems based on an ontological framework as a possible solution for improved coexistence. With the coordination approach, only minor modifications of the existing standards are needed. However, the best solution would be to use coordination together with the LTE-U or LAA.

The experimentation in the area of mobile and wireless communications may be quite demanding because it requires a lot of communication equipment, computer power and a controlled environment. Therefore, it is convenient to use some of the laboratories, or testbeds, that are accessible via Internet, such as : ORBIT [23] at the Rutgers University, USA; NITOS [24] at the University of Tessaly, Greece; 5GIC [25] at the University of Surrey, England; or FUSECO Playground [26] at the Technical University of Berlin, Germany. The experimenter reserves resources online, accesses the testbed, programmatically describes the experiment, executes it and collects the results. The greatest challenge may be the experiment description, since new experimenters possibly are not familiar with the experiment code writing. Because of that, the project SEmantics driven Code GENEration for 5G networking experimentation (SecGENE) [27] develops the automatic code generation for the experiment and this paper will concisely describe it.

The rest of the paper is organized as follows. Section II briefly describes the unlicensed bands and the carrier aggregation technology. The experimentation process is given in Section III, while the automatic code generation is described in Section IV. The experiment results are presented in Section V, and the concluding remarks are provided in Section VI.

II. Unlicensed Bands and Carrier Aggregation

A. *Unlicensed Bands*

Unlicensed bands (UB), that may be of intereres for the LTE bandwidth extension, are comprised of several ISM (Industrial, Scientific and Medical) bands and one U-NII

(Unlicensed National Information Infrastructure) band. ISM bands consist of 900 MHz, 2.4 GHz, and 5.8 GHz, and U-NII band covers frequencies from 5.15 to 5.7 GHz. Each frequency range is divided into a number of 5 MHz wide channels. Due to minimising the interference, not all channels are planned for the use. More precisely, the allowable channels, allowed users and maximum power levels within these frequency ranges are defined by each country's regulations. The mentioned unlicensed bands are used by many communication, industrial, scientific and medical systems. However, the unlicensed bands are primarily occupied by WiFi. WiFi is designed for spectrum sharing with simple implementation and low cost, sacrificing the performance [28]. On the other hand, telecommunication systems designed to operate mainly in the licensed bands, due to the lack of frequency sharing mechanisms, are not suitable for the UB operation. However, as already mentioned, because of growing needs for the unlicensed spectrum use, some new features were introduced in LTE-Advanced, such as carrier aggregation. Qualcomm Inc. has recently introduced such a system, known as LTE in Unlicensed band (LTE-U) [29]. LTE operation in the unlicensed band would offer higher spectral efficiency and a significantly better coverage, compared to WiFi, while integrating licensed and unlicensed bands data flow in a single core network [28].

LTE-U current research is focused on the 5 GHz unlicensed band (5.15 – 5.835 GHz), also used by WiFi 802.11a networks, due to the highest available bandwidth, which has up to 500 MHz of available bandwidth, divided in more than twenty 20 MHz channels (Fig. 2). It is planned to develop downlink unlicensed communications at first, because it is more important to the end user, and later the uplink capacity will also be enlarged in the unlicensed band. It should be noted that the unlicensed spectrum, if available, would only be used for the data rate increase, both in downlink and uplink. The licensed spectrum, having predictable and stable performance, would still be used for the important operations, such as network management, delivery of critical information and guaranteed services.

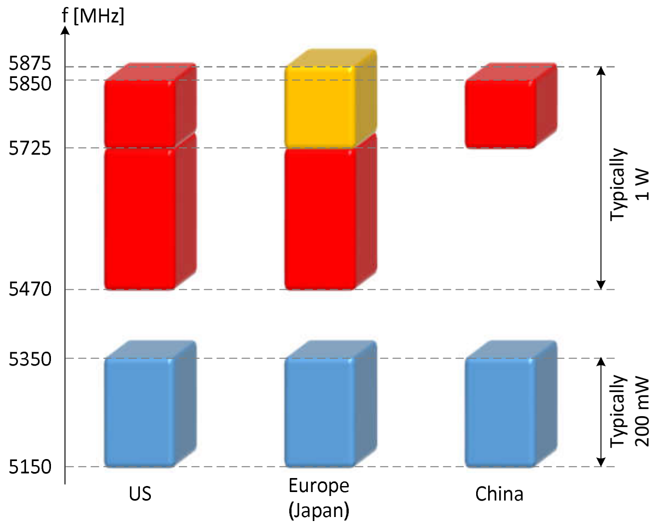

Figure 2. An overview of 5 GHz unlicensed band.

B. Carrier Aggregation

Release-10 of the 3GPP specifications, defining LTE-Advanced specifications, introduced a new functionality, known as carrier aggregation (CA). CA allows LTE to use multiple carriers in different bands and therefore to achieve higher bitrate. At the same time, the backward compatibility with Release-8 and 9 LTE is maintaned. Just like Release-8, Release-10 supports carrier bandwidths of 1.4, 3, 5, 10, 15, and 20 MHz. It is possible to combine up to five carriers, of different or the same bandwidth, in any frequency band. Maximum obtainable bandwidth is 100 MHz, if all five carriers with 20 MHz bandwidth are combined. However, the latest commercial LTE user equipment support up to three carriers.

Carrier aggregation can be used for both possible LTE duplexing modes, FDD and TDD. There are three different CA configurations, as illustrated in Fig. 3. The simplest CA configuration is set up if adjacent component carriers are used within the same frequency band. This configuration is named intra-band contiguous. However, having in mind the licensed spectrum occupancy and the spectrum fragmentation in general, a contiguous bandwidth wider than 20 MHz is not a likely scenario, but it may be used when the unlicensed 5 GHz band is allocated in the future. The other possible solution to the fragmented spectrum problem is so called the non-contiguous spectrum allocation.

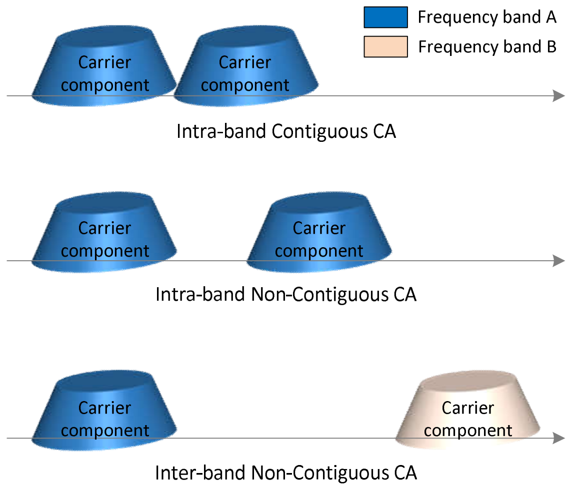

Figure. 3. Three types of carrier aggregation.

Based on the used frequency bands, the non-contiguous spectrum allocation may be divided into intra-band and inter-band. With the intra-band allocation, the component carriers belong to the same operating frequency band, but have a gap or gaps in between. If the component carriers belong to different frequency bands, the carrier aggregation is called inter-band.

III. EXPERIMENT DESCRIPTION

This Section describes an example of the unlicensed band LTE-WiFi coexistence experiment [30]. Since there is no commercial LTE hardware available that operates in any unlicensed band, a software radio based LTE implementation named Open Air Interface (OAI) [31] was used. The Open Air Interface LTE implementation represents the full real-time software implementation of 4th generation mobile cellular systems compliant with 3GPP LTE standards Release-8/10. OAI is implemented in gnu-C. OAI implements both LTE eNB, i.e. LTE base station, and LTE User Equipment (UE), i.e. LTE mobile station. It is designed to work with any hardware RF platform with minimal modifications. Currently, two platforms are supported: EURECOM EXMIMO2 [32], and Universal Software Radio Peripheral (USRP) X- and B- series [33]. In the experiments, USRP B210 was used.

Fig. 4 [30] illustrates the topology of the experiment setup. Nodes 50 and 68 are WiFi stations and they create an ad-hoc WiFi network. Available channels at 5 GHz frequency band are 36, 40, 44, and 48. This is the limit imposed by the regulatory domain, or country code of the WiFi cards. Without the loss of generality, it was chosen to use channel 48. This channel has the central frequency of 5.24 GHz. WiFi adapters output power was limited to 0 and 10 dBm in order to make it less than (0 dBm) or equal to the output power of the USRP devices (10 dBm). The traffic between these two stations is generated using *iPerf* v2 [34] application. The same application is used for the throughput measurement. The OAI LTE eNB is at node 59, and UE is at node 60.

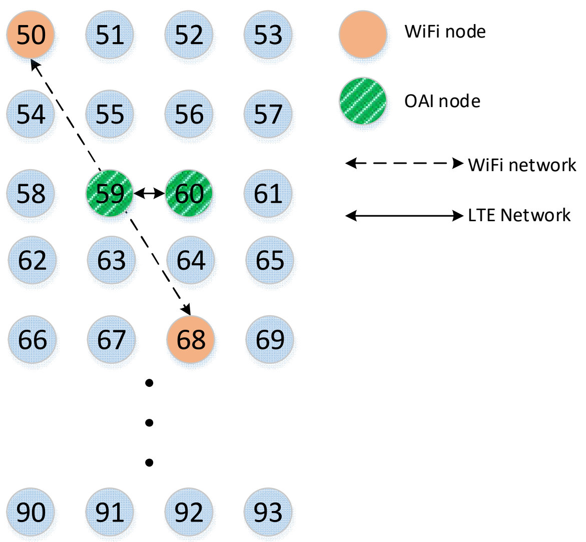

Figure. 4. The experiment setup topology.

The LTE channel width may be configured using the Number of resource blocks (N_{RB}) parameter. Possible channel widths are 1.4, 3, 5, 10, 15, 20 MHz for N_{RB} = 6, 15, 25, 50, 75, 100. However, OAI currently supports 5, 10, and 20 MHz channel bandwidth. Due to CPU requirements, OAI works the best with 5 MHz channel width. Therefore, the OAI is configured to work in FDD mode with 5 MHz channel bandwidth, i.e. the number of resource blocks is set to 25. The downlink frequency is set to be equal to the channel 48 central frequency 5.24 GHz. The uplink frequency offset is set to -100 MHz, i.e. the uplink frequency is 5.14 GHz to avoid multiple interferences with WiFi. The throughput and the round-trip time (RTT) between WiFi stations is constantly measured while the LTE traffic is varied. Again, *iperf* is used, now to generate and traffic in the downlink of the LTE network.

IV. AUTOMATIC CODE GENERATION

The future federations of heterogeneous networks envision common features such as coordination of available resources and intelligent retrieval of available computing and networking resources. By adopting ontologies as a knowledge background for information model of resources and services, advanced manipulations such as deduction of service and infrastructure behaviors become possible. Availability of resources as well as services provisioning can be intelligently deduced if ontologies are used [35]. Examples that prove high potential of using ontologies in networking can be found within several EU FP7 and Horizon 2020 founded projects such as: NOVI [36], FIRE LTE Testbeds for Open Experimentation (FLEX) [37], Federation for future internet research and experimentation (Fed4FIRE) [38], Testbeds for Reliable Smart City Machine to Machine Communication (TRESCIMO) [39], INfrastructures for the Future INternetCommunITY (INFINITY) [40], Software Defined Networks and Network Function Virtualization Testbed within FIRE+ (SoftFIRE) [41] etc. In NOVI [36], OWL ontologies are used to formalize information model and to develop the corresponding data models that enable the communication among system components. The information model describes resources at a conceptual level, including all components required to support operation of the system software. From the other side, the data model describes implementation details based on representation of concepts and their relations provided by the information model. FLEX [37] project, with its CoordSS subproject [42], used ontologies with the basic assumption that semantic technologies could be used to improve coordination in cognitive radio networks. In particular, FLEX directly works with the 5G heterogeneous networking challenge concerning coordination in heterogeneous networks. The spectrum sensing and coordination in such networks is represented as an interactive process consisting of communication between distributed agents and information sharing about a specific spectrum usage effectiveness [43]. Semantic technologies are used to represent conceptual agreement on vocabulary among agents in the network. The knowledge is represented in a form of ontologies, where the standardized way for this representation is used [44], [45]. Fed4FIRE [38], TRESCIMO [39], INFINITY [40] and SoftFIRE [41] used semantic based approaches and mechanisms with semantically annotated graphs, which allows automatic reasoning, linking, querying and validation of heterogeneous data. These projects underlie on individual testbeds as well as federated testbeds environments and used approach of semantic-based management of federated infrastructures [46]. All these projects lead to propositions of new innovative solutions for important challenges of 5G networks, which will operate in a highly heterogeneous environment characterized by the existence of several types of access technologies, multilayer networks, variety of types of devices, and different types of user interactions.

Writing domain specific code for experiments execution on testbed infrastructures is a knowledge intensive process that requires programming as well as domain knowledge. SecGENE builds upon the SoftFIRE platform to assist experimentators by generating automatically software code for experiments from a high-level specification. SecGENE framework uses ontologies to formally represent the knowledge and access it in the process of code generation as needed, as shown in Fig. 5. The SecGENE ontology framework can be used for automatic experiment code generation. It should be noted that the approach is general in a sense that it could be used for different domains and experiments conducting over any testbed or federation of testbeds.

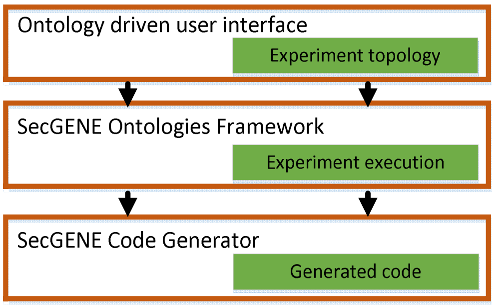

Figure 5. SecGENE Experimentation Framework

The required knowledge for automatic code generation is heterogeneous, including understanding of the radio-related features, knowledge about software and hardware modules available in the used testbeds, and practical knowledge of the domain specific language. In the context of SecGENE, the process starts with the semantic description of the experiment components using Ontology driven user interface. Based on the inputs and the available ontologies, and the needed application wrappers, the experiment source code is generated. The programmatically generated code may be additionally polished manually by the user, if needed. After that, the experiment is executed and the results are collected.

V. EXPERIMENTAL RESULTS

Some experimental results [30, 47] showing the influence of LTE on WiFi network are presented in this section.

Fig. 6 shows the acquired spectrum with and without WiFi activity.

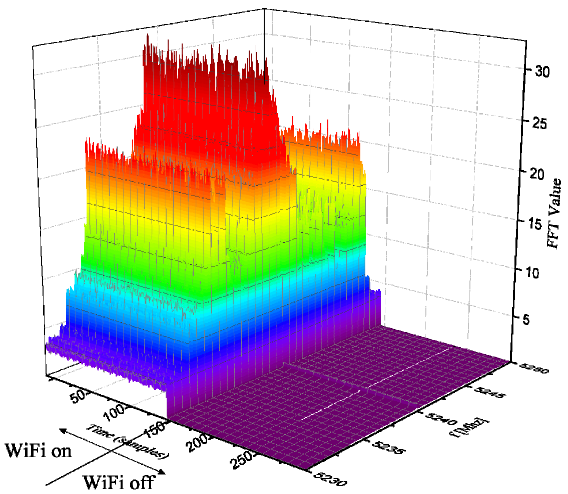

Figure 6. Acquired spectrum with and without WiFi

The WiFi is initially turned on, up to about sample 150. After that, from sample 150 to sample 300, the WiFi is turned off. As can be seen from Fig. 6, WiFi activity may be identified, because there is only noise from sample 150 to sample 300, and there is much higher spectrum power from samples 0 to 150.

Fig. 7 [47] depicts the comparison of the WiFi and LTE spectra. The first fact is that the LTE spectrum has a clearly visible carrier. This carrier may be easily detected in the FFT of the frequency band. On the other hand, the power spectrum density of the WiFi is almost evenly spread, without peaks over the entire channel. Therefore, these two activities may be distinguished during the signal processing.

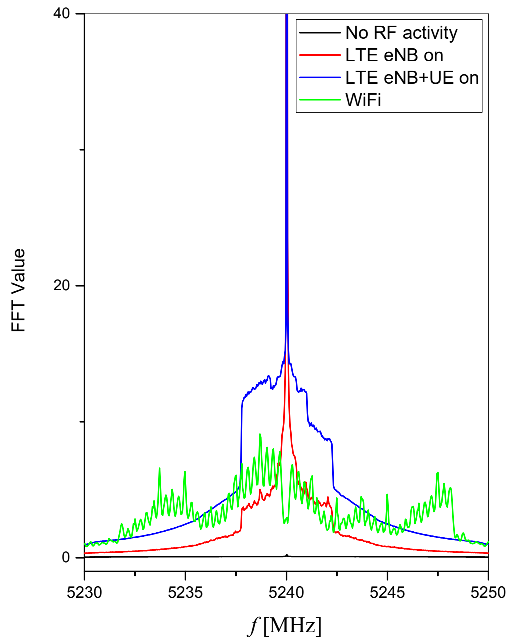

Figure 7. Sensed spectra averaged over time.

The influence of LTE on WiFi is shown in the following two figures. The LTE traffic is varied and its influence on the WiFi throughput is shown in Fig. 8 [30]. Four LTE traffic cases are considered: a) no LTE network present, b) only LTE eNB generating light load with control signals, c) 1 Mb/s, and 10 Mb/s of the downlink LTE traffic.

As already mentioned, the USRP B210 output power is around 10 dBm, so WiFi output power was chosen to be equal to USRP and 10 times lower. It may be noticed that the higher the LTE throughput, the lower the WiFi throughput is. This is the consequence of the WiFi built-in carriers sensing mechanism. Namely, WiFi is able to notice LTE transmission and postpone its own transmission. On the other hand, LTE does not use carrier sensing and it transmits continuously. Fig. 8 also demonstrates that WiFi transmit power has almost no influence on WiFi throughput, except in the case of light LTE traffic with only eNB (curve *b*). If there is no LTE activity, both WiFi powers are high enough to obtain maximum throughput. If there is 1 or 10 Mbps LTE traffic,, WiFi throughput depends mainly on the carrier sense and on the WiFi power. Finally, in the case of eNB-only activity, the high power WiFi throughput is better than the low power one, because stronger WiFi packets are more likely to reach the destination, even if they are hit by the LTE packets during the transmission.

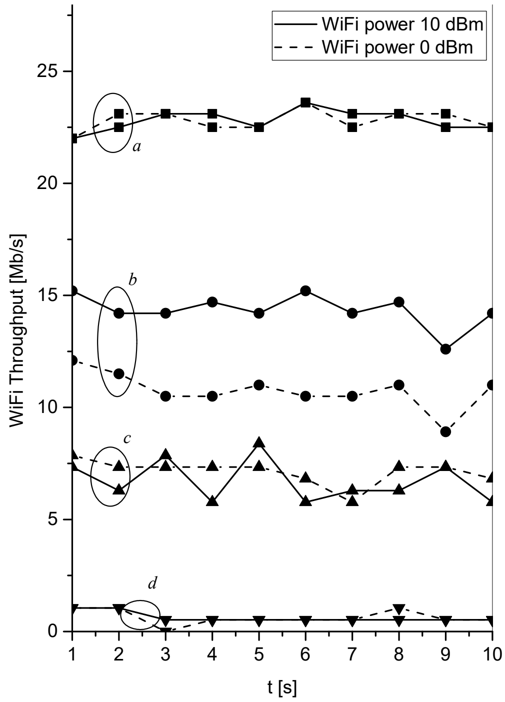

Figure 8. WiFi throughput over time for different LTE traffic intensity: a) No LTE, b) Only LTE eNB, c) 1 Mb/s d) 10 Mb/s

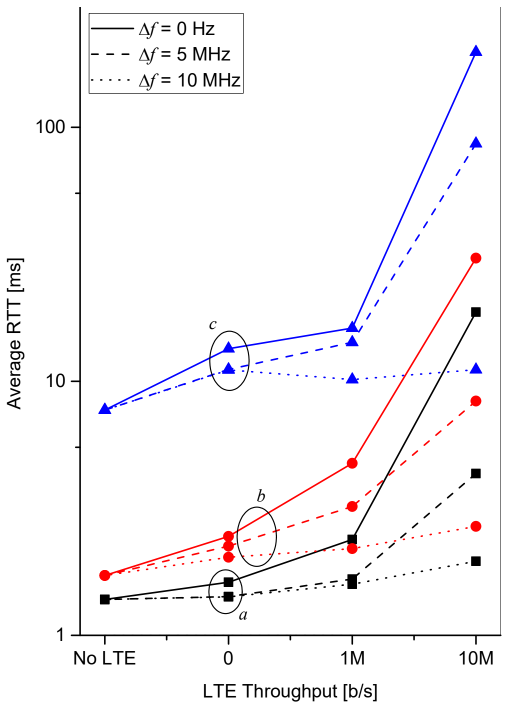

Figure 9. WiFi network average RTT as a function of LTE throughput, for different values of frequency offset between WiFi and LTE carrier frequency Δf, and WiFi packet size a) 100 bytes, b) 1000 bytes, c) 10000 bytes

The analysis of the influence of the carrier frequency offset between the WiFi channel central frequency (f_{WiFi}) and the LTE downlink frequency (f_{LTE}) Δf on the WiFi average RTT is depicted in Fig. 9 [30]. WiFi occupies 20 MHz of bandwidth around WiFi channel central frequency, and LTE occupies 5 MHz of bandwidth around f_{LTE}. Fig. 9 shows that the higher the frequency offset the lower is the influence of LTE on the WiFi network. It is interesting that the highest influence on the WiFi link RTT has the LTE carrier itself, not the whole LTE spectrum. It may be noticed that for 10 MHz offset, a half of the LTE spectrum (2.5 MHz) overlaps with the WiFi spectrum, and the LTE carrier frequency is on the edge, or practically out of WiFi channel. In this case, the LTE network has very little influence on the WiFi network.

VI. Conclusion

The mobile communication networks data transmission capabilities evolved from a few hundreds of bits per second in the first generation (1G), a few hundreds of kilobits per second in the second generation (2G), over a few tens of megabits per second in the third generation (3G), up to a gigabit per second of data throughput in the latest fourth generation (4G) of mobile networks. This is a huge increase in the data transmission capacity, but the needs for the data transfer also evolved from text-only transmission, over the images transmission, to the high-resolution video streaming with the throughput of ~50 Mbps per user. These demands will continue to grow next years and the mobile networks, in its current form, will hardly be able to fulfill all the demands. The problem mainly lies in the fact that the mobile communications licensed frequency bands are almost completely occupied and there is no room for the increase. A solution would be to use, in parallel with the licensed bands, some other frequency band. A good candidate for the bandwidth extension is one of the unlicensed bands, and 3GPP proposed 5 GHz unlicensed band currently used mainly by WiFi. Since there is no LTE 5 GHz hardware, it has to be emulated in the laboratories. Since the description of such an experiment may be complex, it is very important to have some automatic experiment code generation. In this way, the experimentation would be available to a greater number of experimenters and the experimentation process would be significantly shorter. The automatic code generation is based on the semantic descriptions of experiments on the testbeds. This approach is flexible due to the adoption of the domain and system ontologies for formal representation of the semantics of the problem.

This paper experimentally analyzed coexistence of WiFi and LTE in the same unlicensed 5 GHz frequency band. The results show that LTE have a significant negative influence on WiFi if their frequency bands overlap. Also, the higher LTE throughput, the worse is the WiFi performance. The influence weakens as the frequency offset between the LTE carrier frequency and WiFi channel central frequency increases.

Having in mind the presented results, it is clear that the shared access coordination is of highest importance for the WiFi-LTE coexistence.

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