Semantic Coordination Protocol for LTE and Wi-Fi Coexistence

Milorad Tosic, Valentina Nejkovic, Filip Jelenkovic,
Nenad Milosevic, Zorica Nikolic
Faculty of Electronic Engineering
University of Nis, Serbia
{milorad.tosic,valentina,filip.jelenkovic,nenad.milosevic,zorica.nikolic}@elfak.ni.ac.rs

Nikos Makris, Thanasis Korakis
Dept. of ECE, University of Thessaly, Volos, Greece
Informatics and Telematics Institute, CERTH, Greece
{nimakris, korakis}@uth.gr

Abstract — **In this paper, we address the challenges in facilitating the intra-band coexistence of WiFi and LTE technologies in multi-RAT networks and propose a semantic coordination protocol that improves the communication performance among inter-network devices. Effective communication in LTE networks is a critical task to achieve as the heterogeneity of the devices and coexisting technologies arises. This paper introduces an internetwork spectrum coordination across Wi-Fi and LTE systems based on an ontological framework as a possible solution for improved coexistence. We develop and evaluate our approach under real-world settings. The results we obtained using the proposed semantic coordination protocol have shown significant gains for both the under-study Wi-Fi and LTE networks.**

Keywords* — *coordination protocol; Wi-Fi; LTE-U; heterogeneous networks; testbed; semantics

I. INTRODUCTION

Nowadays, wireless industry is facing the 5G mobile networks demands and challenges. The main requirements of 5G networks concern improving the quality of experience and demand for higher data rates caused by the exponential growth of mobile data usage [1]. Wireless industry recognizes *Long-Term Evolution in unlicensed spectrum* (LTE-U) as a promising wireless network technology and as the potential answer to the complex 5G demands based on reusing part of the unlicensed spectrum and coexisting with contemporary Wi-Fi devices. LTE-U offers better efficiency and robust mobility in comparison with other previously used technologies, constituents of 4G networks, such as Wi-Fi, LTE, LTE-A, etc [2].

Unlicensed bands may be freely used by communication systems, with the restriction of using coordination mechanisms for *dynamic spectrum access* (DSA). These coordination mechanisms are essential for achieving efficient coexistence between different systems that are operating in unlicensed spectrum. Detection of free and occupied portions of the considered spectrum, widely known as the *Spectrum Sensing* (SS), is of paramount importance for the frequency selection in any DSA system. By sensing and adapting to the environment, a DSA *user equipment* (UE) is able to fill in spectrum holes without causing harmful interference to other UEs operating in the same spectrum. The problem arises when LTE-U coverage overlaps with other technologies currently operating in unlicensed bands, for example Wi-Fi [8]. Upon the unlicensed spectrum usage, LTE-U network observes the spectrum, selects the channel with the least interference, and dynamically adjusts the operating frequency. Subsequently, a channel that was previously used by a Wi-Fi network can be fully occupied by LTE-U transmissions. In the case where the same channels have to be used, the interference level shall be minimized. In this paper, we derive a novel inter-network coordination protocol that facilitates dynamic spectrum coordination in the multi-RAT networks for efficient spectrum utilization. Such a coordination protocol ensures the coexistence between heterogeneous LTE-U and Wi-Fi technologies. Further, we present some scenarios on using such dynamic spectrum coordination between WiFi and LTE devices.

The novelty of the coordination protocol presented in this paper lays in the adoption of ontologies for knowledge representation that are organized by our Coordination by Spectrum Sensing for LTE-U (CoordSS) ontology framework [14]. We modeled the coordination and spectrum sensing as an interactive process, where system nodes communicate and share knowledge about relevant spectrum conditions. Coordination of WiFi and LTE interference is centralized on a CoordSS Coordination Server (CCS). Semantic channels are established within the system for the interaction between participating communication devices that exploit heterogeneous technologies. We model the interference between LTE and WiFi by using the CoordSS ontology framework and CCS through a testbed-driven experimental evaluation by employing the NITOS testbed [15] and study the viability of the overall approach.

The rest of the paper is organized as follows. Section II provides the background in spectrum sensing, coordination protocols and coexistence of LTE and WiFi particularly in the context of semantic technologies. Section III presents the CoordSS system model and our proposed coordination algorithm. The experiment design is specified in Section V, and the concluding remarks are given in VI.

II. BACKGROUND

A. Spectrum sensing and coordination protocols

The agile wideband radio scheme [4] is one of the most frequently used shared spectrum access concepts. Within this scheme, each node analyses the spectrum availability and adjusts its frequency band and modulation scheme so that the highest allowed interference level is not exceeded. There is no coordination of the chosen parameters between the neighboring nodes, which makes the implementation of this scheme very simple. However, the framework does not take into consideration the so-called hidden nodes, meaning the nodes that are not visible to the station but with which it can interfere.

A more powerful and more complex shared spectrum access concept is the coordinated spectrum access. In this case, each node's radio parameters are coordinated with other nodes. In general, spectrum coordination algorithms may be categorized as reactive spectrum coordination or proactive spectrum coordination.

In reactive spectrum coordination [5], nodes change their parameters, such as the transmission power, rate, or frequency band according to the fluctuations of the wireless environment. The goal is that the transmission quality stays optimal and the criterion of the minimal interference level is fulfilled. This scheme has low hardware and software demands, but its application is constrained to some simple scenarios only. There are three different reactive spectrum coordination mechanisms: Dynamic Frequency Selection (DFS), Reactive Transmit Power Control (RTPC), and Time Agility (TA). The reactive schemes also suffer from the hidden terminal problem.

For the cases of more complex wireless environments, the proactive spectrum coordination schemes might be the more suitable solution. One example of this case is the spectrum etiquette protocol [6], where a distributed coordination between the radio nodes is enabled in order to establish the optimal transmission quality. This is performed by using different radio access technologies (RATs) by the means of either internet services or a separate coordination radio channel.

One form of this approach is the Common Spectrum Coordination Channel (CSCC) [7]. In the CSCC approach, spectrum usage information is periodically exchanged between the stations via a common control channel for spectrum coordination by using a simple protocol. This allows stations to choose the available unoccupied frequencies, not only based on the transmitted power or frequency band information, but on some more complex parameters, such as the type of service or user priority.

B. LTE and WiFi coexistence in unlicensed band

Wi-Fi and LTE will be among the dominant technologies used for radio access purposes over the next few years [1]. Wi-Fi and LTE are different RATs designed for specific purposes at different frequencies. They are required to coexist in the same frequency, time and space, which causes increased interference to each other and an overall system degradation because of a lack of inter-technology compatibility.

Regarding the LTE-U operation, several challenges have to be tackled for the efficient coexistence of LTE and Wi-Fi technologies. The key differences among the two technologies lie in the medium access method; WiFi uses CSMA/CA, a "listen before talk" method in order to access the medium. In case of an unsuccessful transmission, the Wi-Fi device executes an exponential backoff algorithm before accessing the medium again. Contrary to that, and since LTE is designed for use under a licensed band environment, LTE is using OFDMA (Orthogonal Frequency Division Multiple Access). The coexistence of the two different technologies within the same band, can seriously affect the performance of WiFi. Therefore, efficient spectrum management and power control should be employed for accommodating both of these technologies within the same band.

Similar research on the under study field of heterogeneous networks is focusing on spectrum management in shared frequency bands. The research community recently focuses on the coordinated coexistence between Wi-Fi and LTE technologies and has made some initial steps in extending approaches and protocols for spectrum management issues under the assumption of such coexistence. Coexistence is studied from different aspects, such as in-device coexistence [9], slotted channel access [10], study in interference aware power control in LTE [11], etc.. These solutions are based on improving Wi-Fi transmissions, but eventually lead to LTE performance decrease. In [1], authors propose a dynamic spectrum coordination framework, which is enabled by a Software Defined Network (SDN) architecture. SDN can accommodate different radio standards and does not require changes to the existing standards or protocols. This solution is useful for the rapid development of upcoming technologies. Through the presented solution, Wi-Fi/LTE coordination algorithms are based on optimizations in the power and the frequency domain, and do not require any modifications in the existing physical layers of Wi-Fi and LTE, contrary to other proposed solutions, such as [13].

C. Semantic technologies and spectrum sensing

The spectrum mapping as well as the spectrum usage coordination can be modeled as an interactive process between a number of distributed communicating agents that share specific information with a common goal of a high spectrum usage effectiveness. The system architecture is of a distributed, loosely coupled nature, whereas the information communicated within the system is highly heterogeneous. The information may include, but is not limited to, the current spectrum usage state, spatial coordinates of the device, spectrum sensing capabilities of the device, communication protocols available, usage policy, spectrum needs, etc. Standardization, where all potential participants are required to comply with a standardized reference document, is one possibility to address such extensive and heterogeneous information exchange needs. The other possible approach that we adopt in this paper is based on semantic technologies that enable a formal representation of the conceptual agreement between a number of collaborating agents about the vocabulary used in a given domain of discourse. Due to the standardized way to express the formal representation, it enables human as well as software agents to share and exchange descriptions of their individual communication capabilities. In this way, it is possible to harmonize communication between heterogeneous agents with potentially different capabilities with a minimal common compliance. The core knowledge is represented by ontologies whose representation and usage is specified in a standardized way.

III. COORDSS SYSTEM MODEL

A. Network Model

We consider a heterogeneous wireless environment which consists of m base stations (BSs) and n radio user equipment devices (UEs), where BS represents any access point (AP) regardless of the technology. Let us denote the set of BSs as $\underline{BS}$ = {BS_i | i = 1,..., m} and the set of UEs as $\underline{UE}$ = {UE_j | j = 1,..., n}. Fig. 1 shows an example of such a heterogeneous network in which BSs use heterogeneous technologies (LTE, Wi-Fi). Each UE has access to a certain subset of BSs. Between different BSs frequency separation may exist. One UE can be connected at most at one BS at any given time. But a UE can receive signals from one or multiple BSs, depending on the possibility of a UE interface to receive signals from multiple BSs. One UE can handover from one BS to another. For example, a UE with a wireless card 802.11b/g is able to receive signals on few channels within the 2.4 GHz band, where the allowed channels are country dependent. Usually channel numbers are between 1 and 14.

The heterogeneous network that we consider (Fig. 1) does not have any constraints regarding the band to operate and may use the unlicensed band as well. UEs can either communicate with each other or can access the BS. Possible access types on such heterogeneous networks are: 1) UEs transmit to the BS on licensed as well as unlicensed bands; 2) UEs communicate with each other on an ad-hoc manner on licensed as well as unlicensed bands where UEs can have different medium access scheme; 3) UEs may only access the BS through a licensed band. UEs should support the medium access technology of network. In our case we bounded on the unlicensed band and access, where UEs can access the BSs, and ad-hoc access, where UEs can communicate with each other.

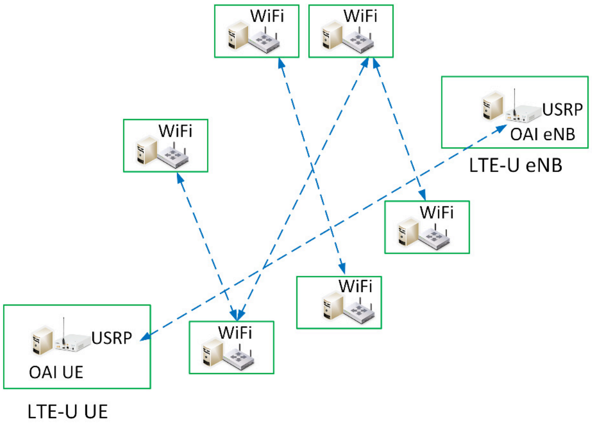

Fig. 1. The heterogeneous network model that we examine

B. *CoordSS Coordination Algorithm*

Fig. 2. presents a conceptual overview of the CoordSS networking architecture. Three verticals and three horizontals can be identified in the architecture. The following verticals represent different views on top of the same set of foundational concepts:

- *Network Environment* - represents the “real” world. This includes hardware devices as well as physical phenomena (such as frequencies) along with their properties. The experimental evolution (Section IV) uses the network environment of the NITOS testbed resources.
- *Ontologies* - are used to formalize domain specific knowledge that is independent of the context. They contain semantic definitions related to the meaning and purpose of the network environment. Ontologies are created by the domain experts and can be viewed, understand and managed by the humans as well as by the machines.
- *Semantic resources* - are the results of a semantic annotation of the network environment by mapping between the environment and ontologies. More precisely, if there is a physical resource that can be understood using the given set of ontologies it becomes the semantic resource.

Horizontals represent the main concepts in our network model. In the coordination algorithm, they play roles of sources and/or destinations:

- *Network resources* – constitute the state and capabilities of the environment where BSs and UEs are working. They are the primary source of data for reasoning during the coordination. On the networking environment level we are using spectrum sensing devices (such as Wiser [15]), connection bandwidth monitoring applications (such as iPerf) and the inventory repository (Note that testbeds regularly provide such a service). The ontologies level consists of the Spectrum Sensing Capability (SSC) ontology (for describing spectrum sensing) and the Wireless ontology (for describing frequencies, channels and radio bands). And at last, semantic resources level contains data for FFT analysis of frequencies, connection speed, device parameters and their changes over time.
- *BSs* – nodes that provides access points for UE. They are a backbone for network communication. The OAI [16] ontology is used to describe such devices. The coordination protocol uses a semantic representation of BSs to decide which parameters can be changed to improve networking. Such parameters include their power signals, position (if applicable) and communication channel.
- *UEs* – client nodes that form networks so they can send and receive data among them. We can have multiple networks, and one UE can belong to any number of networks (but we view it as a separate UE for each network). Therefore, each device is identified by a network name to which it wishes to belong to. Semantic resources for UEs contain client demands for communication.

Coordination is centralized on one machine that is running the CoordSS Coordination server (CCS). The CCS is responsible for running the coordination algorithm, providing client/server communication with the network resources, mapping network resources to semantic resources, maintaining a semantic store that holds ontologies and semantic resources and executing SPARQL queries. The coordination algorithm is invoked in case the network environment changes, namely when a new BS or UE is introduced or when network resources fluctuate (e.g. changes are observed regarding the performance or spectrum). Clients send their spectrum, performance and node description to the server. This data is in a native format. CCS maps such data to semantic resources and stores them in the semantic store. The semantic store is used for storing and retrieving triplets, basic building blocks of ontologies and semantic resources. SPARQL queries are the standard way for retrieving semantic data, and are used by the coordination algorithm for all reasoning as well.

The main objective of our coordination algorithm is to assign radio channels to the networks that are under its control. Any network that participates in our algorithm must have all of its nodes (UEs and BSs) registered to the CCS. Registered nodes send data to the CCS and also receive control messages from it. In our case, only channel allocation control commands are sent, but more elaborated control is also possible. When the algorithm decides to assign a channel to a network, commands are sent to all the nodes belonging to that network to switch to the new channel configuration.

There are two possible scenarios that we consider:

1. (S1) The network is part of the network environment and all of its nodes are aware of the CCS. This network does not have a channel assigned to it, but the coordination algorithm is responsible to provide one.
2. (S2) An uncoordinated network appears in the network environment (LTE or WiFi network). This network uses its own algorithm for channel assignment. This network can interfere with existing coordinated networks. Our algorithm detects such a situation and resolves any interference by re-assign channels of the coordinated networks.

In order to cope with the former scenarios, the algorithm must be aware of the spectrum usage in the network environment. We use the FFT analysis of the frequencies as a measurement of the spectrum usage. They are provided by the spectrum sensing device (SSD) that is a part of the network environment. The SSD constantly reports FFT measurements data to the CCS. These measurements are converted to semantic resources and written to the semantic store. CCS can reason over these measurements, by using the SSC ontology, and concludes which radio channels are free and which are not. Reasoning is performed by executing a corresponding SPARQL query. We can reason in different ways by changing this query. Currently, the reasoning takes into account the FFT analysis of the channel’s central frequency and if this value is above predefined value (which depends on the network environment) then the channel is considered to be occupied. However, it is important to note that change of the reasoning is simply a matter of changing the corresponding SPARQL query.

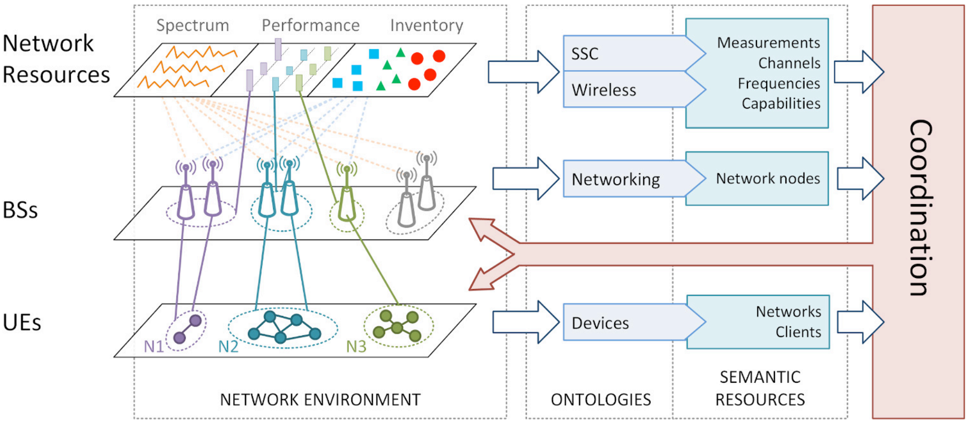

Fig. 2. Coordination architecture overview

The collected information is enough in order to perform channel assignment to the coordinated networks that do not have their communication channel set yet (which corresponds to the S1 scenario). After a network node is registered to the CCS, it starts sending data about itself. This includes the network name that it wants to be a part of and a node type (BS or UE). After each node registers, CCS runs the coordination algorithm that now encounters all registered nodes. Reasoning is used in order to decide if the network with the given name already has its channel assigned. If the channel is not assigned, one of the free channels is assigned to the network. Information about the given network and its channel is stored within the semantic resource that represents it. When a channel for the network is found, the node is informed that it should use that channel.

When a new network is introduced in the network environment that is not aware of the CCS (e.g. it's not coordinated), it selects its own communication channel independently (scenario S2.). If that network is a WiFi network, it can reduce the performance of other networks operating on the same channel. If that network is a LTE network, it can completely shutdown the WiFi network on that channel. A solution for this situation would be to move coordinated networks to other channels. Nevertheless, spectrum utilization information might not be enough to decide whether the newly introduced network is a coordinated or an uncoordinated. The coordination algorithm may use the bandwidth of coordinated networks to detect such situations. Network bandwidth, which is a network resource, is available to the coordination algorithm as a semantic resource. Reasoning is needed to check if the bandwidth of any coordinated networks is not satisfactory. A SPARQL query is responsible for this task. The query finds all the networks with bandwidth less than a predefined percentage. If at least one network is found, the algorithm performs the aforementioned reasoning in order to track free channels. In this way, CCS assigns a free channel to each found network. CCS and its conceptual building blocks are depicted in Fig. 3. The diagram also contains workflows that make the coordination according to the aforementioned scenarios possible.

IV. EXPERIMENTAL EVALUATION

We evaluate the performance of our semantic coordination framework in a real testbed environment. For our evaluation, we employ the NITOS wireless testbed, part of the FLEX infrastructure [18], that provides open access to an experimental heterogeneous network environment [12], using multiple technologies, such as LTE and WiFi. The rich environment that NITOS is offering is utilized in order to configure the suitable environment for the experimental evaluation in real world settings of the CoordSS framework. To this aim, we employ the following testbed components:

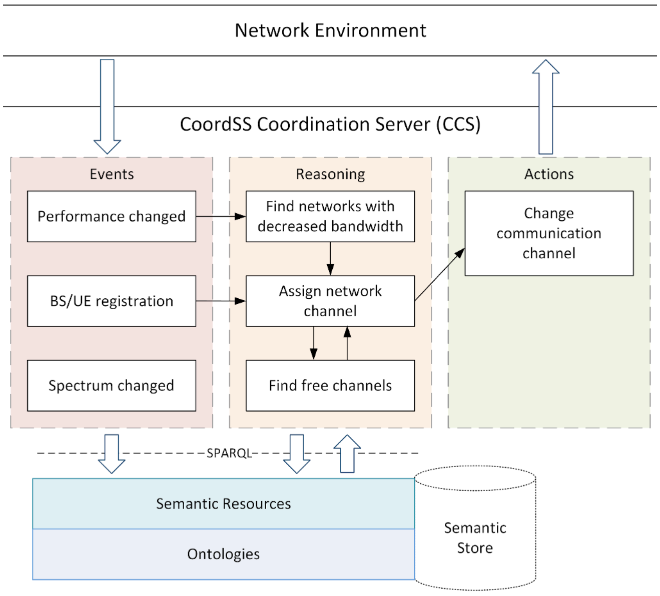

Fig. 3. Conceptual architecture of CoordSS Coordination Server with coordination workflow

- A pair of USRP B210 models, that will serve as the RF front-end of the deployed LTE network
- Several WiFi enabled nodes, that will be used as the contending traffic in the unlicensed under study bands
- The OpenAirInterface (OAI) platform [17], that provides the execution of a 3GPP EUTRAN over commodity hardware, with the appropriate RF front-end. The OAI platform has been extended in order to allow its operation in the unlicensed bands.

The experiments are conducted in a controlled environment, at the Indoor RF Isolated testbed. The topology of the experiment setup is shown in Fig. 4. Nodes 50 and 68 make WiFi network 1 (WN1). Also, nodes 62 and 69 make WiFi network 2 (WN2). The traffic between the nodes in WN1 and WN2 is generated and measured by iperf-oml2 application that stores the measurement results in the testbed database for later analysis. LTE device is an interferer and is represented by eNB at node 59. Node 59 is equipped with USRP B210 device, and it runs the software defined LTE eNB, known as OAI eNB. The experiment was performed at the 5 GHz unlicensed band. Due to the regulatory domain of the used WiFi network cards, the set of WiFi channels was limited to 36, 40, 44, and 48, with the central frequencies of 5.18, 5.20, 5.22, and 5.24 GHz, respectively.

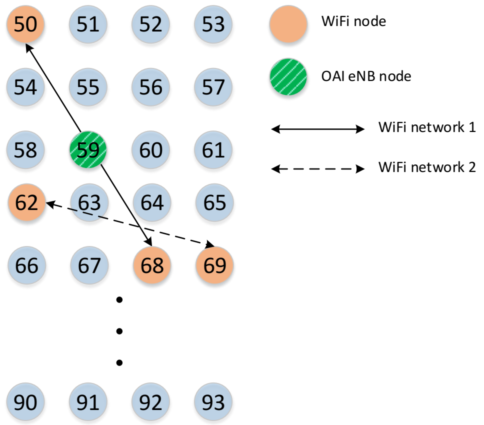

Fig. 4. The topology of the experiment setup

The following methodology was used during the experiment. At first, only WiFi stations were involved. Each WiFi network would randomly choose a channel, and the resulting throughput was measured. This procedure was repeated 100 times and the average throughput was calculated. After that, WN1 randomly chose a channel, WN2 received a channel from CoordSS server, and the throughput was measured. The results are shown in Table 1. The second part of the experiment, besides the coordinated WiFi networks, involved the LTE eNB, with and without coordination. A similar procedure, as in the first part of the experiment, was applied. The results are shown in Table 2.

Table 1. Coordinated and uncoordinated shared spectrum access with WiFi stations

	WiFi throughput [Mb/s]		
	Min	Average	Max
Uncoordinated	11.5	19.6	22.8
Coordinated	22.8	22.8	22.8

Table 2. Shared spectrum access with coordinated WiFi networks and (un)coordinated LTE eNB

	WiFi throughput [Mb/s]		
	Min	Average	Max
Uncoordinated	10.6	16.7	22.8
Coordinated	22.8	22.8	22.8

The results show the importance of the coordinated spectrum usage. Due to a relatively low number of the involved nodes, the average throughput is not very much improved by the coordination. However, the coordinated network has more stable throughput than the uncoordinated one, i.e. the difference between the lowest and the highest throughput is rather large in uncoordinated network. We should also have in mind that the output power of the USRP B210 is relatively low (10 dBm). Therefore, the influence of the dedicated LTE eNB on WiFi would be much higher.

V. CONCLUSION

We studied the dynamics of CoordSS coordination algorithm in heterogeneous networks constituted of WiFi and LTE equipment. We investigated the coexistence of WiFi and LTE and introduced a solution for coordination based on CoordSS ontologies framework. Finally, through measurement-driven simulations we showed that proposed CoordSS coordination algorithm is working with certain reliability.

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