Augmented Wi-Fi: An AI-based Wi-Fi Management Framework for Wi-Fi/LTE Coexistence

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***Abstract*—Recently, the operation of LTE in unlicensed bands has been proposed to cope with the ever-increasing mobile traffic demand. However, the deployment of LTE in such bands implies sharing spectrum with mature technologies such as Wi-Fi. Several studies have discussed this coexistence problem by suggesting that LTE implements different adaptation mechanisms that allow transmission possibilities to Wi-Fi. While such adaptation mechanisms exist, they still negatively impact Wi-Fi performance, mainly due to the lack of collaboration/coordination mechanisms that inform about the co-located networks' activities. In this paper, we propose a distributed spectrum management framework that enhances the performance of Wi-Fi, as a particular case, by detecting harmful co-located wireless networks and changes the Wi-Fi's operating central frequency to avoid them. The framework is based on a Convolutional Neural Network (CNN) that can identify different wireless technologies and provides spectrum usage statistics. Experiments were carried out in a real-life testbed, and the results show that Wi-Fi maintains its performance when using our framework. This translates in an increase of at least 40% on the overall throughput compared to a non-managed operation of Wi-Fi.**

***Index Terms*—Spectrum sharing, Machine learning, Cognitive radios, Coexistence, Experimental demonstration.**

I. Introduction

According to Cisco's Visual Networking Index (VNI) for Global Mobile Data Traffic for 2017-2022 [1], the wireless traffic will account for 71% of total IP traffic by 2022. Additionally, one of the trends for future generations forecasted by Cisco is the multiplicity of devices and wireless connections. Thus, to allocate the massive amount of mobile subscribers, the use of unlicensed bands has been proposed for LTE's operation for traffic offloading [2]. Unfortunately, this situation adds more stress to the currently available spectrum in unlicensed bands and opens new coexistence challenges between competing technologies. Hence, efficient strategies for spectrum access have been proposed targeting fairly coexistence in heterogeneous wireless environments.

Traditionally, Wi-Fi has been the preferred choice in the 2.4 and 5 GHz Industrial, Scientific, and Medical (ISM) unlicensed band as a broadband access technology due to its low deployment cost and decent performance in shared spectrum. Recently, LTE has been proposed to operate in the unlicensed spectrum to cope with the increasing mobile traffic demand. However, the deployment of LTE in these bands can negatively influence Wi-Fi performance. In this scenario, most of the works propose LTE mechanisms that adapt to the wireless environment, protecting Wi-Fi communications. Such mechanisms include Transmission Opportunities (Tx-Opps) during muting periods in a duty-cycled manner (LTE Unlicensed (LTE-U) [3]), channel assessment procedure before a transmission (LTE Licensed Assisted Access (LTE-LAA) [4]), and standalone operation in unlicensed bands (MuLTEfire [5]).

However, such LTE mechanisms are asymmetric in terms of medium access. LTE uses significant long times to transmit and short muting periods, typically of several ms, compared to a standard Wi-Fi transmission that lasts few hundreds of µs [6] without using frame aggregation. Even when longer muting periods are used, LTE control and reference signals can severely degrade Wi-Fi performance by allowing only 16% of the chances of medium access [7].

In this paper, we study the Wi-Fi/LTE coexistence problem by assuming a legacy operation of the interfering technology (LTE), which degrades the throughput of the incumbent technology (Wi-Fi) due to the interference. Moreover, this paper proposes a distributed spectrum management framework based on state-of-the-art Machine Learning (ML) techniques that provides a global view of the spectral resources in wireless environments and helps Wi-Fi identify which wireless technology is transmitting. Based on that, different strategies for spectrum access can be enforced. Furthermore, we show this framework's implementation in a real-life testbed without requiring changes in both Wi-Fi and LTE. Unlike most of the works addressing this topic, this paper suggests instead a collaboration between the two technologies through a third-party.

Our contributions can be summarized as follows:

- We propose a distributed spectrum management framework that:

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- Implements a state-of-the-art ML technique that identifies several wireless technologies and gives statistics about spectrum usage,
  - Includes a rule-based Wi-Fi decision algorithm that adapts to changing conditions and
  - Does not require fundamental changes in current wireless environments and therefore can be deployed in both legacy and Software Defined Networking (SDN)-like setups.
- We evaluate the proposed framework using a testbed of Commercial Off-The-Shelf (COTS) hardware and verify that the performance of Wi-Fi can obtain better chances to reduce its degradation due to interference.

The remainder of this paper is organized as follows. Section II gives an overview of Wi-Fi/LTE coexistence in the unlicensed spectrum and the use of machine learning to solve this challenge. We describe our spectrum management framework for Wi-Fi/LTE coexistence in section III and explain its motivations. Section IV shows the details and the evaluation of the management framework in a real-life scenario. Finally, in section V we conclude the paper.

II. Related Work

Given the design differences between Wi-Fi and LTE, several studies [7]–[9] verify through simulations and mathematical analysis that the performance of Wi-Fi can be severely affected by the standard operation of LTE in the unlicensed spectrum. Therefore, there is a need for efficient mechanisms that guarantee coexistence between the two competing technologies by fairly sharing the spectral resources.

In the last years, only a few works have provided experimental results of LTE's deployment negative impact on Wi-Fi transmissions. The authors in [10] proposed an architecture based on SDN for inter-network cooperation on radio resource management to facilitate coexistence. An analytical model was developed to evaluate Wi-Fi and LTE's performance, and its validity was tested through experiments using real hardware. Afterward, the framework was used to exchange information between the co-located networks to jointly optimize the transmission power of the Access Points (APs) for fair spectrum access. Capretti *et al.* [11] deployed a small testbed using Software Defined Radios (SDRs) and open-source Wi-Fi hardware. They used different configurations of the two technologies, such as channel bandwidth, Modulation and Coding Scheme (MCS), packet size, transmission power. They showed that coexistence could be achieved if LTE employs duty-cycling.

More focused on Artificial Intelligence (AI)/ML-based approaches for improving coexistence, authors in [12] presented DM-CAST, a Q-Learning algorithm to adjust the parameters of a Duty-Cycling LTE to guarantee a fair coexistence with Wi-Fi. The solution was implemented using simulations in ns-3, where they considered different traffic load scenarios. The obtained results showed that the algorithm efficiently adapts to changing conditions while maintaining aggregated throughput. Maglogiannis *et al.* [13] proposed mLTE-U, a novel adaptation mechanism that determines LTE transmissions in the unlicensed spectrum for a variable Tx-Opp followed by a variable muting period. A Q-Learning scheme was implemented for auto-tuning the Tx-Opp and muting periods of mLTE-U for fair coexistence with co-located Wi-Fi. The authors showed that the proposed algorithm adapts well to the changes in a dynamic wireless environment through simulations.

Authors in [14] trained a CNN using COTS hardware to detect co-located LTE and Wi-Fi transmissions. Its results aid in selecting the appropriate mLTE-U configurations that enhance fair coexistence. In that way, Wi-Fi can freely transmit during the muting periods of LTE. The proposal was validated in an isolated real deployment. We refer the reader to [15] for more details on the use of ML in mobile and wireless networks and to [16] for more details on wireless inter-technology coexistence.

Previous literature has focused on providing LTE with the necessary means to adapt its internal settings to the spectrum's shared use in unlicensed bands. However, few studies tackle the coexistence problem by considering Wi-Fi adaptation to changing conditions. This is also founded in design differences. Typically, Wi-Fi is designed to share the spectrum with other Wi-Fi networks using the Carrier-sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism. Meanwhile, LTE is considered to operate in the licensed spectrum without more players involved, and therefore, significant modifications to LTE have to be implemented to support coexistence in unlicensed bands. Moreover, a minor effort has been made to prove the proposed models' validity in real-life deployments. Key differences with previous works are summarized as follows:

- Unlike [7]–[9], our approach's validity is tested using COTS Wi-Fi and LTE hardware.
- Although [10] and [11] validated their proposals on hardware, multiple Wi-Fi parameters such as the frame or packet size, the AP's transmission power, network load, and MCS were manually varied to investigate different operation scenarios. Such parameters are not easy to modify under real conditions on legacy devices.
- Authors in [12]–[14] employed several ML techniques to help the LTE decision-making algorithm to give more Tx-Opps to Wi-Fi. Contrary to these works, our proposal implements a ML technique to help Wi-Fi adapt to changing conditions by providing information on the spectrum's use.

III. Coexistence of IEEE 802.11 (Wi-Fi) and Long-Term Evolution (LTE) in unlicensed bands

This section presents the principal aspects that motivate our spectrum management framework for Wi-Fi and LTE coexistence. Additionally, we present our Wi-Fi rule-based management, enhanced by AI.

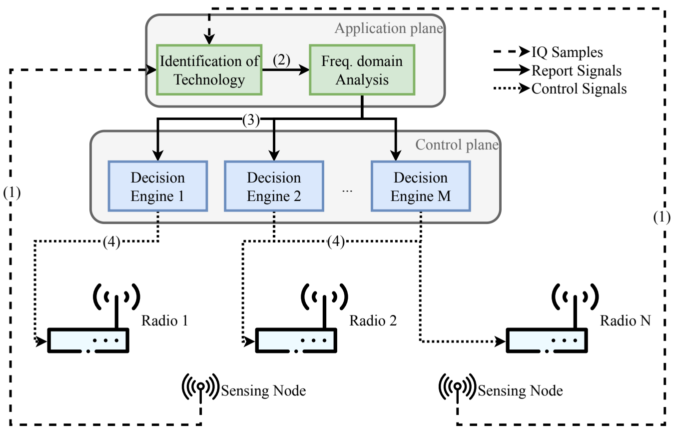

Fig. 1. Proposed spectrum management framework

A. Motivation for Wi-Fi and LTE coexistence in a spectrum management framework

We consider two geographically co-located wireless technologies Wi-Fi and LTE operating simultaneously in the same spectrum. Moreover, we assume that Wi-Fi operates according to the standard, i.e., there is no modification in its standard MAC layer to support spectrum sharing mechanisms.

Under these assumptions, previous literature [7], [17] has shown that according to the CSMA/CA implementation of Wi-Fi, transmissions are only possible after a channel occupancy estimation. In the case of LTE transmissions in a coexistence environment, Wi-Fi nodes detect either that the channel is busy or that there are collisions, resulting in a negative impact on their performance. Therefore, efficient and effective coexistence mechanisms that allow both networks to increase overall performance is vital. Such mechanisms should share information on co-located networks' activities to avoid transmission corruptions and enable global/local optimizations [18].

In that sense, Cognitive Radio approaches based on deep learning techniques [19], [20] help to detect the technology that is accessing the medium. Hence, different management decisions can be made given that some technologies are more benevolent than others [21]. In that way, radios can learn to identify where and when to access the spectrum resources opportunistically. Such deep learning techniques usually do not require feature engineering, making them more attractive to implement in a multi-technology coexistence framework.

B. Framework Architecture

To provide different wireless networks with a broader view of the spectrum resources and help them to make better decisions, we propose a management framework, as depicted in Fig. 1. This framework comprises several steps; on the first step (1) to enable an inter-technology coexistence, a Technology Recognition (TR) module is proposed. This module can detect which technologies are accessing the medium. For this purpose, the TR module receives raw In-phase and Quadrature (IQ) samples from the different co-located radios and identifies their respective signatures. Afterward, (2) a Frequency Analysis (FA) per domain is performed where each identified technology's spectrum occupancy is calculated in each of the monitored frequency channels; (3) this information is shared with different spectrum decision engines that make better-informed decisions suitable to the current working conditions. Once a decision is made, (4) the radios can be notified through control channels. We also highlight in the figure how this management framework can be implemented in an SDN-like architecture. For instance, the TR and FA modules form the application plane while the decision engines form the control plane. Controllers can instantiate applications on an on-demand basis. It is worth mentioning that the decision engines can be separated from the radios or integrated into layer two algorithms to access the medium. The latter is the case of the LTE network.

We implemented the proposed management framework using open-source hardware. Initially, TR monitors two channels, one where Wi-Fi is transmitting and another free channel. The TR and FA modules are integrated into one machine that continuously sends reports of spectrum occupancy of the detected technology on the monitored channels. A co-located LTE simultaneously transmits, causing interference to Wi-Fi. The Wi-Fi controller is connected to the TR module through a publisher/subscriber paradigm. It also implements a rule-based management algorithm that changes its central frequency to a less crowded channel when other technologies' spectrum occupancy is higher than a threshold. In this way, both transmitting technologies can efficiently use the spectrum without performance degradation. The details of the implementation are given as follows.

1) Technology Recognition (TR): Given that technologies beyond 5G are planning to include ML functions in a de-facto mode, our TR module is a CNN-based architecture trained in a semi-supervised way using Autoencoders (AEs) [22]. The architectural design of our TR module is shown in Fig. 2. Thanks to the semi-supervised learning approach, the offline training for wireless technologies recognition is simplified as the amount of labeled data is reduced. The input of the model consists of an IQ vector that is obtained as follows: (i) a Universal Software Radio Peripheral (USRP) B200 mini senses the wireless spectrum at a sampling rate of 20 Msps, (ii) the binary data is interpreted as an IQ stream of data, (iii) the IQ stream is reshaped into a 3-dimensional array with $n = IQ_{length}/1000$ vectors, two dimensions for the IQ components and 1000 samples in the time domain. These vectors are provided to the model, which has been trained to predict three classes: LTE, Wi-Fi, and Noise. The model is trained using both a supervised and unsupervised dataset. The advantage of the model's unsupervised learning capabilities is feature learning without the need for extensive labeled datasets. The AE M_{ED}, as shown in Fig. 2, learns these features by trying to reconstruct the input vector and by having reduced dimensionality at the last layer of the encoder M_E. Afterward, a supervised model M_{EC} is created by attaching a classifier M_C to encoder M_E, which is trained to predict the signal classes, based on the supervised dataset.

The AEs have the following architectural design: the encoder has two convolutional layers with REctified Linear Unit (ReLU) activation function, each one followed by a batch normalization, which accelerates the training, and a dropout layer, which improves generalization. For down-sampling the input, the encoder uses Max-pooling layers and obtains an intermediate code that is 16x smaller than the original input. The decoder follows the same pattern as the encoder but in reverse order; transposed convolutional layers replace the convolutional layers. The supervised part of the architecture comprises the encoder M_E followed by a classifier M_C composed of two dense layers. The last layer has a SoftMax activation function for classification.

2) Rule-Based Wi-Fi management: The Wi-Fi controller then follows the algorithm depicted in Algorithm 1, which is enhanced by AI by having a detailed report of the status of the channels that TR is monitoring. Once a report is received, it checks if the spectrum occupation of different technologies in the current working channel is higher than a given threshold. This threshold represents the maximum spectrum occupation of a technology that Wi-Fi tolerates; it can be dynamically calculated or learned and adjusted per Wi-Fi client to guarantee Quality of Service (QoS) requirements.

Algorithm 1: Wi-Fi ruled-based spectrum manager

```
input : Spectral Occupation per technology per
        channel
output: Operating Channel
while report in queue do
    Receive report from TR ;
    if occupation from other technologies > threshold
     then
        Get current working channel ;
        Rank Channels using Eq. 1 ;
        if Best-ranked channel ≠ working channel then
            Change to best-ranked channel ;
        end
    end
end
```

$$rank = \alpha \cdot \sum_{i \in I, i \neq WiFi} SpOcc_i + \beta \cdot SpOcc_{i,i=WiFi} + \gamma \cdot SpOcc_{free} \quad \forall c \in C \tag{1}$$

If this condition is met, the algorithm ranks every reported channel using Eq. 1, where I is the set of all technologies identified by the TR module, and C is the set of channels that TR is monitoring. α is the weight assigned to the spectrum occupation of other technologies except for Wi-Fi; β is the weight assigned to the spectrum occupation of Wi-Fi and γ is the weight assigned to the unoccupied spectrum. These weights represent the preference of the algorithm. For instance, an unoccupied channel is preferred over a channel with only Wi-Fi transmissions. If the current working channel is different from the best-ranked channel, the controller instructs the AP to change channels. We make use of the Channel Switch Announcement (CSA) procedure defined by the *h* amendment in 2003, which was fully integrated into the IEEE 802.11-2012 standard [6], the most widely supported standard for Wi-Fi transmission. In this procedure, the AP informs the associated Wi-Fi users that the operating channel will change in a given number of beacon frames, so users do not disassociate from the current AP.

3) Long-Term Evolution (LTE): In this study, a private LTE network implementation that can operate in both private and unlicensed bands [23] has been used to introduce interference in the unlicensed channel in which Wi-Fi operates. The private LTE network operates in different frame configurations, with different combinations of uplink, downlink, and blank subframes. By varying the frame configuration of the LTE transmission, the proposed coexistence scheme can be evaluated for different scenarios.

IV. Experimental Validation

This section reports the results obtained during the experimental evaluation of the Wi-Fi performance when LTE is interfering by considering two coexistence approaches.

In the first approach, no collaboration beyond the standard layer two algorithms nor communication exist between the two co-located technologies (non-managed, legacy solution).

The second approach integrates the Wi-Fi controller following Algorithm 1 with the proposed spectrum management framework to mitigate the LTE interference (our solution).

A. Experimental setup

To test our solution, we build a small testbed, as shown in Fig. 3. In particular, we use a Netgear WNDR4300 as AP running OpenWRT 19.07 and a wireless card with Atheros AR9344 chipset using IEEE 802.11n in the 2.4GHz band. Due to frame aggregation, oversized frames such as video are partitioned into multiple sub-frames in IEEE 802.11n. In the case of interference, some sub-frames might be lost. However, on average, the receiver aggregates most of the data to reproduce the original frame, reducing the probability of data loss. Technologies such as IEEE 802.11b/g cannot aggregate frames; thus, the data loss is expected to be more significant. As a consequence, the throughput is even more affected in such technologies. On the contrary, technologies as IEEE 802.11ac allow frame aggregation, and therefore the improvements in throughput are expected to be more or less the same. However, IEEE 802.11n in the 2.4 GHz band was selected because it is a good transition between legacy networks (i.e., b/g) and recent networks (i.e., ac). Moreover, the adoption of IEEE 802.11ac is not so broad as it is for IEEE 802.11n.

As a Wi-Fi controller, we employ an Intel NUC7i5BNH running Ubuntu 18.04 LTS with the Algorithm 1. As a Wi-Fi, client we use a MacBook Air 7,2 with a wireless card

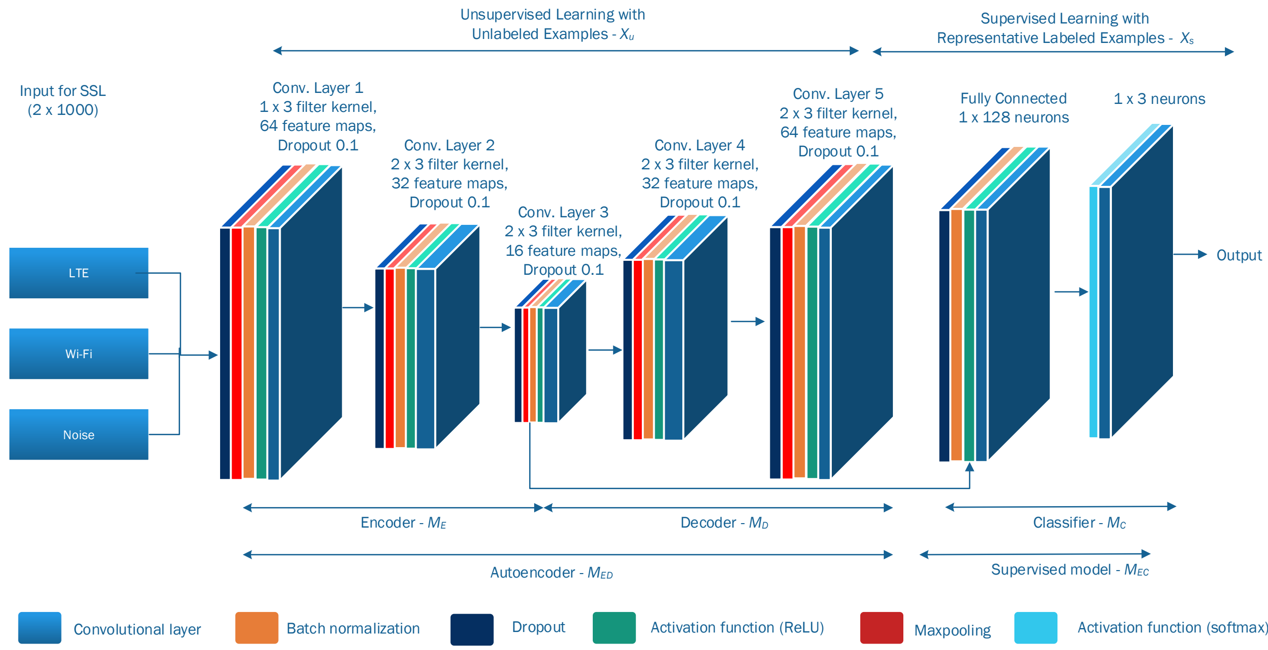

Fig. 2. Semi-supervised learning architecture implemented using AEs.

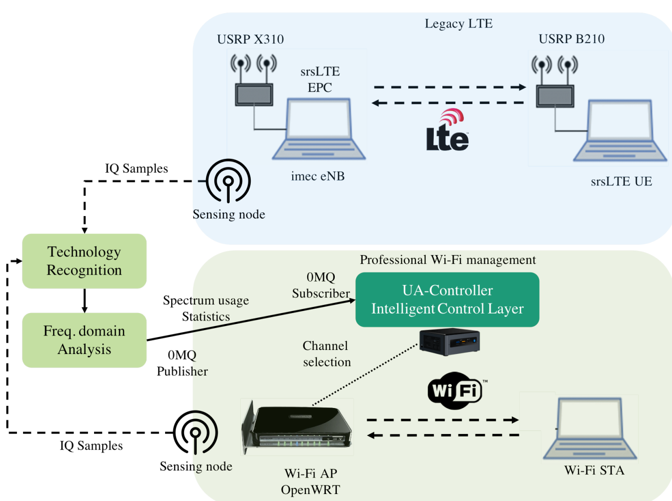

Fig. 3. Small testbed composed of a Wi-Fi setup, a legacy LTE setup and a technology recognition module

Broadcom BCM4360 1.0 (7.77.37.31.1a9). The controller, AP, and client are connected in the same sub-network. We use iperf to generate traffic between AP and client.

The TR module continuously monitors the spectrum and captures IQ samples using USRPs at a sampling rate of 20 MHz. Three USRPs were used and centered at three non-overlapping Wi-Fi channels 1, 6, and 11, respectively, monitoring the complete 60 MHz Wi-Fi spectrum. The IQ samples from each USRP are transformed into data vectors and are provided to the AEs. Finally, the FA module calculates the spectrum occupancy information per technology on each of the three channels from the identification results and publishes it.

As for the LTE part, SDR equipment has been used for the eNB and the UE. The eNB transmits and receives LTE IQ samples using a USRP X310, while the UE uses a USRP B210. Each USRP is attached to a host computer where the corresponding eNB and UE software runs. At the UE side, srsLTE UE software implementation has been used. On the eNB side, the private LTE implementation proposed in [23] is used. The LTE frame configuration was varied to illustrate different traffic scenarios such that the LTE uses different portions of the spectrum. Furthermore, srsLTE core network implementation has been used for the LTE Evolved Packet Core (EPC).

We communicate every system using the publisher/subscriber paradigm implemented in ZeroMQ. Here, the TR module acts as the publisher and is connected to the Wi-Fi controller using other sub-network. The messages containing the spectrum occupation per technology and per channel are formatted using Protocol Buffers. They are sent approximately every 4s to a ZeroMQ queue that later is processed by the Wi-Fi controller.

B. Results and discussion

We performed two sets of experiments on two different days. In the first set of experiments (Day 1), we tested our solution's effectiveness compared to a non-managed solution. During this day, the experiment's room was not completely isolated from other wireless interactions (e.g., other Wi-Fi networks and Bluetooth connections). We generate 30 Mbps

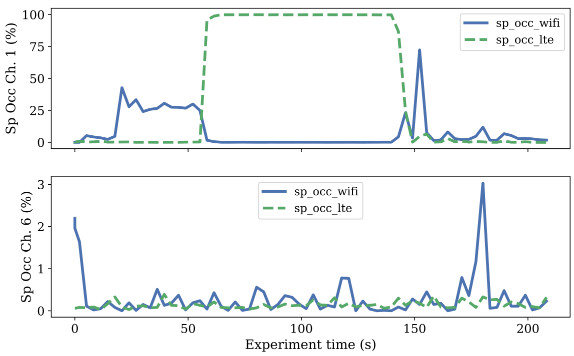

Fig. 4. Spectrum Occupation given by TR in both reported channels, no Wi-Fi management activated

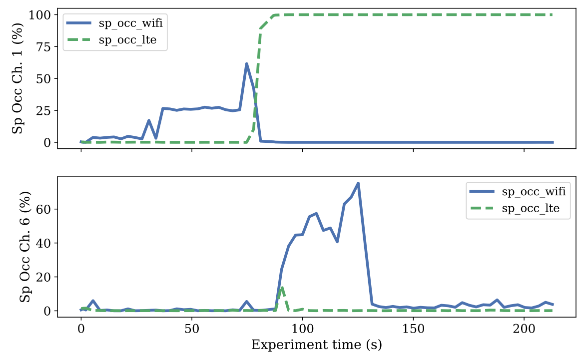

Fig. 6. Spectrum Occupation given by TR in both reported channels, Wi-Fi management activated

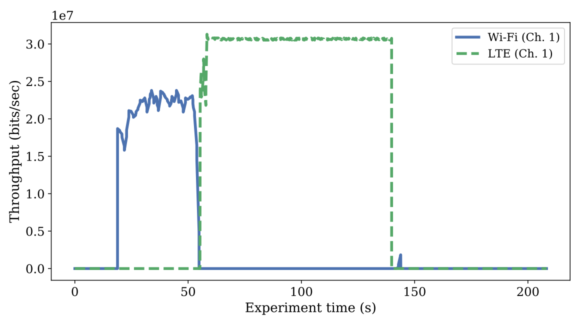

Fig. 5. Effective throughput of Wi-Fi and LTE clients, no Wi-Fi management activated

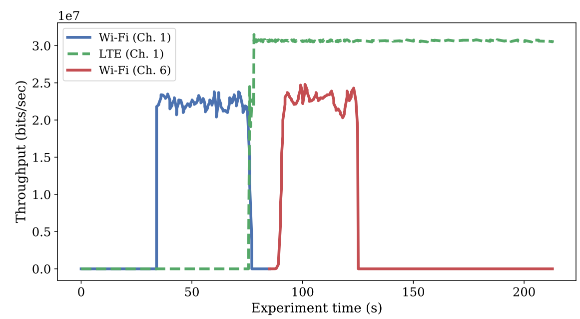

Fig. 7. Effective throughput of Wi-Fi and LTE clients, Wi-Fi management activated

of Wi-Fi UDP traffic from the client to the controller on channel 1. After a while, we start the transmission of LTE, generating 30 Mbps of bi-directional UDP traffic. According to Algorithm 1, our solution is activated if the occupation of other wireless technologies reported by TR is above a threshold, which we set to 40%. Then, the reported channels are ranked according to Eq 1 in which the values for α, β, and γ are set 0.4, 0.3, and 0.3, respectively. The value of α must be low enough, so the impact of other technologies' interference remains low while the value of γ must be high, so an occupied channel is preferred. Later we will show the effect of different parameter values in the threshold. Every experiment has a duration of 2 minutes (120 s) approximately.

Figs. 4 and 5 show the results obtained with the non-managed solution. More specifically, Fig. 4 shows the reports on spectrum occupancy received by the Wi-Fi controller from the TR and FA modules in both channels over time. As can be seen, Wi-Fi occupies around 30% of channel 1, where the transmission was started. Once the LTE traffic starts, the occupation of Wi-Fi drops completely. After the LTE transmission stops, Wi-Fi occupation increases during a short period, probably because it tries to resume its transmissions with a lower MCS.

Wi-Fi performance, in terms of effective throughput, is shown in Fig. 5. As expected, when LTE is not interfering, Wi-Fi freely uses the channel achieving around 20-25 Mbps of throughput. This shows the impact of the interference of more benevolent technologies like Bluetooth. Once the LTE transmission starts, the Wi-Fi throughput decreases as there is no mechanism activated to mitigate LTE's effect. Despite that other channels remain unused, the spectrum occupation of Wi-Fi drops until zero, and contrary, LTE takes control over the entire channel. At the beginning of the LTE transmission, the throughput does not reach its maximum level (30 Mbps) as it has to share the spectrum with Wi-Fi. It is not until Wi-Fi performance degrades that the LTE throughput reaches its maximum.

Figs. 6, and 7 show the results obtained with our solution. Now, the Wi-Fi controller takes action to mitigate LTE interference. The messages received by the Wi-Fi controller from the TR and FA modules reporting the spectral occupation per technology and per channel are shown in Fig. 6. Wi-Fi spectral occupation is around 30%, as in the first case. However, once the LTE transmission starts, the spectrum occupancy increases for a short time as the MCS is lowered to protect current communications. Unlike the first case, this time, the Wi-Fi controller decides to change the AP and its associated clients to channel six as it is reported to be free. As it can be observed, the reported Wi-Fi spectral occupation on channel six increases and remains relatively high until the experiment ends.

The performance regarding throughput in Fig. 7 confirms the effectiveness of our solution. After the threshold of spectrum occupancy of other technologies is reached, the controller decision is triggered, and the CSA is activated. Wi-Fi is briefly affected by the decision of changing channels, which is due to CSA. However, the throughput before the channel change was again achieved. Wi-Fi's reaction time is difficult to assess, given that the experiments were not performed in an isolated environment. Although we defined three beacons to perform the CSA, the time to process this instruction depends on the processes that are present in the AP, plus the time to receive the report from the TR at the controller side. Notice that none of the entities involved in the experiment is synchronized in time.

In the second set of experiments (Day 2), we tested our solution's behavior under different LTE Tx-Opps and compared it with the non-managed solution. This time, an environment without many interfering technologies was set, and 20 Mbps of Wi-Fi UDP traffic and 30 Mbps of bi-directional LTE UDP traffic were generated. Values for α, β, and γ are maintained as in the first experiment.

Fig. 8 shows the averaged throughput of the non-managed and our solution with different threshold levels. An LTE Tx-Opp of 0.8 means that Wi-Fi uses 20% of the spectral resources. As can be seen, the more resources are given to Wi-Fi, the better the performance. More specifically, the throughput of the non-managed solution decreases while our solution can preserve the throughput as the LTE Tx-Opp increases. When LTE operates at a 20% Tx-Opp, the Wi-Fi throughput is more or less similar for both solutions given that Wi-Fi can use 80% of the spectral resources. Unfortunately, LTE performance is severely affected in this configuration. Its effective throughput lies around 3 Mbps, which is a decrease of almost 90% of its expected performance, as shown in Fig. 9. This situation is not desirable as, ideally, a fair coexistence must be achievable. It can also be seen how the Wi-Fi throughput is severely affected by the control signals emitted by LTE at the beginning of the transmission.

Cases where our solution does not perform that well are given when an 80% threshold is used, and LTE is not using all the spectral resources (i.e., a Tx-Opp of 0.5 or 0.8). In such cases, the spectral occupation of other technologies reported by TR is not higher than the threshold. Therefore, no channel transition is made, causing a decrease in performance. Fig. 10 shows the spectrum occupancy on both channels when our solution uses an 80% threshold and LTE is giving 50% Tx-Opp. As it is observed, the reported Wi-Fi occupation is around 80% on channel one until LTE starts its transmission, where both technologies fairly share the spectral resources. However, as shown in Fig. 8, Wi-Fi performance is around 13 Mbps, translated into a decrease of 25% of its expected performance (20 Mbps).

Finally, Fig. 11 shows the effect of the weights (α, β, γ) in the overall throughput. For this experiment, we configured LTE on legacy mode and varied α, β, and γ, as shown in the figure. As the channels' rank is based on the weights and the spectral

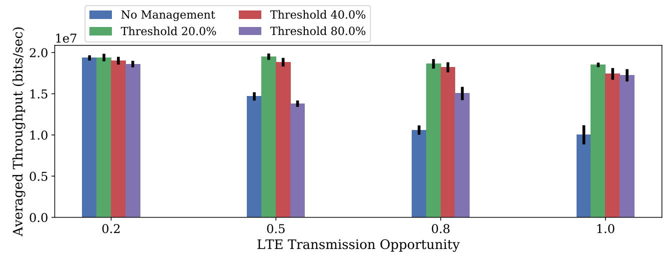

Fig. 8. Averaged Wi-Fi throughput of non-managed solution vs. our solution varying the threshold level under different LTE Tx-Opps

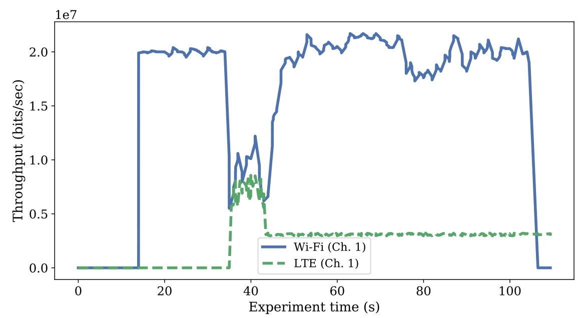

Fig. 9. Effective throughput of Wi-Fi and LTE clients, Wi-Fi management activated, 80% threshold, 20% LTE Tx-Opp

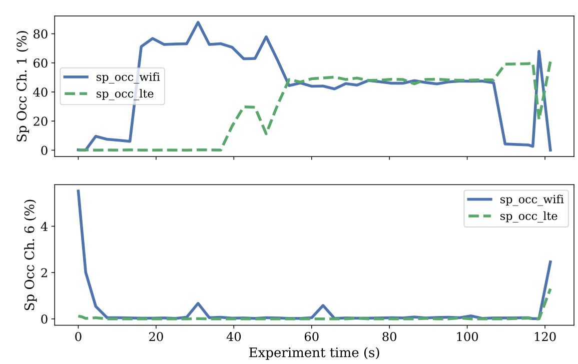

Fig. 10. Spectrum Occupation reported by TR in both channels, Wi-Fi management activated, 80% threshold, 50% LTE Tx-Opp

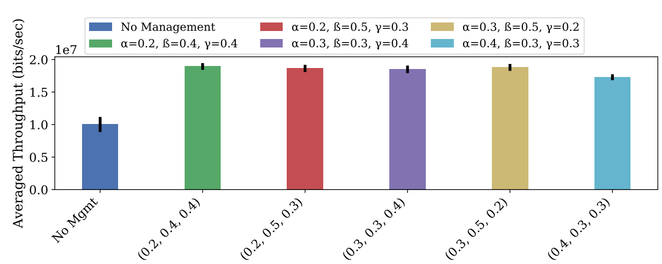

Fig. 11. Averaged Wi-Fi throughput of non-managed solution vs. our solution varying the parameters (α, β, γ) to rank channels

occupation reported by TR, and as both reported channels were only occupied by the transmissions involved in the experiment, the effect of the ranking on the Wi-Fi performance is not that pronounced. The values of α, β, γ used for the first set of experiments represent a non-ideal setting as the achieved throughput is the lowest among the used configurations. This can be explained as follows. α is relatively high; thus, the channel's rank where LTE is causing interference will be higher than the free channel. More significant differences are expected when more wireless traffic is accessing the medium and more channels are available. However, independently of the chosen configuration, the overall throughput of our solution is at least 40% higher compared to the non-managed solution as our proposal has an enhanced view of the spectrum and can transition to a better channel to maintain its throughput.

V. Conclusions and Future Work

In this paper we have proposed a spectrum management framework enhanced by AI for improving coexistence in the unlicensed bands between two widely used technologies, namely, Wi-Fi and LTE. The spectrum management framework is a modular solution composed of Technology Recognition (TR) and Frequency Analysis (FA) modules that identifies the each technology's signatures using a CNN and reports the spectrum occupancy per channel. These modules are integrated with a Wi-Fi controller through a publisher/subscriber paradigm that enhances the controller's view of the spectrum resources.

Moreover, we deployed a testbed to test our solution using open-source software and standard-compliant hardware. We have demonstrated that Wi-Fi can also adapt to guarantee coexistence with other wireless networks if an augmented view of the spectral resources is provided. Results showed that using our approach, Wi-Fi maintains its throughput even when LTE uses all the spectral resources of a given channel. These results can be extended to other Wi-Fi technologies as IEEE 802.11b/g/ac by re-training the TR module to recognize new technologies.

Thanks to the separation of the Wi-Fi controller with the AP, this work can be easily incorporated in much more powerful wireless management frameworks so that handovers can not only be performed at frequency level (using CSA) but also in space (moving clients among physical APs). Additionally, the quality of the decisions can be improved by internal statistics, typically collected by such frameworks. Finally, our interest in this paper was mainly towards LTE's interference and how Wi-Fi can adapt, but given that new wireless technologies are emerging, we can surely exploit TR's capabilities to create a technology-agnostic spectrum management framework.

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