LTE-U and WiFi coexistence in the 5 GHz Unlicensed Spectrum: A Survey

Hager Ben Hafaiedh *, Inès El Korbi*, Leila Azouz Saidane* and Abdellatif Kobbane †
* National School of Computer Science, CRISTAL Lab, University of Manouba, 2010 Tunisia
† ENSIAS, Mohammed V University of Rabat, Morocco
hafaiedhhager@yahoo.com, ines.korbi@ensi.rnu.tn, leila.saidane@ensi-uma.tn, abdellatif.kobbane@um5.ac.ma

***Abstract*—This paper addresses the channel occupation and the channel selection problem for the Long Term Evolution Unlicensed (LTE-U) technology when coexisting with the WiFi system on the unlicensed spectrum (typically the 5 GHz band). For instance, LTE is a communication standard developed by the 3GPP corporation based on the GSM/EDGE and the UMTP/HSPA technologies and conceived for high-spaced wireless communications. If we focus on LTE-U, it is an extension of the LTE-A (LTE-Advanced) scheme in unlicensed bands. In this paper, we will discuss the coexistence matters between the WiFi and LTE-U technologies. Therefore, we review the different solutions discussed in literature that addressed the coexistence issue. These works are either based on fair spectrum allocation between LTE-U and WiFi technologies or on the game theory paradigm where multi channel access and inter-dependance scenarios are discussed. As a future work, we intend to further investigate the coexistence issues between LTE-U and WiFi systems, especially in the case of inter-dependance scenarios and other configurations including hidden/exposed terminal problem in WiFi networks.**

Keywords: LTE-U, WiFi, coexistence, Spectrum allocation, Game theory.

I. Introduction

During the past few decades, the number of communicating devices and the amount of data exchanged between them are continuously growing leading to an exponential increase in demanding resources and QoS requirements across the world. This is why it is expected to find a network technology that is needed to satisfy increasing traffic demands and make better use of the licensed spectrum.

Back in 2014, a band of 295 MHz in the 5 GHz spectrum was opened for unlicensed commercial purpose, which motivates new research activities to use the unlicensed bands along with the licensed ones to bring complementary capacity in Long Term Evaluation (LTE) network based on the current LTE network architecture [12].

The Long Term Evolution (LTE) [2] evolved from an earlier 3GPP system known as the Universal Mobile Telecommunication System (UMTS), which in turn evolved from the Global System for Mobile Communications (GSM).

The Licensed spectrum includes frequencies that are licensed by the government to cellular companies, as an example. The unlicensed frequency bands however, especially the 5 Ghz frequency band, are normally exploited for short scale transmissions which apply to medical, military, scientific and industrial fields. Besides its low cost, since spectrum licensing fees are not required, the unlicensed band is known to be rapid to deploy, leading to unparalleled flexibility in rolling out communications systems. In this context, this paper represents a survey of the different works that addressed the problem of the coexistence between LTE-U and WiFi technologies in the unlicensed bands [1].

The rest of this paper is organized as follows. Section IILTE-U fundamentalssection.2 will explicit the fundamental concepts of the LTE-U technology and how it was designed to increase the bandwidth of the native LTE system that operates on the licensed spectrum. Section IIILTE-U Channel access in the Unlicensed Spectrumsection.3 depicts the different challenges that arise when the LTE-U technology has to co-exist with the WiFi network on the unlicensed spectrum and briefly describes the different solutions in literature that addressed the coexistence problem. In Section IVFair Spectrum Allocation between LTE-U and WiFisection.4, we present the major works that focused on a fair spectrum allocation between LTE-U and WiFi on unlicensed bands. Section VGame Theory based Spectrum Sharing between LTE-U and WiFi Systemssection.5 further investigates the channel allocation problem between LTE-U and WiFi where the medium access attempts, achieved by both technologies, can be modelled as competitive or cooperative games depending on the considered network scenarios. Section VIConclusion and future worksection.6 concludes the paper and presents our future directions.

II. LTE-U fundamentals

The need to ensure the continuity of competitiveness of the 3G systems for the future is becoming more of an emergency as the amount of data and the QoS expectations are growing. Besides, as those expectations become more significant, the cost and complexity of the network deployment and exploitation should be low. Given all these motivations, it was found reasonable that we should exploit the LTE technology in the unlicensed available radio bands in the 5 GHz spectrum [1]. But these bands were initially used by the WiFi technology as it exclusively relies on free radio access on this band. Thus, extending the LTE technology on this unlicensed spectrum, in order to increase the bandwidth resources, is a challenging task as the coexistence on the 5 GHz band must not starve the already established WiFi technology [4].

If we focus on the native LTE technology [2], it brings improved performance, compared to the early 3G system, including peak data rates exceeding 300 Mbps, delays and latencies below 10 ms and manifold spectrum efficiency gains. The LTE unlicensed (LTE-U) is an extension of the regular LTE, developed by Qualcomm for the use of the 4G LTE radio communications technology in the unlicensed spectrum [1]. It is essentially based on the carrier aggregation which allows using multiple communication channels to transfer data in parallel. The unlicensed LTE can potentially provide us with valuable contributions like the reuse of existing infrastructures to reduce additional cost, thanks to the cheapness of the unlicensed spectrum. The whole core network and sites deployed for licensed LTE will be reused in unlicensed spectrum, with only updates in LTE-U base stations (BSs) called eNB (E-UTRAN Node B).

The PHY layer of LTE includes the UL (uplink) and DL (downlink) features. The requirements of this layer are high peak transmission rates, spectral efficiency and multiple channel bandwidths. Therefore, in order to meet these requirements, the Orthogonal Frequency Division Multiplex (OFDM) technology is used due to its robustness against interference and fading, besides the MIMO (Multi Input Multi Output) which helps increasing the channel capacity and increasing the robustness of transmitted signals. The MAC layer, on the other hand, gives an interface between logical and physical channels.

The main expectations of the LTE-U are its ability to take advantage of the existing unlicensed frequency bands, thus ensuring the coexistence with other wireless networks such as WiFi and/or Zigbee. The LTE-U network generic architecture consists of one Base Station (BS) that is central for uplink and/or downlink transmission from/to several User's equipment (UE's).

There are two operation modes for LTE-U:

- The Supplemental Downlink (SDL): only the downlink transmissions are operating in the unlicensed spectrum. Typical applications for this mode are music/file downloading and online video streaming.
- The Time Division Duplex (TDD): both uplink and downlink transmissions can be used in the unlicensed spectrum. Though more expensive, TDD offers the flexibility to adjust the resource allocation between downlink and uplink modes.

From an operational point of view, a common radio access network (RAN) framework across the whole network allows unified operation and management between licensed and unlicensed spectrum, including configuration, authorization, charging and radio resource management (RRM). Moreover, joint scheduling and flexible traffic offload between both layers can be easily achieved, since the secondary component cells (LTE-U layer) could be activated/deactivated by primary cells (LTE layer) in the time scale of tens of milliseconds and the network can select licensed or unlicensed layers for traffic offload in a dynamic way [12]. Figure 1The Carrier Aggregation in LTEfigure.1 illustrates how LTE-U extends the native LTE spectrum through the usage of unlicensed bands.

Due to the unlicensed transmission power limitations [12] and because of the low power restrictions imposed by regula-

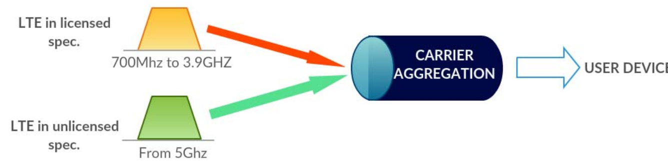

Fig. 1. The Carrier Aggregation in LTE

tions on transmissions in the unlicensed spectrum, the LTE-U technology will be mainly used for small cells (femto and pico cells), even though the small cells may operate on both licensed and unlicensed bands. Also the data meant to be transmitted within the heterogenous network will be classified according to its QoS requirements and reliability. For instance, data that are reliable and have high QoS expectations will be transmitted in licensed spectrum band. The rest of the data will be transmitted in the unlicensed band. To transmit data on the unlicensed bands, LTE-U needs to cope with other technologies such as WiFi or Zigbee. Moreover, several mechanisms can be identified when it comes to the harmonious coexistence, such as channel selection or channel access. In general, those mechanisms exploit the time/frequency domains for the coexistence purpose. In the next Section, we discuss the main issues encountered by LTE-U when trying access the unlicensed spectrum.

III. LTE-U Channel access in the Unlicensed Spectrum

Due to the significant differences between LTE-U and other wireless technologies (such as WiFi), the coexistence/cohabitation of these technologies on the same unlicensed spectrum is a relatively hard task [1]. For instance, on the 5 GHz free accessed spectrum, LTE-U is a very dominant system compared to WiFi: LTE-U systems usually have transmissions in every subframe with meaningful power. Moreover, the WiFi technology is designed with a feature called "Listen mode" which may block the WiFi stations (STAs) from properly accessing the radio resources. Even if a WiFi system has a chance to transmit its packets, the odds of its interference with the LTE-U network will be high.

Another reason that makes the coexistence of LTE-U and WiFi difficult is the lack of compatibility between the radio resource management schemes used by LTE and WiFi. For instance, in LTE-U, the base stations referred as eNBs will achieve a centralized scheduling between UEs when allocating the radio resources. Whereas, in IEEE 802.11-based WiFi [8], all the STAs will execute a distributed coordination function (DCF) based on the Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA) method to estimate the channel availability (idle or busy) each time slot. In [12], the authors discussed the major challenges for the LTE-U/WiFi coexistence. Figure 2Example of LTE-U/WiFi network topologyfigure.2 (GAME THEORY-BASED CHANNEL SELECTION FOR LTE-U,2016,p.17) illustrates a typical topology of an LTE-U network coexisting with a WiFi system.

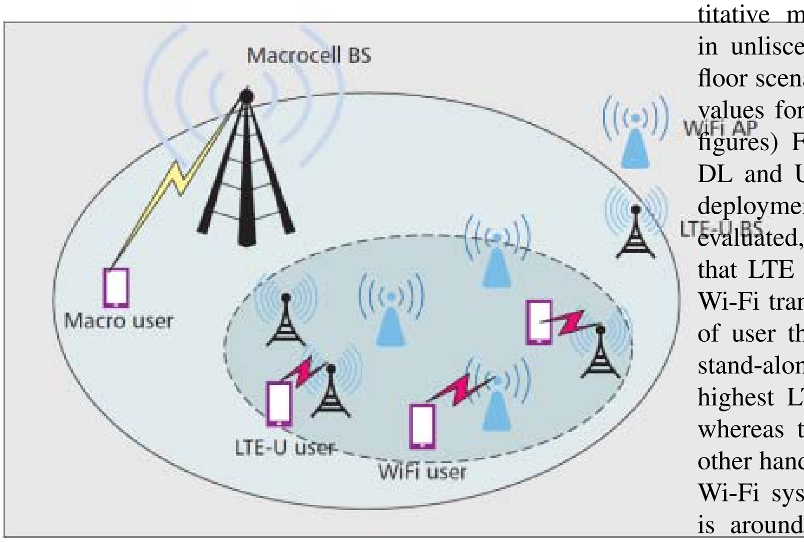

Fig. 2. Example of LTE-U/WiFi network topology

Early works that were interested in the coexistence scenarios between LTE-U and WiFi focused on achieving fair spectrum allocation between both systems. For instance, [14] proposed a Listen Before Talk (LBT) scheme by enabling carrier sensing at each LTE eNB. While the scheme can enable fair coexistence between U-LTE and WiFi, it results in spectrum under-utilization because of the carrier sense operation in the LBT scheme. [3] studied the LTE network's channel access probability using a carrier sense adaptive transmission (CSAT) mechanism for LTE-U transmissions to ensure the fairness between LTE-U and WiFi. A recent work [15] proposed an inter-network coordination architecture to enable dynamic interference management between coexisting LTE-U and WiFi networks. In [16], the authors proposed an LTE-U/WiFi coexistence scheme by allowing LTE and WiFi to transmit together and decode the interfered signals. The scheme requires to redesign the physical-layer protocol stack for both LTE and WiFi networks. Recently, in [17], the authors propose a cognitive based radio access for LTE equipment on the unlicensed bands to ensure a continuous access to wireless STAs and to not starve the WiFi network.

Although the transmission of a portion of small cells traffic on the unlicensed bands will improve the performance of LTE systems, but due to the heterogeneity of the protocols and the devices (BS, UEs, wireless APs, STAs) of both LTE-U and WiFi technologies, new challenges arise to make the coexistence even more efficient. In fact, if the LTE BSs continuously transmit over the unlicensed bands, wireless APs (WAPs) will experience high interference from BSs resulting in large backoff durations that will deteriorate the WiFi network's performance. On another hand, if BSs reduce their traffic on unlicensed bands to cope with WiFi characteristics, this will directly impact the QoS guarantees that can be provided by the BSs in the LTE system.

To backup those results, it was interesting to have quantitative measures of interferences between WiFi and LTE in unliscenced band. In [?],both the single-floor and multi-floor scenarios were discussed,according to chosen parameters values for channel modeling and PHY/MAC of the LTE.(see figures) Figure (i) shows the aggregated (i.e., combined of DL and UL links) mean user throughput for the considered deployment cases. Two sets of number of STAs per system are evaluated, i.e., 10 and 25 STAs. From these results, we observe that LTE system in coexistence mode is slightly affected by Wi-Fi transmissions. For all cases, LTE performance in terms of user throughput is very close to the obtained when LTE stand-alone operation (labeled as LTE only) is employed. The highest LTE user throughput reduction is around 3.85STAs whereas the lowest one is 0and 10 APs/10 STAs. On the other hand, coexistence causes a significant degradation on the Wi-Fi system performance. Wi-Fi user throughput reduction is around 70case (4 APs/25 STAs) and higher than 9810 APs/25 STAs. This happens because Wi-Fi nodes suffer an almost constant and meaningful amount of interference from LTE system along the time. This interference blocks the WiFi channel all the time for most Wi-Fi nodes, making these nodes to stay on LISTEN MODE for a considerable amount of time.

Hence, the traditional spectrum sharing approaches between LTE-U and WiFi networks need to be modified to account for the interdependence between the devices in the two networks which motivates the adoption of game-theoretic solutions [9]-[7]. These solutions can either be based on competitiveness between LTE-U and WiFi or the cooperation between these two technologies. The discussion of game-theory based solutions that addressed the LTE-U/WiFi coexistence issues will be conducted in Section VGame Theory based Spectrum Sharing between LTE-U and WiFi Systemssection.5.

IV. Fair Spectrum Allocation between LTE-U and WiFi

The first category of techniques that addressed the coexistence issue between LTE-U and WiFi technologies are based on fair spectrum allocation between these two technologies. In this category, one of the most notorious schemes is the Listen Before Talk (LBT) scheme, introduced in [14], where a new MAC protocol was proposed for LTE-U BSs to access the spectrum in the presence on an already established WiFi network. The wireless users in this network use the traditional DCF scheme to access the medium. With LBT, the LTE-U BSs are required to detect the channel status before transmission, i.e. whether the target channel is occupied by other systems (such as WiFi or Zigbee) at a millisecond scale. This means that the LTE-U BSs have to wait for a period of time called ”backoff time”, after which if the air is still clear, the device can transmit. With LBT, there will be a lower risk of interference with the WiFi network when the coexistence attempt takes place. Figure 3Listen Before Talk mechanism of the LTE-U BSfigure.3 illustrates how the LTE-U eNBs access the spectrum using the LBT scheme.

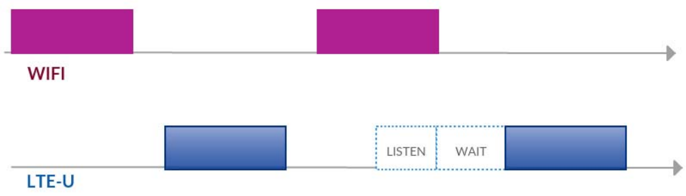

Fig. 3. Listen Before Talk mechanism of the LTE-U BS

To evaluate the performance of LBT when co-existing with the DCF scheme, the authors in [14] proposed an analytical model based on Markov chains to retrieve the capacity of each access network. Therefore, the LBT scheme will be modeled by a Markov chain, as shown in Figure 4The Markov model for the LBT-enabled LTE-U BS when coexisting with WiFi networkfigure.4, where the LTE BS will only access the channel after a fixed sensing window of H time slots. Therefore there will be H states, ranging from 0 to $H-1$, representing the remaining backoff counter of the LTE-U BS. In the case a BS succeeds to reach the unlicensed band, it will occupy it for a duration T_L .

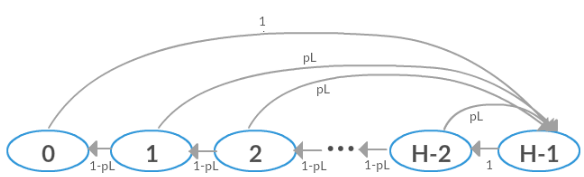

Fig. 4. The Markov model for the LBT-enabled LTE-U BS when coexisting with WiFi network.

In the opposite to the WiFi network, when the LTE-U BS is in state $H-1$, it has almost a probability 1 to find an empty channel. This is due to the fact that the WiFi network in the previous slots should have been in data transmission states and a busy channel appears in this slot only if the WiFi STA(s), that transmitted in the previous slots, transmit again which is very unlikely to happen. Let p_L be the probability that an LTE BS finds the channel busy at any time slot. Now, if the LTE-U BS finds an idle channel in state 0, it accesses the channel for data transmission and then transits to the state $H-1$ to wait for its next channel access chance. We denote by q_h the steady probability of state h. According to the aforesaid procedures, the state transition q_h should satisfy the following conditions:

$$(1-p_L)q_h = q_{h-1}, h\epsilon[1,2,...,H-2] \quad (1)$$

$$\sum_{h=0}^{H-1} q_h = 1 \quad (2)$$

$$q_{H-1} = q_{H-2} \quad (3)$$

From the above system of equations, we can derive the probability that an LTE-U BS transmits its packets, given the collision probability p_L, as:

$$\tau_L = q_0 = \frac{(1-p_L)^{H-2}(p_L)}{1+p_L-(1-p_L)^{H-1}} \quad (4)$$

with:

$$q_h = q_0(1-p_L)^h, h\epsilon[1,2,...,H-2] \quad (5)$$

From the WiFi system perspective, the LBT mechanism can be modelled by considering the DCF feature of the WiFi. DCF operates in a way if a channel is idle for a period of time equal to distributed interframe space (DIFS), the WiFi STA will access the channel to send the data. If the channel is busy, the STA generates a random integer b called "backoff counter", such that: $0 < b < W_0$ .W_0 is the initial contention window. The Backoff counter is used to decrease the collision probability with other potential transmitters from the LTE-U network or the WiFi network itself. The backoff counter decrementing procedure is detailed below:

- At each time slot with length of γ, the STA decrements the backoff counter by 1, if the channel is still available during this slot.
- If during this time slot the channel is busy, the backoff counter will be frozen and will only resume to decrement if the channel is free again for a DIFS.
- If the backoff counter b reaches 0, the STA will automatically transmit its packets, with a risk of collision nonetheless, in which case the contention window W_0 will double its value and the iteration will repeat until the contention window reaches a maximum value after which a new random value of b will be generated.
- If the STA successfully transmits its packet with no collision, the contention window will be reset to its initial value W_0 .

The above DCF procedure is modelled by the Markov chain in Figure 5The WiFi DCF model when co-existing with LTE-Ufigure.5 (Proportional Fairness-based Resource Allocation for LTE-U Coexisting with Wi-Fi,2016,p.6) when coexisting with LTE-U. In this Markov chain, each STA's state will be represented by the couple (m, b) such as m is the remaining number of attempts of the STA's re-transmission of the current packet and b is the "backoff counter" for this packet. p_w is the probability that a STA's packet collides.

By considering the same analysis as for LBT, we can derive the probability that a STA transmits in this network configuration. Performance evaluation of the Markov chains given by figures 4The Markov model for the LBT-enabled LTE-U BS when coexisting with WiFi networkfigure.4 and 5The WiFi DCF model when co-existing with LTE-Ufigure.5 show long term fairness among different users in LTE-U and WiFi networks.

In addition to [14], other less notorious MAC schemes have been proposed for the WiFi/LTE-U coexistence. In [3], a Carrier Sensing and Adaptive Transmission (CSAT) mechanism

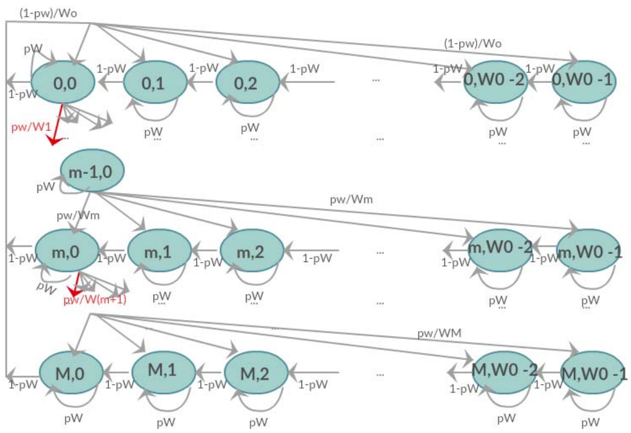

Fig. 5. The WiFi DCF model when co-existing with LTE-U

was introduced to schedule LTE transmissions according to a desired duty-cycle. The CSAT allows the LTE-U network to share the unlicensed band with WiFi networks via time division multiplexing. Despite achieving some fairness with the WiFi network, the CSAT scheme neglects the channel status when a transmission is programmed to start. Moreover, it is considered less fair than LBT regarding the channel allocation because it doesn't abide to the same technical rules as WiFi.

In [6], a resource allocation scheme was proposed to balance the traffic over licensed and unlicensed bands while the throughput of WiFi network is maintained via a utility-based optimization framework. However, in [6], only one UE is considered in the LTE-U network while resource allocation for a multiple-UE scenario requires considerable efforts to achieve the harmonious coexistence among all the devices. Therefore, to account for the requirements of all the devices in both networks, new spectrum sharing techniques should be introduced to achieve an efficient resource allocation in LTE-U/WiFi co-existing networks mainly based on the game theory paradigm.

V. Game Theory based Spectrum Sharing between LTE-U and WiFi Systems

When exploiting the unlicensed spectrum, LTE-U may attempt to use several free accessed "sub-bands" in the available spectrum. In that case, the channel selection is one of the main mechanisms that are vital to the coexistence between LTE and other networks in the unlicensed spectrum. The channel selection consists in finding a 20 MHz operating channel, as shown in Figure 6Dynamic channel selection in the unlicensed bandsfigure.6, that is free for a period of time in order to use it. To achieve efficient resource allocation in LTE-U network on the unlicensed bands, the game theory paradigm has been recently proposed as a good alternative to address such an issue [9]-[7].

For instance the game theory formalism [18] is the study of decision-making, that involves many agents or "players", each of which has to choose an action that either end up with a "reward" or a "sanction". Since the obvious goal of the player in game theory modeled situations is to maximize its gain, the player has to make a strategy or a policy which consists of several actions that will be determined depending on the external environment and the other players' situations. A game-theory based algorithm is considered optimal, if and only if it converges to what it is called the "Nash Equilibrium".

Several works were proposed to use the game theory paradigm, to achieve channel allocation in LTE-U on the unlicensed bands. Most of these works relay on non-cooperative game solutions to achieve spectrum allocation between LTE-U and WiFi systems [9]-[11]. Despite the inter-dependance between the two networking systems, few works consider cooperative game solutions to achieve channel allocation on the unlicensed bands [10]-[7].

One of the early works that considered the game theory paradigm to solve the LTE-U spectrum allocation problem on unlicensed bands is [9]. In particular, [9] proposes a fully distributed approach where each LTE small cell (pico or femto) autonomously selects the channel to set-up an LTE-U carrier. The problem is modeled using a non-cooperative repeated game and the Iterative Trial and Error Learning - Best Action (ITEL-BA) learning algorithm is used to drive convergence towards a Nash Equilibrium.

Therefore, the authors in [9] model their LTE-U system as a set S of small cells (SCs) using the 5 GHz unlicensed band as a supplemental downlink. The total band will be organized in K channels of bandwidth B. Let $A = 1, ..., K$ be the set of available channels. The channel selection problem consists of the decision making process, individually undertaken by each SC to decide the operating channel where it will set up an LTE-U carrier. The global process can be modeled as a repeated game, where each SC is a player in the game. At the beginning of every time step, each player performs an action that consists in the selection of a channel to set-up an LTE-U carrier. Action $a_i(t)\ \epsilon A$ denotes the channel selected by SC i in time step t. At the end of a time step, each SC obtains a reward $r_i(a_i(t))$ or payoff as a result of the selections made by all the SCs.

In order to select the channel, an algorithm called "ITEL-BA" is used for the players. The algorithm can be summarized to three major steps:

1) The player chooses an action according to the policy.
2) The player measures the outcome or reward of that action, taking into account the external environment in order to verify whether or not the player played its part well.
3) Improvement of the action choice for the next round.

Like in every game theory related algorithm, each player has a benchmark action which corresponds to the benchmark reward. This is used in order to be compared to the last action played and its reward to evaluate whether the action outcome was a gain or a loss. The framework proposed in [9] has been evaluated in an indoor scenario under different conditions regarding the number of players and the presence of external

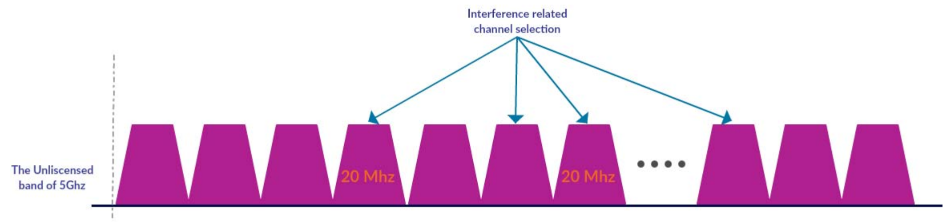

Fig. 6. Dynamic channel selection in the unlicensed bands

influences. Results have revealed the capability of the proposed framework to converge to Nash Equilibrium.

In the same context, the authors in [13] modeled the sharing problem of unlicensed bands among operators as one-shot and repeated non-cooperative game. In [5], a similar problem is also formulated as a repeated non-cooperative game for more general utility functions. The authors in [11] formulated the unlicensed spectrum allocation problem with uplink-downlink decoupling as a non-cooperative game in which the UEs are the players that select the unlicensed channels over which they serve their users. The goal of the UEs is to optimize the uplink and downlink sum-rate while balancing the licensed and unlicensed spectrums between the users.

Despite being interesting, most of these works consider models in which the dependence between the LTE and WiFi networks is ignored. In fact, in LTE-U, the inter-network interactions can significantly impact the outcome of the resource allocation models. Thus, rather than focusing on competition between the two network technologies, LTE-U and WiFi can operate in a cooperative mode to achieve their mutual purposes. In this context, few studies addressed the cooperation between LTE-U and WiFi on the unlicensed bands. For instance, [10] proposed a framework for LTE's cooperation with WiFi in the unlicensed spectrum by designed a reverse auction for the LTE provider to exclusively obtain the channel from the WiFi access point owners by onloading their traffic. Compared to traditional coexistence mechanisms like LBT and CSAT, the auction based cooperation scheme in [10] can potentially avoid the interference between the LTE and WiFi access point owners. In the same context of cooperation, a new multi-game framework was proposed in [7] as a promising approach for modeling resource allocation problems in LTE-U. In such a framework, multiple, co-existing and coupled games can be formulated to capture the specific characteristics of LTE-U equipment and their interdependence with the existing WiFi network.

VI. Conclusion and future work

This paper tackled the coexistence problem between LTE-U and WiFi technologies on the unlicensed spectrum, typically the 5 Ghz band. For instance, due the heterogeneity of components and protocols used by LTE-U and WiFi technologies, a set of issues should be solved before making the co-habitation between these two systems possible and efficient. Therefore, we first presented the concepts of the LTE-U technology and how it was designed to expand the LTE system bandwidth on the unlicensed spectrum. Then, we exposed the different problems/issues that raised when we consider the exploitation of the unlicensed spectrum by LTE-U devices given the presence of the already established WiFi network on these bands. Different solutions have been introduced to address this issue. Some of these solutions proposed fair channel allocation between LTE-U and WiFi. In this context, LBT is the most notorious scheme that allows a proportional radio resource allocation between LTE-U and WiFi. Other solutions, mainly based on the game theory paradigm, considered the problem from a different point of view where LTE-U and WiFi devices have to compete to gain access on the available resources. In this context, most of the works model the coexistence problem as non-cooperative games. Whereas, in reality the interdependence between the two systems is trivial and their cooperation is mandatory to satisfy their respective requirements. Few works, based on the cooperation between LTE-U and WiFi, were proposed in literature to address the spectrum allocation problem. As a future work, we will clearly identify the different network configurations where the cooperation between both systems is required in a way to fit the bandwidth requirements of wireless devices and the quality of service of eNBs/UEs in the LTE-U system. Moreover, more realistic scenarios in the WiFi network should be considered as multi-hop communications, the hidden/exposed terminal problem and the mobility issue.

References

[1] 3GPP TR 36.889, "Study on Licensed-Assisted Access to Unlicensed Spectrum (Release 13)", November, 2014.

[2] 3rd Generation Partnership Project, "Requirements for Evolved UTRA (E-UTRA) and Evolved UTRAN (E-UTRAN) (Release 7)," 3GPP TR 25.913, ,http://www.3gpp.org/ftp/Specs/html-info/25913.htm.

[3] C. Cano and D. J. Leith, "Coexistence of WiFi and LTE in unlicensed bands: A proportional fair allocation scheme," in Proc. IEEE ICC Workshops, London, U.K., Jun. 2015, pp. 2288–2293.

[4] C. Cano, D. López-Pérez, H. Claussen, and D. J. Leith. (2015). Using LTE in Unlicensed Bands: Potential Benefits and CoExistence Issues. [Online]. Available: https://www.scss.tcd.ie/Doug.Leith/pubs/lteWiFi_2015.pdf

[5] F. Teng, D. Guo, and M. L. Honig, "Sharing of unlicensed spectrum by strategic operators," in IEEE Global Conference on Signal and Information Processing (GlobalSIP), 2014, pp. 288–292.

[6] F. Liu, E. Bala, E. Erkip, M. C. Beluri, and R. Yang, "Smallcell traffic balancing over licensed and unlicensed bands," IEEE Trans. Veh. Technol., vol. 64, no. 12, pp. 5850–5865, Dec. 2015.

[7] H. Yu, G. Iosifidis, J. Huang and L. Tassiulas, "Auction-Based Coopetition Between LTE Unlicensed and Wi-Fi", IEEE journal on selected areas in communications, Vol. 35, No. 1, January 2017.

[8] IEEE 802.11 WG part 11b. Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications, Higher Speed PHY Layer Extension in the 2.4 GHz Band, http://www.ieee802.org/11, 1999.

[9] J. Pérez-Romero, O. Sallent, H. Ahmadi, I. Macaluso. "On Modeling Channel Selection in LTE-U as a Repeated Game". In Wireless Communications and Networking Conference, IEEE WCNC 2016, 3-6 April 2016, Doha, Qatar.

[10] K. Hamidouche, W. Saad and Merouane Debbah, "A Multi-Game Framework for Harmonized LTE-U and WiFi Coexistence over Unlicensed Bands", IEEE Wireless Communications Journal, Vol. 23, No. 6, December 2016.

[11] M. Chen, W. Saad, and C. Yin, "Optimized uplink-downlink decoupling in lte-u networks: An echo state approach," in IEEE International Conference on Communications (ICC), Mobile and Wireless Networks Symposium, May 2016.

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

[13] R. Etkin, A. Parekh, and D. Tse, "Spectrum sharing for unlicensed bands," IEEE Journal on Selected Areas in Communications, vol. 25, no. 3, pp. 517–528, 2007.

[14] R. Zhang, M. Wang, L. X. Cai, X. S. Shen, L.-L. Xie, and Y. Cheng, "Modeling and analysis of MAC protocol for LTE-U co-existing with Wi-Fi", IEEE GLOBECOM, San Diego, CA, USA, Dec. 2015, pp. 1–6.

[15] S. S. Sagari, "Coexistence of LTE and WiFi Heterogeneous Networks via Inter Network Coordination," in Proc. of MobiSys PhD Forum, Bretton Woods, NH, June 2014.

[16] S. Yun and L. Qiu, "Supporting WiFi and LTE coexistence," in Proc. of IEEE INFOCOM, Hong Kong S.A.R., PRC, April 2015.

[17] Z. Guan and T. Melodia, "CU-LTE: Spectrally-Efficient and Fair Coexistence Between LTE and Wi-Fi in Unlicensed Bands", in Proc. of IEEE INFOCOM, 2016.

[18] Z. Han, N. Dusit, W. Saad, T. Basar, and A. Hjørungnes, Game theory in wireless and communication networks: theory, models, and applications. Cambridge University Press, 2012.

[19] Andre M. Cavalcante, Erika Almeida, Robson D. Vieira, Fabiano Chaves, Rafael C. D. Paiva and Fuad Abinader,Sayantan Choudhury, Esa Tuomaala and Klaus Doppler, "Performance Evaluation of LTE and Wi-Fi Coexistence in Unlicensed Bands", 2013 IEEE.