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Wireless Networks Coexistence in Unlicensed Bands

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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 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 in 5 GHz frequency band will be shown in this paper. Since there is no available LTE hardware operating in 5 GHz band, it has to be made in a laboratory using the software radio approach. The description of such an experiment may be complex, and therefore we describe and propose the concept of the automatic experiment code generation. The automatic code generation is based on the semantic descriptions of experiments, and it is flexible due to the adoption of the domain and system ontologies for formal representation of the semantics of the problem.**

***Keywords - LTE; 5G; heterogenous newtworks; unlicensed band; coexistence; automatic code generation*.**

I. INTRODUCTION

In order to fulfill the increasing demands for data transmission, put by the fast-developing mobile communication networks, the offered capacity of the networks is in constant growth. In the first generation of cellular wireless systems, analog modulation schemes were used. These systems were primarily focused on voice transmission services.

With the advancement in technology, more processor power was available and the second generation (2G) mobile communication systems [1] were introduced. 2G systems used digital modulation, but were still voice oriented. Digital modulation enabled application of several technologies to increase the capacity and bring better user experience. One of them is Time Division Multiple Access (TDMA), where multiple users can utilize the same frequency channel in different time slots. Furthermore, more powerful coding techniques, 2003 better channel equalization techniques and spectrally efficient digital speech codecs were available. In terms of user experience quality, better voice quality was provided, but also new applications, like the Short Messaging Service (SMS), were offered. Another very important feature of 2G systems was the support for low data rate mobile data applications. At first, it was circuit switched data transfer at 9600 bps. Packet data transmission was introduced later. The limitations of 2G mobile data services were numerous: low data rate, only certain type of information available, low processing power, memory and display capacity of 2G mobile devices. Thus, in order to make the Internet content available to mobile devices, some specialized technologies, like the Wireless Access Protocol (WAP), appeared.

The GSM Packet Radio Systems (GPRS), often referred to as 2.5G, was first introduced by mid-1990s and in 2000 opened as a packet-switched data service embedded to the channel-switched cellular radio network GSM. GPRS connected mobile terminals worldwide and in this way extended the availability of the fixed Internet. GPRS and GSM systems had the same frequency bands, time slots, and signaling links. Using different channel coding, GPRS could support different data throughputs per slot (up to 20 kbps). Since there are eight slots in TDMA frame, the maximum theoretical data rate was 160 kbps. However, the obtained practical data rates were up to 80 kbps, because the number of the allocated time slots was on average up to four. The next improvement of the GSM standard mobile data transfer speed came with the Enhanced

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Data Rate for GSM Evolution standard (EDGE), referred to as 2.75G. EDGE was introduced in 1997 and first implemented on a GSM network at the beginning of 2003. By supporting 8PSK modulation, EDGE increased 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 huge step in the evolution of mobile communication systems was the introduction of the third generation (3G) systems. 3G systems offered much higher data rates and voice capacity, as well as advanced services and applications, including multimedia. More powerful mobile devices were also part of this improvement. Universal Mobile Telephone Service (UMTS) was first introduced as the 3G system based on the evolution of GSM. It includes a core network (CN) that provides switching, routing, and subscriber management; the UMTS Terrestrial Radio Access Network (UTRAN); and the User Equipment (UE). UMTS retained the basic architecture of the GSM/GPRS architecture, thus stayed compatible with previous mobile systems, with each element enhanced for 3G capabilities. On the other hand, the 3G radio interface called Wide-band CDMA (W-CDMA) was totally different 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, scrambling and bit rate of 4.096 Mbps. The operating bandwidth is broadened to 5 MHz and peak data rates from 384 to 2 Mbps are provided. Also, the system implements the power control. The 3rd Generation Partnership Project (3GPP) brought the High-Speed Packet Access (HSPA), which consists of two significant enhancements 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 with up to 14.4 Mbps peak theoretical throughput, using QPSK and 16QAM modulations. HSUPA was supporting up to 5.8 Mbps peak uplink throughput, employing dual BPSK modulation. In 2007 the 3GPP Release 7 was published, containing further evolution of HSPA. Release 7 [4] HSPA (HSPA+) contained large number of additional features. The downlink speed was increased by employing 64QAM modulation scheme and on the uplink, support for 16QAM is provided. In this way, maximum downlink and uplink data rates of 21.1 Mbps and 11.5 Mbps were achieved, respectively. Furthermore, MIMO (multiple input multiple output) transmission with up to two transmit antennas in the base station and two receive antennas in the mobile unit was introduced. This increased the peak downlink theoretical rate to 28 Mbps. While the simultaneous use of 64QAM and MIMO was not allowed in Release 7, this combination was introduced in 3GPP Release 8, which provided the maximum downlink data rate of 42 Mbps. Of course, the practically achieved rates almost never approach the maximum theoretical ones.

As the demand for higher data speeds for mobile users continued to grow, 3GPP became an ever-evolving standard that fulfills those demands. Long Term Evolution (LTE), or 4G, is the next step towards higher data speeds, but staying compatible with 2G/3G. LTE was first defined in 3GPP Release 8 [5]. It theoretically provides data speeds greater than 1000 Mbps on the Downlink and 500 Mbps on the Uplink by using wide bandwidths, Orthogonal Frequency Division Multiplexing (OFDM) and MIMO antenna schemes. As for 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 all makes 4G/LTE very attractive to be applied for better spectrum utilization.

Today, almost complete mobile data transfer is done over the licensed spectrum. Considering predictions of 12 times cellular data traffic growth in years ahead, Fig. 1 [6], it is reasonable to assume that it will be very hard for the licensed band communications to fulfill such a high bandwidth demand. Possible solution to this would be to use the unlicensed bands as the bandwidth extension out of the dedicated licensed band.

In order to meet the requirements of 4G mobile networks, LTE was upgraded to LTE–Advanced (LTE-A) in 3GPP Release 10 [7]. The main improvement of the LTE-A is the possibility of simultaneous use of multiple frequency bands by the means of the Carrier Aggregation (CA) technology. In this way the unlicensed spectrum can be used by the LTE devices.

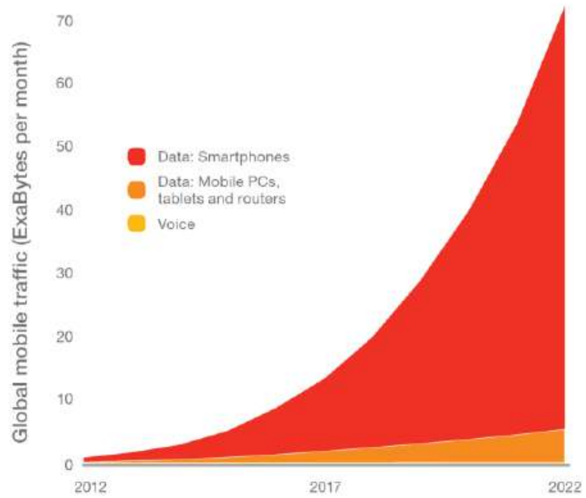

Figure 1. Mobile data growth.

The use of the unlicensed band by different communication systems must be still performed in accordance to some regulations, such as Dynamic Frequency Selection (DFS) and listen-before-talking (LBT). Thereby, different technologies, such as carrier sense multiple access or spectrum sensing [8], may be used. These coordination mechanisms, that are variants of dynamic spectrum access (DSA), are necessary, so that efficient co-existence between different systems in unlicensed spectrum can be maintained. Since IEEE 802.11ac WiFi networks operate in 5GHz band, the coordination between the LTE and WiFi is very important. However, unlike WiFi, the LTE does not have shared access mechanisms, since the LTE is designed to operate in a dedicated, licensed band. In [9, 10] simulation and theoretical results on the co-existence of LTE and WiFi networks can be found, respectively. It is shown that some sort of coordination between these two networks is necessary. In [11] experimental results for the 2.4 GHz band WiFi communication influenced by LTE are shown, where the

LTE is represented only by the base station, without any mobile stations.

WiFi and LTE networks co-existence can be realized in two ways. In the first one, a modification of the LTE standard is performed. LTE-U (LTE-Unlicensed) was proposed by LTE-U forum [12] and it uses LTE with a duty cycle. In this way, pauses in transmission are made and WiFi can transmit its data during the silent periods of the LTE-U. Moreover, LTE-U access point tries to predict the WiFi usage patterns and to adapt to them. Licensed Assisted Access (LAA) includes several coexistence mechanisms: mechanism for channel sensing based on listen-before-talk (LBT), discontinuous transmission (DTX) on a carrier with limited maximum transmission duration, and dynamic frequency selection (DFS). The DTX and LBT have the most important influence on downlink physical channel design, channel state information (CSI) estimation and reporting, hybrid automatic repeat request (HARQ) operation and radio resource management (RRM). LTE-LAA is a part of the 3GPP LTE Release-13 standard (Downlink) [13, 14] and Release-14 (Uplink) [15]. In [16] standardization progress and the survey of the LAA can be found. Preliminary LAA designs and coexistence evaluations are presented in [17, 18]. In [19] Markov-chain-based analysis of LTE-WiFi coexistence with simplified LBT and no random backoff is given. Also, an operator level system performance is analyzed for several scenarios. It is shown that LTE capacity can be significantly increased when LAA and LBT are applied. In [20] the influence of clear channel assessment threshold of the LAA on the performance of both LTE and WiFi networks is considered and the design process of LBT for the LAA system is described. The proposed LBT algorithm is proven to be able to improve LAA and to keep low interference to WiFi.

The second approach is to introduce a coordinated access to the shared channel. There are two general approaches to spectrum coordination as follows [21]: reactive spectrum coordination and proactive spectrum coordination. The most straightforward reactive spectrum coordination concept is so called agile wideband radio scheme [22]. 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 [23]. 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 changes 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 [24]. 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 [24, 25] 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 [26] 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 field of mobile and wireless communications 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 [27] at the Rutgers University, USA; NITOS [28] at the University of Tessaly, Greece; 5GIC [29] at the University of Surrey, England; or FUSECO Playground [30] at the Technical University of Berlin, Germany. During the experiment, the resources are reserved online, the experimenter 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) [31] 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 interest 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 (902 – 928) MHz, 2.4 (2.4 – 2.5) GHz, and 5.8 (5.725 – 5.875) 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 minimizing 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 [32]. 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) [33]. 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 [32].

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 (Fig. 2), divided in more than twenty 20 MHz channels. The transmitter power in the frequency bands 5.150 – 5.350 GHz and 5.470 – 5.875 Ghz is limited to 200 mW and 1 W, respectively, in all countries. However, the usage of 5.725 – 5.875 GHz band in Europe and Japan is still under consideration, whilst China does not allow the usage of 5.470 – 5.725 GHz band.

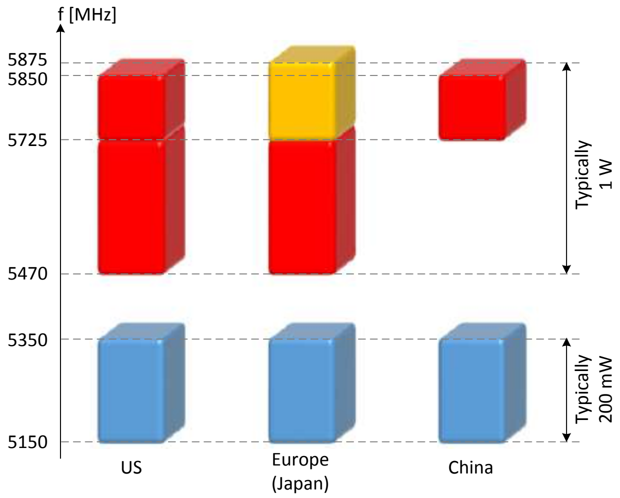

Figure 2. An overview of 5 GHz unlicensed band.

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.

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 maintained. 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.

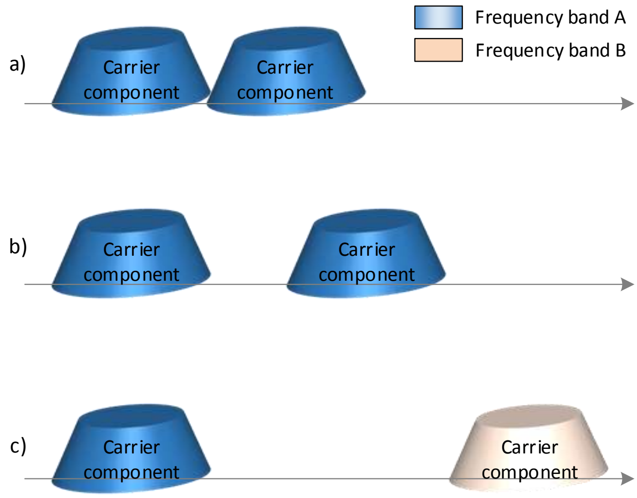

Figure 3. Types of carrier aggregation a) Intra-band contiguous, b) Intra-band non-contiguous, c) Inter-band non-contiguous

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 [34]. 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) [35] 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 [36], and Universal Software Radio Peripheral (USRP) X- and B- series [37]. In the experiments, USRP B210 was used.

Fig. 4 [34] 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 [38] application. The same application is used for the throughput measurement. The OAI LTE eNB is at node 59, and UE is at node 60.

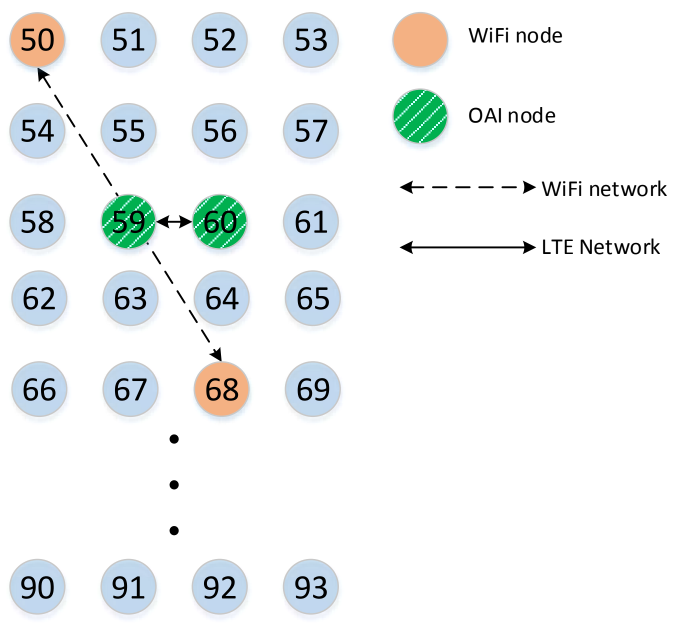

Figure 4. The experiment setup topology.

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 are 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

Since the federations of heterogeneous networks are based on coordination of available resources and intelligent retrieval of available computing and networking resources, ontologies can be recognized as possible solution for enabling such network features. Ontologies can be adopted as knowledge background for information model of resources and services, advanced manipulations, for example deduction of service and infrastructure behaviors become possible. Services provisioning and resources availability can be intelligently deduced in the case of using ontologies [39]. Evidence of high potential of using ontologies in networking can be reflected on different EU FP7 and Horizon 2020 founded projects: NOVI [40], FIRE LTE Testbeds for Open Experimentation (FLEX) [41], Federation for future internet research and experimentation (Fed4FIRE) [42], Testbeds for Reliable Smart City Machine to Machine Communication (TRESCIMO) [43], INfrastructures for the Future INternetCommunITY (INFINITY) [44], Software Defined Networks and Network Function Virtualization Testbed within FIRE+ (SoftFIRE) [45] etc.

In order to formalize information model and to develop the data models that enable the communication among system components, ontologies are used in NOVI project. Resources are described by the information model at a conceptual level, while the data model describes implementation details based on representation of concepts and their relations provided by the information model. Ontologies are used with assumption that semantic technologies could be used to improve coordination in cognitive radio networks within FLEX project, with its CoordSS subproject [46]. The spectrum sensing and coordination in 5G heterogeneous networks is represented as an interactive process consisting of communication between distributed agents and information sharing about a specific spectrum usage effectiveness [47]. Ontologies are used to represent the knowledge with the standardized way for representation [48, 49]. The following four projects Fed4FIRE, TRESCIMO, INFINITY and SoftFIRE used semantic based approaches and mechanisms with semantically annotated graphs allowing automatic reasoning, linking, querying and validation of heterogeneous data. All these four projects underlie on federated testbeds environments and used semantic-based management of federated infrastructures [50]. These projects would give new innovative solutions for 5G networks challenges, which will support a highly heterogeneous environment. The main characteristics of such environment are the existence of several types of access technologies, multilayer networks, variety of types of devices, and different types of user interactions.

In order to write domain specific code for experiments execution on testbed infrastructures, it is necessary programming and domain knowledge. SecGENE builds upon the testbed platform to assist experimenters by generating automatically software code for experiments from a high-level specification. Ontologies are used for formal knowledge representation. In the process of code generation that knowledge is used as needed. This approach of automatic code generation is general in a sense that it could be used for different domains and experiments conducting over any testbed. The knowledge in the process of automatic code generation is heterogeneous, including in our case ratio-related features understanding, knowledge about software and hardware modules of used testbed, and practical knowledge of the domain.

Fig. 5 depicts SecGENE experimentation framework, where semantic description of the experiment components represents the first step in the process of the automatic code generation. Experiment design starts by defining experiment topology using semantic descriptions, which defining are provided by Ontology driven user interface. Each testbed platform has variety of tools and services that provides to experimenter. For example, some testbeds provide JFed tool for experiment topology defining and resources provisioning. In such JFed supported environment, RSpec file describes topology, which is further processed by another tool FitEagle which converts it to the semantic description. SecGENE platform can be used to import semantic description of the experiment topology into the existing domain knowledge, since it offers experiment flow editor. The editor provides intuitive GUI that gives navigation through the process of creating experiment flow. In order to support semantic describing of the experiment topology semantic knowledge of the networking domain is captured using ontologies. Editor contains experiment components that user can use to construct experiment by performing simple drag/drop and connect actions on these components. Each component describes experiment flow task on the high level of conceptualization.

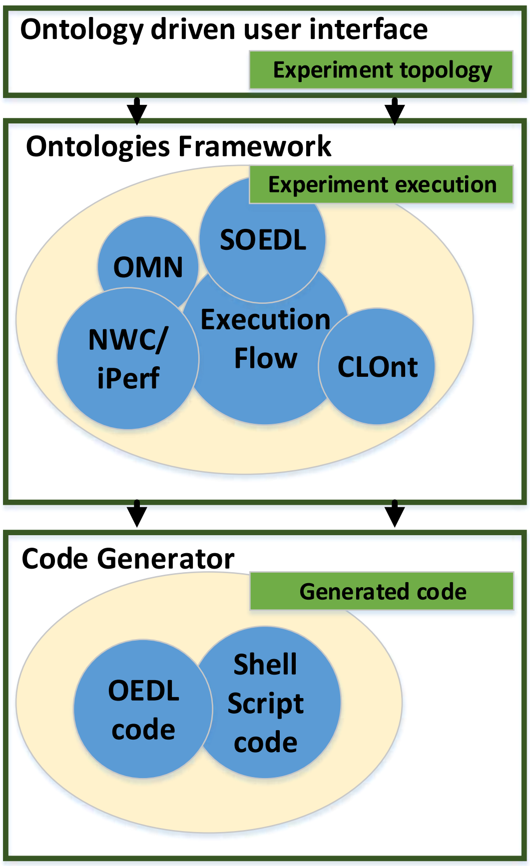

Figure 5. SecGENE Experimentation Framework.

As shown in Fig. 5, SecGENE includes a set of the domain and system ontologies. They are used for semantic descriptions of the SecGene client, network sensing, and experiment execution flow. Some ontologies are adopted, such as OMN, CLOnt and SOEDL ontologies. OMN ontology is used for defining experiment topology. Some ontologies are developed inside SecGENE in order to extend knowledge, such as Network Sensing and Network Capability ontologies. Software tool *iperf* in the environment is used for implementation of network sensing and to measure network parameters. Thus, Network Sensing ontology extends existing knowledge by defining *iperf* as networking component and defines its parameters and command line arguments needed for execution. Network Capability ontology provides semantic relationships between *iperf* component and throughput measurement, definitions of concepts of *iperf* parameters, component and experiment execution. This ontology is complemented with Command Line ontology (CLOnt) and Semantic OEDL ontology (SOEDL). CLOnt is reused from the CoordSS ontologies framework [46]. Execution experiment flow provides semantic definitions for sequencing of execution steps in an experiment flow.

Based on the experimenter inputs and the ontologies, the experiment source code is generated. In our case OEDL and Shell Script is generated. The format of code is based on testbed, and any type of code can be generated. The programmatically generated code may be additionally polished manually by the user, if needed. After code generation, the experiment could be executed.

V. EXPERIMENTAL RESULTS

Some experimental results [34, 51] showing the influence of LTE on WiFi network are presented in this section, while other results are already presented in [52].

Figs. 6 and 7 show the visualized spectrum for two cases: 1) eNB is turned on and UE is off, where eNB transmits only control packets, and 2) UE is attached to eNB and some downlink traffic is generated between them [51].

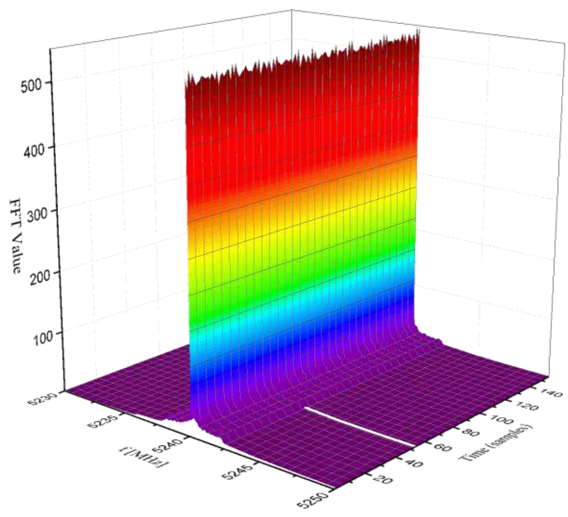

Figure 6. Sensed spectrum with eNB only.

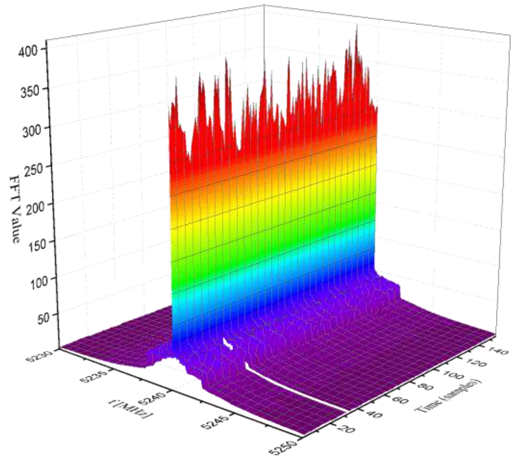

Figure 7. Sensed spectrum with eNB + UE.

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 [34]. 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.

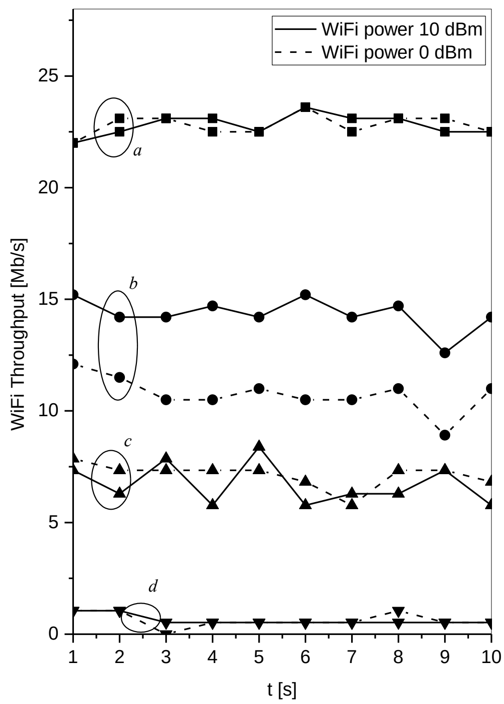

Figure 8. WiFi throughput over time for different LTE traffic intensity: a) No LTE, b) Only LTE eNB, c) 1 Mb/s d) 10 Mb/s.

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.

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 [34]. 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.

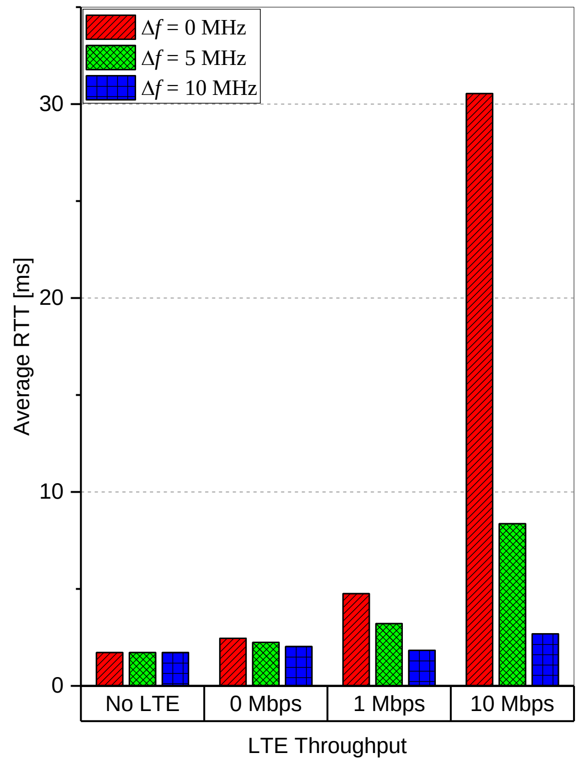

Figure 9. WiFi network average RTT as a function of LTE throughput, for different values of frequency offset between WiFi and LTE carrier frequency Δf, and WiFi packet size of 1000 bytes.

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, as shown in Fig. 10. In this case, the LTE network has very little influence on the WiFi network.

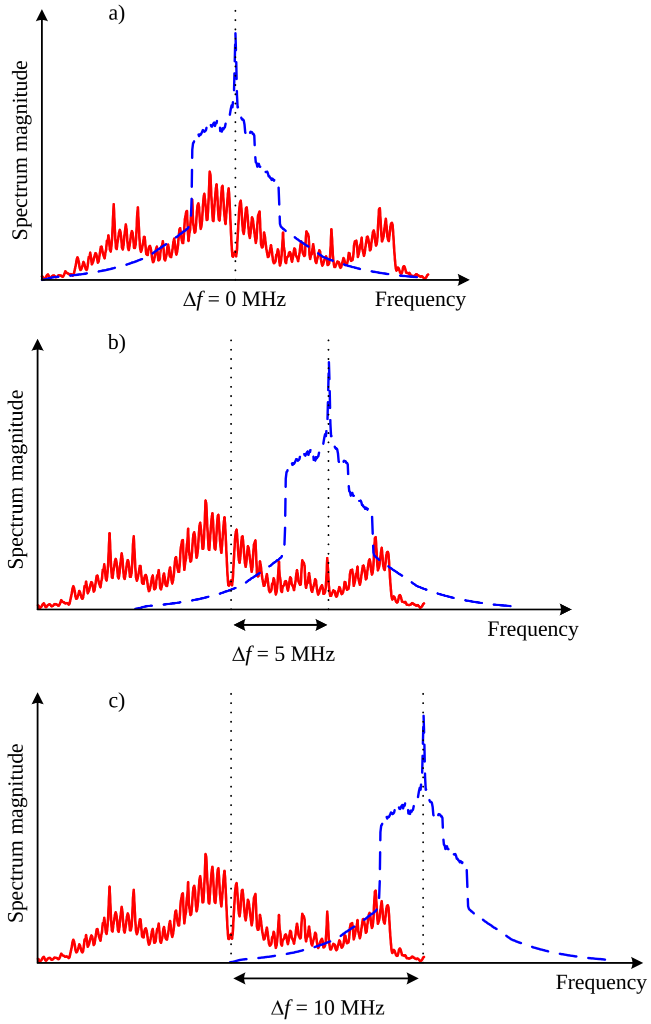

Figure 10. Mutual position of the WiFi (solid line) and LTE (dashed line) spectra for different carrier frequency offset a) 0 MHz, b) 5 MHz, c) 10 MHz.

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 has 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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REFERENCES

[1] A. Ghosh, J. Zhang, J. G. Andrews, and R. Muhamed, Fundamentals of LTE, 1st ed. Upper Saddle River, NJ, USA: Prentice Hall Press, 2010.
[2] 3GPP, "Release 5," 2000.
[3] 3GPP, "Release 6," 2000.
[4] 3GPP, "Release 7," 2003.
[5] 3GPP, "Release 8," 2006.
[6] Ericcson, "Ericsson Mobility Report 2017," 2017.
[7] 3GPP, "Release 10," 2009.
[8] R. Deka, S. Chakraborty, and R. Jibendu Sekhar, "Optimization of spectrum sensing in cognitive radio using genetic algorithm," Facta Univ. - Ser. Electron. Energ., vol. 25, no. 3, pp. 235–243, 2012.
[9] J. Jeon, H. Niu, Q. C. Li, A. Papathanassiou, and G. Wu, "LTE in the unlicensed spectrum: Evaluating coexistence mechanisms," in 2014 IEEE Globecom Workshops, GC Wkshps 2014, 2014, pp. 740–745.
[10] A. Babaei, J. Andreoli-Fang, Y. Pang, and B. Hamzeh, "On the Impact of LTE-U on Wi-Fi Performance," Int. J. Wirel. Inf. Networks, vol. 22, no. 4, pp. 336–344, 2015.
[11] S. Sagari, S. Baysting, D. Saha, I. Seskar, W. Trappe, and Di. Raychaudhuri, "Coordinated dynamic spectrum management of LTE-U and Wi-Fi networks," 2015 IEEE International Symposium on Dynamic Spectrum Access Networks, DySPAN 2015, 2015, pp. 209–220.
[12] "LTE-U Forum." [Online]. Available: http://www.lteuforum.org. [Accessed: 10-Oct-2017].
[13] 3GPP, "Release 13," 2012.
[14] 3GPP, "New Work Item on Licensed-Assisted Access to Unlicensed Spectrum," 2015.
[15] 3GPP, "Release 14," 2014.
[16] R. Ratasuk, N. Mangalvedhe, and A. Ghosh, "LTE in unlicensed spectrum using licensed-assisted access," 2014 IEEE Globecom Workshops, GC Wkshps 2014, 2014, pp. 746–751.
[17] A. Mukherjee et al., "System architecture and coexistence evaluation of licensed-assisted access LTE with IEEE 802.11," 2015 IEEE International Conference on Communication Workshop (ICCW), 2015, pp. 2350–2355.
[18] J. Jeon, H. Niu, Q. Li, A. Papathanassiou, and G. Wu, "LTE with listen-

before-talk in unlicensed spectrum," 2015 IEEE International Conference on Communication Workshop, ICCW 2015, 2015, pp. 2320–2324.

[19] C. Chen, R. Ratasuk, and A. Ghosh, "Downlink performance analysis of LTE and WiFi coexistence in unlicensed bands with a simple listen-before-talk scheme," IEEE Vehicular Technology Conference, 2015, vol. 2015.

[20] Y. Li, J. Zheng, and Q. Li, "Enhanced listen-before-talk scheme for frequency reuse of licensed-assisted access using LTE," IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC, 2015, vol. 2015–Decem, pp. 1918–1923.

[21] D. Raychaudhuri, X. Jing, I. Seskar, K. Le, and J. B. Evans, "Cognitive radio technology: From distributed spectrum coordination to adaptive network collaboration," Pervasive and Mobile Computing, vol. 4, no. 3. pp. 278–302, 2008.

[22] K. Challapali, S. Mangold, and Z. Zhong, "Spectrum agile radio: Detecting spectrum opportunities," Proc. Intern. Symp. Advanced Radio Technologies., Boulder, CO, USA, 2004, pp. 61–65.

[23] X. Jing, S. C. Mau, D. Raychaudhuri, and R. Matyas, "Reactive cognitive radio algorithms for Co-existence between IEEE 802.11b and 802.16a networks," GLOBECOM - IEEE Global Telecommunications Conference, 2005, vol. 5, pp. 2465–2469.

[24] D. Raychaudhuri and X. Jing, "A spectrum etiquette protocol for efficient coordination of radio devices in unlicensed bands," IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC, 2003, vol. 1, pp. 172–176.

[25] X. Jing and D. Raychaudhuri, "Spectrum Co-existence of IEEE 802.11b and 802.16a Networks Using Reactive and Proactive Etiquette Policies," Mob. Networks Appl., vol. 11, no. 4, pp. 539–554, 2006.

[26] M. Tosic et al., "Semantic coordination protocol for LTE and Wi-Fi coexistence," 2016 European Conference on Networks and Communications (EuCNC), 2016, pp. 69–73.

[27] "OrbitLab." [Online]. Available: http://www.orbit-lab.org. [Accessed: 10-Oct-2017].

[28] NITOS, "NITlab." [Online]. Available: http://nitos.inf.uth.gr. [Accessed: 10-Oct-2017].

[29] University of Surrey, "5G Innovation Centre." [Online]. Available: http://www.surrey.ac.uk/5gic. [Accessed: 10-Oct-2017].

[30] Fraunhofer Institute, "FUSECO Playground." [Online]. Available: https://www.fokus.fraunhofer.de/go/de/fokus_testbeds/fuseco_playground. [Accessed: 10-Oct-2017].

[31] "SEmantics driven Code GENEration for 5G networking experimentation (SecGENE)." [Online]. Available: http://infosys1.elfak.ni.ac.rs/secgene. [Accessed: 10-Oct-2017].

[32] Qualcomm Research, "White paper: LTE in Unlicensed Spectrum: Harmonious Coexistence with Wi-Fi," 2014.

[33] Qualcomm Research, "White paper: Extending the benefits of LTE Advanced to unlicensed spectrum," 2014.

[34] N. Milosevic, B. Dimitrijevic, D. Drajic, Z. Nikolic, and M. Tosic, "LTE and WiFi co-existence in 5 GHz unlicensed band," Facta Univ. - Ser. Electron. Energ., vol. 30, no. 3, pp. 363–373, 2017.

[35] OpenAirInterface Software Alliance, "OpenAirInterface," 2015. [Online]. Available: http://www.openairinterface.org. [Accessed: 10-Oct-2017].

[36] TELMAT Industrie, "EURECOM - ExpressMIMO2." [Online]. Available: http://www.expressmimo2.com/. [Accessed: 10-Oct-2017].

[37] ETTUS, "USRP X- and B- Series." [Online]. Available: https://www.ettus.com.

[38] "iPerf." [Online]. Available: https://iperf.fr. [Accessed: 10-Oct-2017].

[39] W. Adianto, C. de Laat, and P. Grosso, "Future Internet Ontologies: The NOVI Experience," Semant. Web J., 2009.

[40] "Network Innovation over Virtualized Infrastructures (NOVI)." [Online]. Available: http://www.fp7-novi.eu. [Accessed: 10-Oct-2017].

[41] "FIRE LTE testbeds for open Experimentation (FLEX)." [Online]. Available: http://www.flex-project.eu. [Accessed: 10-Oct-2017].

[42] "Federation for Future Internet Research and Experimentation, (Fed4FIRE)." [Online]. Available: https://www.fed4fire.eu. [Accessed: 10-Oct-2017].

[43] "Testbeds for Reliable Smart City Machine to Machine Communication (TRESCIMO)." [Online]. Available: https://trescimo.eu. [Accessed: 10-Oct-2017].

[44] "Infrastructures for Future Internet Community (INFINITY)." [Online]. Available: http://www.fi-infinity.eu. [Accessed: 10-Oct-2017].

[45] "Software Defined Networks and Network Function Virtualization Testbed within FIRE+ (SoftFIRE)." [Online]. Available: https://www.softfire.eu. [Accessed: 10-Oct-2017].

[46] "Coordination by Spectrum Sensing for LTE-U (CoordSS)." [Online]. Available: http://infosys1.elfak.ni.ac.rs/coordss. [Accessed: 10-Oct-2017].

[47] M. Tosic, Z. Nikolic, V. Nejkovic, B. Dimitrijevic, and N. Milosevic, "Spectrum Sensing Coordination for FIRE LTE Testbeds," Proceedings of the 2nd International Conference on Electrical, Electronic and Computing Engineering, 2015.

[48] D. McGuinness and F. van Harmelen, "OWL Web Ontology Language Overview."

[49] G. Klyne and J. J. Carroll, "Resource Description Framework (RDF): Concepts and Abstract Syntax," W3C Recomm., vol. 10, no. October, pp. 1--20, 2004.

[50] A. Willner and D. Nehls, "Semantic-based management of federated infrastructures for future internet experimentation," Technische Universität Berlin, 2016.

[51] N. Milosevic, Z. Nikolic, F. Jelenkovic, V. Nejkovic, and M. Tosic, "Spectrum sensing experimentation for LTE and WiFi unlicensed band operation," Telfor J., vol. 8, no. 2, pp. 76–80, 2016.

[52] Z. Nikolic, M. Tosic, N. Milosevic, V. Nejkovic, and F. Jelenkovic, "Mobile Heterogeneous Telecommunications Networks Coexistence in Unlicensed Bands," XVI International Symposium INFOTEH-JAHORINA 2017, 2017, pp. 151–158.

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