LTE/Wi-Fi Coordination in Unlicensed Bands: An SD-RAN Approach

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***Abstract*—In this article, we experimentally measure the throughput performance of a Wi-Fi, 802.11n, network when it is affected by LTE downlink transmissions. Our practical approach is based on a modular experimental test-bed. We initially compare our measurement results with the case without LTE interference; and further discuss that even the 3GPP features cannot guarantee coexistence in all cases and this might hamper the practicality of mobile technology in the unlicensed radio spectrum. For this reason, we enhance our test-bed introducing the Software-Defined Radio Access Network (SD-RAN) controller 5G-EmPOWER. Thus borrowing from the higher agility of software-defined networking. By using the SD-RAN control to adaptively tune LTE-eNB downlink transmission parameters, we experimentally prove the validity of this approach to improve Wi-Fi network throughput, as well as we shed light onto the new potentials that the SD-RAN controller can lead to automate network optimization.**

***Index Terms*—Co-existence, LAA, SD-RAN, Wi-Fi, u-LTE, Unlicensed Bands**

I. Introduction

Along the way of developing the full-fledged 5G system, unlicensed LTE (u-LTE) stems as an attempt to achieve performance improvements in cellular networks without adding new licensed spectrum. Although utilization of unlicensed frequency bands is appealing for mobile operators, the challenge of coexistence with other radio systems already in operation stands as a logical consequence. Specifically, the interference to pre-existing unlicensed systems such as Wi-Fi [1]–[3]. As Wi-Fi uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) to access the channel, the additional interference caused by LTE transmissions can potentially hamper the performance of the clear channel assessment operation. Generically denoting with u-LTE any LTE communication in unlicensed spectrum regions and Wi-Fi as the equivalent incumbent network, high Packet Error Rate (PER) on access terminals is another effect of simultaneous transmissions of u-LTE and Wi-Fi. To relieve the effects of u-LTE on Wi-Fi performance, 3GPP developed two methods: 1) LTE Unlicensed (LTE-U) which is introduced in Release 12 and is based on an adaptive on-off duty cycling [4]; 2) Licensed-Assisted Access (LAA) [1] in Release 13 and 14, which is based on a Listen Before Talk (LBT) mechanism similar to Wi-Fi. Although these two methods can decrease the negative effects of u-LTE on Wi-Fi performance, they cannot solve the problem entirely: first, by introducing LAA the Energy Detection (ED) threshold of the sensing mechanism for both technologies turns to be a new challenge [5], [6]; second, in either of the proposed methods hidden node problems can still arise, thus adding new difficulties on the medium access control sublayer since packet collisions increase [7]. If such problems remain, transmissions of mobile network technology over unlicensed radio spectrum might remain niche or even be dropped. Considering also that the new generation of 5G technology will soon witness the first set of roll outs, the importance of tackling also unlicensed bands is still up-to-date. The high number of research contributions hace produced in few years on this topic make evident its importance which some of the last findings are surveyed in [8], [9].

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A. Contributions of the Work

The assessment of the effects of u-LTE transmissions on Wi-Fi performance is carried out in this paper in which we experimentally measure the Wi-Fi throughput in the worst case of a continuous LTE transmission. We compare the results with the baseline situation where there is no active u-LTE interfering transmitter. The controllability level is achieved exploiting the new concept of software-defined Radio Access Network (SD-RAN). Therefore, a centralized SD-RAN controller that can control both Wi-Fi Access Points (AP) and LTE-eNB is used. Specifically, we use two modules of the 5G-EmPOWER controller called network monitoring and network reconfiguration [10]. The controller monitors the network continuously and is able to reconfigure it when both technologies are in operation. In light of the discussion undertaken above, to the best of our knowledge, there is still lack of studies that introduce the new dimension of a centralized intelligent entity such as an SD-RAN controller that can monitor and tune transmissions parameters in both Wi-Fi and u-LTE at runtime in order to reach fair coexistence. Therefore, the research contribution of this work is twofold: 1) we carry out measurements in a realistic office environment when the reception of Wi-Fi station is affected by u-LTE and 2) we use the results of the measurements to leverage the functionality of the SD-RAN controller.

The rest of the paper is organized as follows: Section II describes the system model and test beds we have used for the measurements while Section III shows some measurement results of the u-LTE/Wi-Fi coexistence. In Section IV we introduce the architecture of our SD-RAN controller for the u-LTE/Wi-Fi coordination. Finally, Section V are depicted to future plants and the conclusion of the work, respectively.

II. Test-Bed Description

In this work, we consider having one u-LTE eNB connected to the 4G Evolved Packet Core (EPC) while one active LTE User Equipment (UE) attached to it. As the goal of the work is to evaluate the effects of LTE transmissions on Wi-Fi throughput, the LTE eNB transmits continuously on the 5 GHz unlicensed band in downlink while all the uplink traffic is transmitted on the licensed LTE carrier. The choice of this set-up results in a heterogeneous radio network in which the shared communication channel is accessed in an Aloha-like access scheme for both systems. This configuration allows us to completely evaluate the benefits of the SD-RAN controller. The scenario allows us to compare the Wi-Fi throughput in an environment without LTE interference with the one with LTE. The number of active LTE networks is purposely limited to one considering that different channel access mechanisms have been developed to reduce the likelihood of a situation in which the Wi-Fi network is overwhelmed by u-LTE transmissions. In this context, we measure the Wi-Fi throughput when various LTE parameters such as transmit power, modulation and coding scheme (MCS) and bandwidth are changed.

A. Test-Bed Components

1) srsLTE, An Open Source LTE Library: Software Radio Systems LTE (srsLTE) is a high-performance LTE library for software-defined radio applications [11]. Supporting EPC, eNodeB and UE in different modules, the library has minimal inter-module dependencies, which makes it simple to use for developers. Its current version provides an interface to the Universal Hardware Driver (UHD), which is supported by the Ettus USRP family of devices [12]. Specifically, our test-bed relies on the Ettus B210 radio boards. We are able to deploy an LTE small cell where the UE can attach to the eNB, and the eNB can perform downlink data transmissions to the UE. We configure the measurement environment with LTE interference that overlaps in time and frequency with the Wi-Fi network communications. Moreover, manipulating the source code, we are able to tweak the transmit power of the eNB, as well as the modulation and coding scheme and the LTE downlink bandwidth during runtime of the measurements.

2) OpenWRT: In our testbed, the Wi-Fi AP is built upon the PCEngines ALIX 2D board (x86 architecture based), to which a Wi-Fi card based on the Atheros AR9220 chipset is connected. The Wi-Fi AP we use in our test-bed is based on the OpenWRT Operating System 15.05.01 version, and is configured to deploy an IEEE 802.11n network with 5.18 GHz carrier frequency in channel 36. Furthermore, the Wi-Fi AP is configured to use one spatial stream, which determines the UDP data rate up to 28 Mbps.

B. Measurements Environment

Figure 1 sketches the implementation of the test-bed put in place to do the interference measurements. The LTE-eNB, the Wi-Fi AP, and the LTE-EPC are connected to the network switch NETGEAR GS 108E and the switch is connected to a network router and thus to the Internet through a LAN cable. The LTE setting for LTE-UE, LTE-eNB and LTE-EPC includes three laptops in which Linux operating system is installed. The eNB transmits to the UE a stream of bits generated at random in continuous mode in order to create a controllable interference environment on Wi-Fi. As a remark, the downlink data is transmitted in the Physical Downlink Shared CHannel (PDSCH) through Transport Blocks (TBs) whose size depends on the modulation and coding scheme used for UE transmissions by the eNB. The Wi-Fi AP is connected to a laptop with a LAN cable; therefor, we are able to control different parameters of AP through its operating system (OpenWRT). Further, we use another laptop as the Wi-Fi client, where the spectrum analyzer on the same device shows us the received power at the client side.

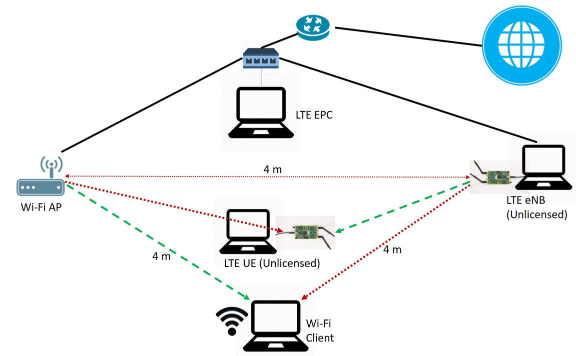


Fig. 1: u-LTE/Wi-Fi test-bed implementation

Referring to Figure 1, measurements are carried out in an office environment with desks and walls. The Wi-Fi client is located 4m away from the Wi-Fi AP and with the same distance from the LTE eNB. Since in a realistic indoor environment u-LTE and Wi-Fi systems might co-exist in a relatively close proximity, we consider the case of interference in which the two transmitters, AP and eNB, are quite close to each other. Following this approach, the LTE transmitter, the Wi-Fi AP and the Wi-Fi client form a triangle. In this work, the LTE performance is not studied and we focus on measuring the Wi-Fi throughput in various interference environments, assuming that this is the incumbent system to protect.

The Wi-Fi throughput is measured in the downlink and the system bandwidth is 20 MHz. The transmitted power of the Wi-Fi AP is fixed to the maximum value of 20 dBm (i.e. 100 mW). LTE also transmits in the down-link in the same band of Wi-Fi at the 5.18 GHz carrier frequency. For the LTE system we vary the transmit power and the bandwidth (BW). Moreover, as per the 3GPP standards, the LTE transmitted power can vary between -40 dBm and 18 dBm (or 24 dBm for some scenarios). To measure the Wi-Fi throughput, we use the measurement tool iperf when we send application data over the User Datagram Protocol (UDP) for 2 minutes, and we record the average data rate as well as the packet loss and received signal power at the client side.

III. Coexistence Experiments of u-LTE and Wi-Fi

A. Evaluation Methodology

In this section, we describe the experimental methodology used to carry out the coexistence study between u-LTE and Wi-Fi. The challenge of any experimental set-up is to be able to reproduce realistic conditions that can take place in an actual deployment, while putting in place a controllable experimental environment. The obvious advantage is to obtain realistic measurement results. Since we target an indoor office environment propagation effects of the radio signals such as path-loss and fading are included in the measurement results.

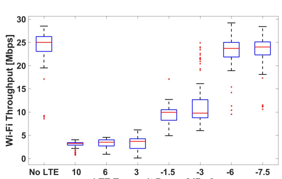
B. Impacts of the LTE Transmitted Power

In the first experiment we vary only the transmitted power of the LTE eNB for downlink transmissions since the uplink traffic is transmitted over the licensed LTE carrier. For fine tuning of the transmitted power in dBm, we connect the output of the USRP-B210 board to the MS2036A-VNA spectrum analyzer to validate the exact value of the power over different bandwidths. In order to realize the exact value of the cable loss we used also the calibrated signal generator USB-TG124A, with which a signal at 5.18 GHz is generated. We report that the loss measured for the cable is approximately 1.5 dB.

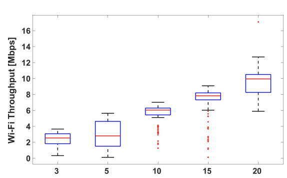
Figure 2(a) shows the measured Wi-Fi throughput behavior with the relative dispersion interval for different values of the LTE transmitted power. The number of resource blocks in the LTE downlink transmission is set to 100 while the modulation and coding scheme index is fixed to 10. As a result, we have an LTE bandwidth of 20 MHz, modulation 16-QAM and transmission block size of 17568 bits. The leftmost result in the figure stands for the case without LTE downlink interference. As expected, we can observe that increasing the value of the LTE transmitted power will degrade the Wi-Fi performance. The results show the average Wi-Fi throughput within 100 sec time window of the experiment. Analyzing the results, for LTE signal with transmitted power of 10 dBm the Wi-Fi throughput mostly fluctuates between 3-4 Mbps, whereas for a LTE transmitted power of -7.5 dBm it will vary between 23-25 Mbps, which is approximately the same Wi-Fi throughput measured without LTE interference.

C. Impacts of the Number of LTE Resource Blocks

The second set of measurements relates to quantifying the effect of the number of resource blocks (LTE bandwidth) used in the LTE eNB downlink transmission. For the measurements, we set the parameters of the eNB to constant values in such a way that the LTE transmitted power corresponds to -1.5 dBm when the LTE bandwidth is equal to 20 MHz. Changing the number of resource blocks in LTE , the transmitted power over the whole bandwidth is automatically scaled in the eNB while the power per resource block remains nearly constant. Further, the MCS-index in these measurements is set to 10 as before. Figure 2(b) shows the Wi-Fi throughput for different values of the LTE bandwidth in which the number of physical resource blocks varies from 15 to 100. The behavior shown by the figure highlights that decreasing the LTE bandwidth, the Wi-Fi throughput decreases as well. Although for a larger bandwidth the LTE transmitted power is higher, it will affect less the Wi-Fi throughput performance. As a matter of fact, looking at Table I, we may notice that the LTE link spectral efficiency is lower with a larger bandwidth and this reduces the negative effects on the Wi-Fi throughput.



(a) Impacts of transmitted power



(b) Impact of Bandwidth

Fig. 2: Impacts of LTE on Wi-Fi Throughput

TABLE I: Parameters to evaluate effects of LTE-BW

Bandwidth	Bit Rate (Mbps)	(dBm)/PRB	(bit/sec)/Hz	TX block size (bits)
3 MHz	12.5	$\simeq$ -20	4.1	2344
5 MHz	14.5	$\simeq$ -20	2.9	4008
10 MHz	24	$\simeq$ -20	2.4	7992
15 MHz	26	$\simeq$ -20	1.7	11832
20 MHz	26.5	$\simeq$ -20	1.3	15840

IV. Dynamic Interference Coordination

Referring to the measurements shown in Section III, we observe that the modification of different parameters of the LTE transmission can have different effect on the Wi-Fi performance. Also, we may infer that without an intelligent entity that can analyze the key performance indicators of both technologies, fair coexistence between the two networks is not straightforward to achieve. In this section, we introduce the centralized SD-RAN controller concept and we discuss how this can be the tool to enable fair coexistence between u-LTE and Wi-Fi since the controller can give priority to either of the technologies dynamically. To demonstrate the performance improvements introduced by the new centralized entity in an actual environment, we will define different scenarios for u-LTE and Wi-Fi coexistence in which we insert the new dimension of the controller in the measurements. At first, we describe in detail the architecture and the different components of the 5G-EmPOWER controller. Afterward, we apply the it to the u-LTE and Wi-Fi co-existence problem, while comparing the throughput performance of Wi-Fi with the case of uncoordinated transmissions.

A. 5G-EmPOWER Controller

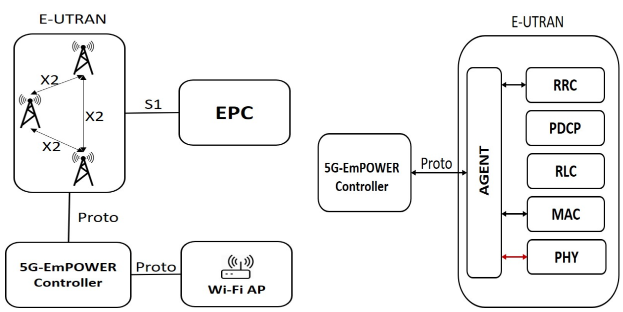
5G-EmPOWER is a multi-access software-defined RAN controller which supports heterogeneous access technologies such as LTE and Wi-Fi. The 5G-EmPOWER protocol allows remote management of various RAN elements, as well as network service programmability through an intent-driven application framework. Compliantly with the philosophy of Software-Defined Networking, the control plane is separated and taken care of by the controller itself, whereas the Wi-Fi AP and the LTE-eNB are the Network Elements (NEs) which are controlled by 5G-EmPOWER. The identity (i.e. MAC address) of each entity connected to 5G-EmPOWER can be defined in the controller and whenever a Wi-Fi AP or an LTE-eNB is activated the controller receives a notification showing whether they are available to provide service or not. This is, in fact, the network monitoring aspect that is done inside the controller. Furthermore, 5G-EmPOWER provides developers with full visibility of the network state while allowing them to dynamically orchestrate network services.

1) 5G-EmPOWER Agent: The 5G-EmPOWER Agent, hereinafter referred to Agent, handles incoming messages inside the eNB protocol stack. The purpose of the Agent is to create interfaces with distinct layers of the eNB protocol stack in order to set/get specific parameters to/from the controller.

2) 5G-EmPOWER Protocol: Referring to Figure 3, the 5G-EmPOWER protocol, hereinafter referred to as Proto, is an interface between the controller and the Agent to enable the communication between the two entities whenever required. The exchange message using Proto interface includes 4 parts: 1: The *Header* contains the general information that has to be carried out by any exchanged message (cell ID, message length and so on). 2: The *Event Header* embeds the information related to the type of events (Single, Scheduled or Trigger events). 3: *Action* specifies the operation that has to be executed by the Agent. 4: Finally, the field *Data*, which is appended at the end of the message and can be used to exchange any information that is needed between 5G-EmPOWER controller and Agent.

B. SD-RAN Enabled Test-Bed Architecture

Figure 3 sketches the general architecture of the proposed u-LTE/Wi-Fi coordination approach that is implemented through the 5G-EmPOWER controller, as well as the terminology used throughout the rest of the paper. The controller is able to control both Wi-Fi AP and LTE-eNB access nodes. The 5G-EmPOWER architecture consists of three layers: *infrastructure*, *control*, and *service*. The infrastructure layer where the data plane network elements are located consists of LTE-eNB and Wi-Fi AP, whilst the 5G-EmPOWER runtime is located at the control layer. The role of the runtime is to convert the service layer policies (e.g. u-LTE/WiFi interference management) to the commands for the infrastructure elements. Figure 3(b) illustrates in detail how each eNB can communicate with the controller through the Proto interface. Reconnecting to the set of measurements detailed in Section III, the parameters of the LTE-eNB like transmitted power, bandwidth and the MCS-index are defined in the physical layer of the srsLTE-eNB. By developing an interface between the Agent and the physical layer, we are able to modify these parameters at runtime. The loop is closed considering that the Agent can communicate with the 5G-EmPOWER controller through the Proto interface. As illustrated by Algorithm 1, in the first place the controller sends an initialization request to the Agent to receive information regarding the parameters already set inside the eNB physical layer. The Agent will reply with a scheduled message the requested parameters within a predefined time interval. The parameters include the transmitted power, bandwidth and MCS-index used by the eNB for downlink transmissions. As soon as the controller notice activation of Wi-Fi AP in downlink, it will command the eNB to lower the transmit power and increase the transmission bandwidth, as demonstrated in Section III, in order to preserve the Wi-Fi throughput.



(a) u-LTE/WiFi architecture with centralized control (b) eNB architecture, communication with the controller

Fig. 3: Centralized coordination of Wi-Fi/LTE

Figure 4 shows the sequence diagram for the procedure that we have developed to improve the coexistence between u-LTE and Wi-Fi networks through the use of the 5G-EmPOWER controller. As soon as the LTE-eNB begins a downlink transmission, it will communicate the physical layer parameters that are currently used to the controller through the Agent using the Proto interface. The controller can control the Wi-Fi AP and it is aware of whether it is transmitting in the same band of LTE or not. Whenever the Wi-Fi AP starts transmitting in downlink in the same band of LTE, the controller will decide a new set of parameters for the eNB and will enforce them in the eNB physical layer again by means of the Agent. Finally,

Initialization: Send schedule msg;
while *LTE-eNB connected* **do**
    GET the PHY parameters reports;
    if *Wi-Fi AP is transmitting* **then**
        if *PHY param acceptable* **then**
            Do nothing
        else
            Minimize the eNB transmit power;
            Maximize the eNB Bandwidth ;
        end
    else
        SET Max transmit power of eNB;
    end
end

Algorithm 1: u-LTE/Wi-Fi algorithm application

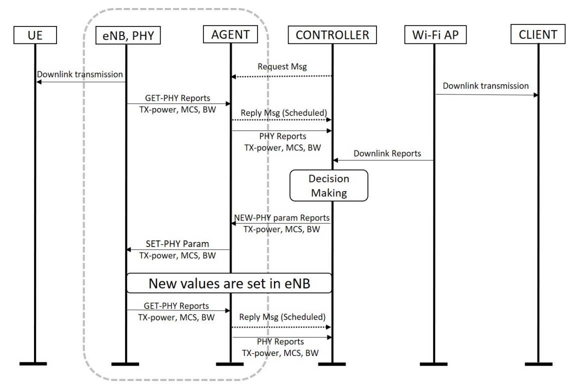
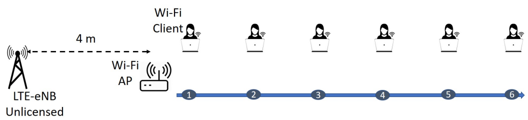


Fig. 4: Sequence diagram showing the proposed approach to control eNB physical layer parameters

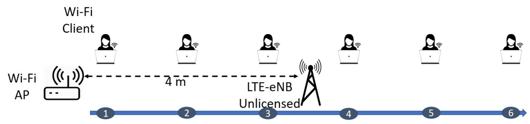
the new values of eNB physical layer are reported back to the controller until a new decision stage is performed.

C. Measurement Results

Relying on the lessons learned from the first set of measurements shown in Section III, we provide the results of another set of experiments in which we measured the throughput that can be achieved by the Wi-Fi network when the 5G-EmPOWER controller is added to measurements to perform adaptation of u-LTE transmission parameters when the Wi-Fi downlink transmission is activated. For the purpose, we initially configure the LTE-eNB physical layer parameters with -1.5 dBm transmitted power and 20 MHz of bandwidth. These parameters are reported to the controller within a scheduled event. When the Wi-Fi AP starts transmitting, the controller can adjust the LTE-eNB power to -6.2 dBm, while the bandwidth is unmodified since it is already set to the maximum. To understand the benefits of the centralized control action, we define two different scenarios as shown in Figure 5. The distance between the Wi-Fi AP and the LTE-eNB is fixed to 4m as before. In the first scenario shown in Figure 5(a), the Wi-Fi client is moved away from the LTE-eNB, whereas in the second scenario shown in Figure 5(b) the it is moved in the direction of the LTE-eNB. The choice for the measurement set-up is motivated by thinking to scenarios of indoor mobility in which the client moves in proximity of the Wi-Fi AP following a simplified linear motion. The two scenarios motivates two distinct sets of measurements in which the performance are aggregated using the measurement

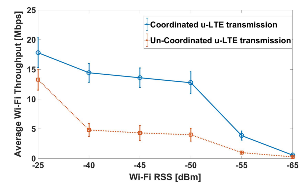


(a) Scenario 1: Wi-Fi client moved away from LTE-eNB

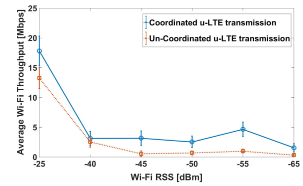


(b) Scenario 2: Wi-Fi client moved toward LTE-eNB

Fig. 5: 5G-EmPOWER controller measurements environment



(a) Wi-Fi client moves away from LTE-eNB



(b) Wi-Fi client moves towards LTE-eNB

Fig. 6: Coordinated Vs Un-coordinated Coexistence

tool iperf when data traffic is sent over the UDP transport protocol. Unlike to the previous set of measurements, we record also the important parameter provided by the Wi-Fi Received Signal Strength (RSS). For the scenario in which the Wi-Fi client is moved away from the LTE-eNB, Figure 6(a) compares the measurement results obtained in the situation of uncoordinated LTE transmissions with static transmitted power to the situation in which LTE-eNB transmission parameters are adjusted by the 5G-EmPOWER controller for different values of the RSS measured at the Wi-Fi client side. The measurement results for the scenario in which the Wi-Fi client is moved toward the LTE-eNB are shown in Figure 6(b). Both figures prove the clear throughput performance improvement that arises from the centralized coordination action performed by the centralized SD-RAN controller. Even the simple action of dynamically adapting the LTE-eNB transmitted power can yield Wi-Fi throughput improvements. Comparing Figure 6(a) to Figure 6(b), we may also notice that the 5G-EmPOWER control action is more effective when the Wi-Fi client is moved away from the LTE-eNB. The explanation is quite intuitive since the channel propagation affects in a non-linear manner the radio signals. Increasing the distance separation between the interfering eNB and the Wi-Fi client, the control action performed by 5G-EmPOWER has a non-linear effect on both LTE-eNB and Wi-Fi AP transmitted signals until reaching a certain distance at which the radio signal of the Wi-Fi AP becomes too low. Based on the measurements in which 5G-EmPOWER can coordinate both LTE and Wi-Fi technologies, we can learn that, to cope with the variety of situations that may arise in an indoor environment, though the action of the centralized SD-RAN controller is evidently positive, even more sophisticated techniques beyond transmitted power adaptation are needed on top of the controller. This aspect is further discussed as part of the future work activities that we plan to carry out to extend the present work considering newer 802.11 protocol (i.e 802.11ac and 802.11ax).

V. Conclusion

This paper presented measurements results that quantify the effects of LTE transmissions in the unlicensed 5 GHz band on the Wi-Fi throughput performance in an actual office environment. In our testbed we have used the open source srsLTE libraries and the OpenWRT operating system. Our methodology is based on adopting a new degree of controllability added by the 5G-EmPOWER SD-RAN controller to coordinate the transmissions of both technologies, thus leveraging on the network programmability paradigm. First, we have presented an experimental set of results for the Wi-Fi network throughput affected by LTE transmissions showing the sensitivity of Wi-Fi with respect to LTE parameters such as transmitted power and system bandwidth. We measured the Wi-Fi throughput by modifying the eNB transmission parameters as the source of interference to Wi-Fi and compared the results with the case in which LTE interference is not present. In addition, we have developed an approach to improve coexistence by means of the 5G-EmPOWER controller, which we illustrated through a sequence diagram in order to enable modification of the LTE-eNB parameters based on network conditions to preserve the Wi-Fi downlink throughput. Measurement results demonstrate the viability of our approach and the improvement that can arise from controlling the LTE transmission parameters.

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