Multi-Armed Bandit for LTE-U and WiFi Coexistence in Unlicensed Bands

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***Abstract*—In order to cope with the phenomenal growth of mobile data traffic, unlicensed spectrum can be utilized by the Long Term Evolution (LTE) cellular systems. However, ensuring fair coexistence with WiFi is a mandatory requirement. In one approach, periodically configurable transmission gaps can be used to facilitate a coexistence between WiFi and LTE. In this paper, a Multi-Armed Bandit (MAB) based dynamic duty cycle selection method is proposed for configuration of transmission gaps ensuring a better coexistence for both technologies. Then the concept is further strengthened with downlink power control mechanism using the same algorithm leading to a high energy efficiency and interference reduction. Performance results are given for different user equipment and WiFi station densities in which it is shown that significant improvements in overall throughput and energy efficiency can be achieved.**

***Index Terms*—Energy efficiency, Epoch greedy algorithm, LTE-U, Multi-Armed Bandit, WiFi.**

I. Introduction

The Long Term Evolution (LTE) technology has been the dominant technology in the past several years for broadband wireless communications for higher throughputs, coping with the insatiable traffic demands and better quality of service (QoS) to cellular users. With the proliferation of mobile devices and diverse mobile applications, the wireless data is increasing exponentially every year. Since the licensed spectrum is limited and expensive, one of the solutions is to expand the LTE operation in the unlicensed bands. This is an attractive choice due to the availability of wider bandwidths in 3.5 GHz, 5 GHz, 28 GHz and 60 GHz along with densely congested 2.4 GHz and 900 MHz bands [1]. Further, the solution is backward compatible with existing WiFi devices ensuring an uninterrupted operation of them even for upcoming several years.

The usage of unlicensed spectrum is subject to regulatory requirements and LTE needs to coexist with other technologies like WiFi and radar systems as well as amongst cellular operators. The expansion of LTE-Unlicensed (LTE-U) in the bands of 3.5 GHz and 5 GHz is an enticing choice because of limited spectrum occupancy, low implementation cost, and wider spectrum [2]. Since WiFi adopts a contention based medium access control mechanism with random backoff [3] for channel access and LTE uses dynamic scheduling for users, the unrestrained LTE operation generates continuous interference on WiFi services. Then for a simultaneous operation of LTE-U and WiFi in the same bands, a fair and reasonable coexistence mechanism is an indispensable requirement. The adverse impact on downlink (DL) and uplink (UL) WiFi transmissions due to LTE deployment in the same band is analyzed in [4], [5] emphasizing the need for rigorous studies.

To facilitate coexistence between LTE-U and WiFi in the same band, three techniques are proposed: 1) Listen Before Talk (LBT), 2) Dynamic channel selection (DCS), and 3) Coexistence gaps. In [6], carrier aggregation from licensed to unlicensed band is proposed with LBT using request-to-send (RTS) and clear-to-send (CTS) prior to LTE transmission. In [7], LBT is presented considering inter radio access technology (RAT) and intra RAT. A channel selection policy for LTE-U is suggested by Qualcomm in [2], where LTE duty cycle of ON/OFF transmission is adaptively adjusted based on WiFi activity. The concept is further developed in [8] with Q-learning increasing the overall throughput while sharing the channel. Alternatively a blank subframe allocation mechanism for LTE is presented in [9] where LTE transmission is restrained facilitating the WiFi transmission.

Multi-Armed Bandit (MAB) is a machine learning technique designed to maximize the long-term rewards through learning provided that each agent is rewarded after pulling an arm. In [10], a MAB based distributed channel selection is proposed to use vacant cellular channels in device to device (D2D) communication. To enhance handover process and increase throughput, MAB techniques based context-aware mobility management scheme is studied in [11]. In this paper, we propose a MAB based adaptive duty cycle selection scheme for ensuring coexistence between LTE-U and WiFi. Moreover, a DL power control (PC) scheme is introduced leading to further interference reduction while increasing the overall energy efficiency. Using Time Division Duplex (TDD)-LTE and beacon enabled IEEE 802 systems in the 3.5 GHz band, network performance is evaluated under different percentages of transmission gaps, and for different densities of user equipment (UE), WiFi stations (STAs), base stations (BSs) and WiFi access point (APs).

The rest of the paper is organized as follows. In Section II, we provide details of the considered system model and problem formulation. Section III introduces the proposed MAB based dynamic duty cycle selection approach. Simulation results with various parameter configurations are presented in

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Section IV. Finally, Section V provides concluding remarks.

II. System Model and Problem Formulation

To evaluate the coexistence performance of LTE-U with WiFi in the unlicensed band, a collocated LTE-U and WiFi network scenario is considered. The sets of LTE-U BSs, WiFi APs, LTE-U UEs for BS i and WiFi STAs for AP w are given by $\mathcal{B}_{\mathrm{L}}$, $\mathcal{B}_{\mathrm{W}}$, $\mathcal{Q}_{\mathrm{L}}^{i}$ and $\mathcal{Q}_{\mathrm{W}}^{w}$, respectively. $\mathcal{Q}_{\mathrm{L}} = \left\{\mathcal{Q}_{\mathrm{L}}^{1}, \mathcal{Q}_{\mathrm{L}}^{2}, \ldots, \mathcal{Q}_{\mathrm{L}}^{i}, \ldots, \mathcal{Q}_{\mathrm{L}}^{|\mathcal{B}_{\mathrm{L}}|}\right\}$ and $\mathcal{Q}_{\mathrm{W}} = \left\{\mathcal{Q}_{\mathrm{W}}^{1}, \mathcal{Q}_{\mathrm{W}}^{2}, \ldots, \mathcal{Q}_{\mathrm{W}}^{w}, \ldots, \mathcal{Q}_{\mathrm{W}}^{|\mathcal{B}_{\mathrm{W}}|}\right\}$ represent the sets of all UEs and STAs. For LTE-U, TDD-LTE is considered. For synchronization of WiFi STAs with the corresponding APs, a periodic beacon transmission is used as in [8].

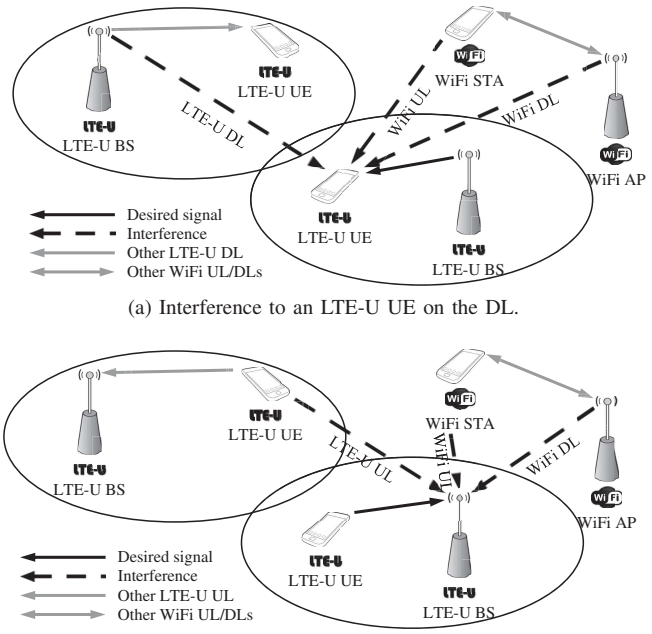
*1) **Interference on DL and UL Transmissions**:* Interference caused to an LTE-U UE and an LTE-U BS during DL and UL transmissions are shown in Fig. 1. A similar TDD frame structure to that in [12, Fig. 6.2] under synchronous operation is considered for all the BSs and UEs. As shown in Fig. 1(a), in the simultaneous operation of an LTE-U UE within a WiFi coverage area, the DL LTE-U radio link experiences interference from other LTE-U DL and WiFi DL/UL transmissions. During an UL transmission subframe, shown in Fig. 1(b), LTE-U BS is interfered by the UL transmission of LTE-U UEs, as well as the UL/DL transmissions of both WiFi STAs and WiFi APs. Similarly, WiFi DL transmission is interfered by other LTE-U DLs where the UL received signal of a WiFi AP is interfered by other LTE-U UL transmissions. In the coexistence scenarios, WiFi transmissions get delayed degrading their capacity performance due to the use of carrier sense multiple access with collision avoidance (CSMA/CA) mechanism [13]. This is an additional degradation other than the performance reduction experienced due to LTE-U transmissions operated on the same spectrum and this is valid only for WiFi APs and STAs.

*2) **Duty Cycle of LTE-U**:* In the case of designing a duty cycle for LTE-U, multiple LTE TDD frames are considered. For that purpose, five consecutive LTE frames [12, Fig. 6.2(a)] are used to construct a duty cycle. Similar to [8], the LTE-U transmission ON/OFF condition is used to define a duty cycle which is shown in Fig. 2 (e.g., 40% duty cycle: during the first two consecutive LTE-U frames, transmission is turned on and it is turned off during the following three frames). One out of these two configurations is used by the UEs and BS in an LTE cell during a duty cycle period. According to this structure, a constant UL:DL duty cycle value is maintained.

*3) **Capacity Calculation and Power Control**:* For any BS, there are R resource blocks (RBs) for the DL. For a given UE u associated to BS i, R_u^i RBs are allocated where $R = \sum_{u=1}^{|\mathcal{Q}_{\mathrm{L}}^{i}|} R_u^i$. $p_{s,r}^{i}$, $p_{s,r}^{b}$, $p_{s,r}^{a}$ and $p_{s,r}^{q}$ are transmit power values associated with RB r and the transmit power index s from the LTE-U BS i, LTE-U BS $b\,(i \neq b)$, WiFi AP a and WiFi STA q. The ith BS is considered as the desired BS where the BSs indexed by p are the interference generating BSs. For any BS, AP, UE or STA total transmit power is equally distributed among all RBs. However in every BS, the total transmit power is dynamically changed for every duty cycle. The $h_{u,r}^{i}$, $h_{u,r}^{b}$, $h_{u,r}^{a}$ and $h_{u,r}^{q}$ are the channel gain values from BS i to UE u from BS b to UE u, from AP a to UE u and from WiFi STA q to UE u, respectively. All channel gain values are taken after accounting for path losses and shadowing. In that case interference generated to UE u from BSs, APs and STAs are given by I_{BS}^{u}, I_{AP}^{u} and I_{STA}^{u}, respectively. Since a synchronized transmission is considered, there is no interference from the UL transmission of LTE-U UEs. Noise variance is denoted by σ^2. The Signal-to-Interference-plus-Noise Ratio (SINR) expression for UE u served by BS i on RB r at time interval n is given as

$$\mathrm{SINR}_{u,r}^{i}[n] = \frac{p_s^i h_{u,r}^{i}}{\underbrace{\sum_{b\in\mathcal{B}_{\mathrm{L}}\setminus i} p_s^b h_{u,r}^{b}}_{I_{\mathrm{BS}}^{u}} + \underbrace{\sum_{a\in\mathcal{B}_{\mathrm{W}}} p_s^a h_{u,r}^{a}}_{I_{\mathrm{AP}}^{u}} + \underbrace{\sum_{q\in Q_{\mathrm{W}}} p_s^q h_{u,r}^{q}}_{I_{\mathrm{STA}}^{u}} + \sigma^2}, \quad (1)$$

where $b, i \in \mathcal{B}_{\mathrm{L}}$. The amount of successfully transmitted data bits N_{B} from the ith LTE-U BS during T_{OFDM} time interval



(a) Interference to an LTE-U UE on the DL.

(b) Interference to an LTE-U BS on the UL.

Fig. 1: DL and UL interference scenarios for LTE-U transmissions.

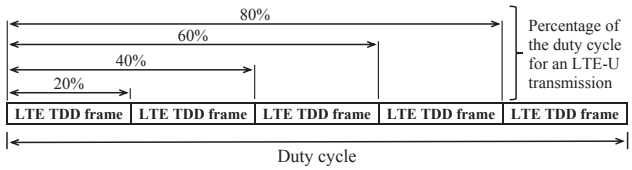


Fig. 2: Structure of the duty cycle.

n within an active DL subframe/s of a duty cycle is given by

$$N_{\mathrm{B}}^{i} = \sum_{n}^{\mathcal{N}^{i}} \sum_{u \in Q_{\mathrm{L}}^{i}} \sum_{r}^{R_u} W_{u,r}^{i} \log_2 \left(1 + \mathrm{SINR}_{u,r}^{i}\left[n\right]\right) T_{\mathrm{OFDM}}. \quad (2)$$

T_{OFDM} is the orthogonal frequency division multiplexing (OFDM) symbol duration, $T_{\mathrm{Tx}}^{i} = \mathcal{N}^{i} T_{\mathrm{OFDM}}$ and $\mathcal{N}^{i}$ is the total number of transmit T_{OFDM} time intervals for the considered duty cycle. The total allocated bandwidth for RB r for UE u served by BS i is $W_{u,r}^{i}$. The average capacity over a duty cycle period is used as a performance measure in this study as in [8]. The DL capacity C_i of LTE-U BS i is given as

$$C_i = \frac{N_{\mathrm{B}}^{i}}{T_{\mathrm{Tx}}^{i} + T_{\mathrm{Wait}}^{i}}, \quad (3)$$

where T_{Wait}^{i} is the waiting time due to silent subframe allocation.

The capacity C_i in (3) is used as a performance measure for each LTE-U BS. Since the transmit power of one BS contributes to the interference power of the other BS, neighboring BSs are coupled in terms of interference. The goal of every BS is to maximize C_i while minimizing the DL transmit power $p_s^i, \forall i \in \mathcal{B}_{\mathrm{L}}$. By minimizing the transmit power values p_s^i and p_s^b, the goal is to achieve a comparatively higher energy efficiency than the case of constant DL transmit power. In the same time a reduction in interference is also expected while guaranteeing a minimum capacity. Moreover, $P_{\min} \leq p_s^b \leq P_{\max}$ where $P_{\min}$ and $P_{\max}$ are the minimum and maximum transmit power constraints, respectively. The minimum capacity corresponding to a given action is denoted by $C_j^{\min}$. The objective is to maximize the average capacity while minimizing the transmit power, which can be written as:

$$\text{maximize} \quad \frac{\sum_{i=1}^{|\mathcal{B}_{\mathrm{L}}|} C_i}{|\mathcal{B}_{\mathrm{L}}|} \quad (4)$$

$$\text{minimize} \quad p_s^i \qquad \forall i \in \mathcal{B}_{\mathrm{L}} \quad (5)$$

$$\text{subject to} \quad \left\{p_s^i, p_s^b\right\} \leq P_{\max}, \ \forall i, b \in \mathcal{B}_{\mathrm{L}}, \quad i \neq b, \ s \in S \quad (6)$$

$$\left\{p_s^i, p_s^b\right\} \geq P_{\min}, \ \forall i, b \in \mathcal{B}_{\mathrm{L}}, \quad i \neq b, \ s \in S \quad (7)$$

$$C_i > C_j^{\min}, \quad \forall i \in \mathcal{B}_{\mathrm{L}}, \forall j \in J. \quad (8)$$

In the case of energy efficiency, several parameter configurations are considered for (8) as

$$\frac{C_i}{p_s^i} > \frac{C_j^{\min}}{p_s^i}, \text{ or } \frac{C_i}{p_s^i} > \frac{C_j^{\min}}{P_{\min}}, \text{ or } \frac{C_i}{p_s^i} > \frac{C_j^{\min}}{P_{\max}}. \quad (9)$$

Due to same denominator, $\frac{C_i}{p_s^i} > \frac{C_j^{\min}}{p_s^i}$ is simplified to (8), which can be used as a proportional measure of energy efficiency. The problem is reformulated defining a new objective to maximize energy efficiency as follows:

$$\text{maximize} \quad \frac{\sum_{i=1}^{|\mathcal{B}_{\mathrm{L}}|} \frac{C_i}{p_s^i}}{|\mathcal{B}_{\mathrm{L}}|} \quad (10)$$

$$\text{subject to} \quad (6), (7) \text{ and } (9).$$

III. MAB Techniques for LTE-U WiFi Coexistence

In order to dynamically optimize LTE-U transmission parameters, (i.e., duty cycle and transmit power), a variant of MAB learning techniques, called Epoch-Greedy [14] algorithm is applied. The scenario is formulated as a multi-agent problem $\mathcal{G} = \left\{\mathcal{B}_{\mathrm{L}}, \{\mathcal{A}_i\}_{\{i \in \mathcal{B}_{\mathrm{L}}\}}, \{C_i\}_{\{i \in \mathcal{B}_{\mathrm{L}}\}}\right\}$, considering the BSs as players where $\mathcal{A}_i$ is the action set for player i. During the entire process, each BS needs to strike a balance between exploration and exploitation, where there are M exploration and L exploitation steps, indexed with m, $1 \leq m \leq M$, and l, $1 \leq l \leq L$, respectively.

- **Agents:** LTE-U BSs, $\mathcal{B}_{\mathrm{L}}$.
- **Action:** The action set of agent i, $\mathcal{A}_i$ is defined as $\mathcal{A}_i = \left\{d_j^i, p_s^i\right\}_{j \in J, s \in S}$. $\left\{d_j^i, p_s^i\right\}$ is the pair of duty cycle and transmit power elements. Configurations of duty cycles are used as part of the action space $\mathcal{D}$ where $\mathcal{D}$ is common for all players. A given BS i selects d_j^i, $d_j^i \in \mathcal{D}$ according to the Algorithm 1 where $J = \{1, 2, \ldots, |\mathcal{D}|\}$, $j \in J$ and $J \in \mathbb{Z}^+$. Probability spaces of positive integers is denoted by $\mathbb{Z}^+$. The set of first elements of the action vector $\mathcal{D}_i = \left\{d_1^i, d_2^i, \ldots, d_{|\mathcal{D}|}^i\right\}$ of BS i is associated with the duty cycles as $\{20\%, 40\%, \ldots, 80\%\}$, respectively. The transmit power values set $\mathcal{P}$ is represented as $S = \{1, 2, \ldots, |\mathcal{P}|\}$, $s \in S$ and $S \in \mathbb{Z}^+$. p_s^i is the transmit power of player i where $\mathcal{P}_i = \left\{p_1^i, p_2^i, \ldots, p_{|\mathcal{P}|}^i\right\}$. However, in the case of PC, if $C_i > C_j^{\min}$, s is decreased by one $(s \leftarrow s - 1)$ reducing the transmit power p_s^i by one level for the next step $m + 1$ and vice versa. Further, when $C_i > C_j^{\min}$ a reward.
- **Decision function:** The DL capacity of a BS i, C_i is used as the utility function. In order to select a duty cycle, a decision function based on the policy UCB1 [15] is used where the accumulated rewards achieved due to values given by C_i are exploited. The decision value for the duty cycle d_j^i related to the exploration step m of BS i, $v_{i,m}\left(d_j^i\right)$ is given in (11) while d_k^i based on the decision is given in (12),

$$v_{i,m}\left(d_j^i\right) = \bar{x}_{i,m}\left(d_j^i\right) + \sqrt{\frac{2\ln\left(m + |\mathcal{D}_i|\right)}{n_{i,m}\left(d_j^i\right)}}, \quad (11)$$

$$d_k^i = \underset{d_j^i \in \mathcal{D}_i}{\arg\max}\left(v_{i,m}\left(d_j^i\right)\right), \quad (12)$$

where $\bar{x}_{i,m}\left(d_j^i\right) = \frac{R_i\left(d_j^i\right)}{n_{i,m}\left(d_j^i\right)}$. The argument of the maximum value is given by $\arg\max(\cdot)$. $\bar{x}_{i,m}\left(d_j^i\right)$, $R_i\left(d_j^i\right)$ and $n_{i,m}\left(d_j^i\right)$ are the average reward obtained from d_j^i during the exploration step m, total rewards gained form the same d_j^i and the total number of times d_j^i has been played, respectively. Selection of s is totally independent from the decision function.

The multi-agent learning problem is addressed using a MAB algorithm. In the contextual MAB problem handled by the Epoch-Greedy algorithm [14], current and previous

information (i.e., history) are used for the selection of an arm or (i.e., action). This scheme is an extended version of the ϵ-Greedy algorithm. Initially $d_j^i, \forall j \in J$ are played once with $p_s^i = p_{|\mathcal{P}|}^i$. Based on the accumulated reward $R_i\left(d_j^i\right)$, the parameters s, $n_{i,0}\left(d_j^i\right)$ and $v_{i,0}\left(d_j^i\right)$ are updated. In the learning process, the accumulated reward is used to play the role of the accumulated hypothesis defined in [14]. Subsequently, agents balance between M exploration and L exploitations steps. During the exploration steps, d_j^i is selected randomly where d_j^i, $d_j^i \in \mathcal{D}_i$, $j \in \{\mathcal{U}\left(1, |\mathcal{D}_i|\right) \cap J\}$ where a uniform distribution with the minimum and maximum values x_1 and x_2 are given by $\mathcal{U}\left(x_1, x_2\right)$. s is decided based on the last available values of (8). Subsequently the same set of parameters is updated. At the end of each exploration step, based on (8) and the accumulated rewards an action is selected. Then the same action is repeatedly played for all the L exploitation steps of that particular exploration step as explained in Algorithm 1.

Algorithm 1 Epoch-Greedy Algorithm

Initialization:
Set the minimum capacity values $C_j^{\min}$, $\forall j \in J$. Select $d_j^i, \forall j \in J$, update s, $n_{i,0}\left(d_j^i\right)$, $v_{i,0}\left(d_j^i\right)$ and accumulated hypothesis / reward $R_i\left(d_j^i\right)$ based on $C_i > C_j^{\min}$
Exploration:
for $m = 1, 2, 3, ..., M$ **do**
  Select d_j^i, $d_j^i \in \mathcal{D}_i$, $j \in \{\mathcal{U}\left(1, |\mathcal{D}_i|\right) \cap J\}$ and update s, (8)
  Execute $\left\{d_j^i, p_s^i\right\}$, observe C_i and update $n_{i,m}\left(d_j^i\right)$
  if $C_i > C_j^{\min}$ **then**
    Reward, $R_i\left(d_j^i\right) = R_i\left(d_j^i\right) + 1$
    Update s $(s \leftarrow s - 1)$ and $v_{i,m}\left(d_j^i\right)$, (11)
  else
    Reward, $R_i\left(d_j^i\right) = R_i\left(d_j^i\right) + 0$
    Update s $(s \leftarrow s + 1)$ and $v_{i,m}\left(d_j^i\right)$, (11)
  end if
  if $R_i\left(d_j^i\right) = R_i\left(d_a^i\right)$, $d_j^i, d_a^i \in \mathcal{D}_i$, $j \neq a, \forall j, a \in J$ **then**
    Select d_k^i, $d_k^i \in \mathcal{D}_i$, $k \in \{\mathcal{U}\left(1, |\mathcal{D}_i|\right) \cap J\}$
  else
    Select d_k^i, (12)
  end if
  Exploitation:
  for $l = 1, 2, 3, ..., L$ **do**
    Execute the action $\mathcal{A}_i = \left\{d_k^i, p_s^i\right\}$
  end for
end for

IV. Simulation Results

For LTE-U, TDD-LTE is considered and it is assumed that all the LTE-U UEs are synchronized in both time and frequency domains as in [8] with the serving BSs. A beacon is transmitted periodically for the purpose of synchronization of WiFi STAs with the corresponding APs. To evaluate the performance, an architecture containing two independently operated layers of cellular deployments is considered as shown in Fig. 3. Hexagonal cells with omni directional antennas are assumed. LTE-U layer encompasses $|\mathcal{B}_{\mathrm{L}}| = 7$ BSs and $|\mathcal{Q}_{\mathrm{L}}|$ UEs where the WiFi layer includes $|\mathcal{B}_{\mathrm{W}}| = 7$ APs and $|\mathcal{Q}_{\mathrm{W}}|$ WiFi STAs. In each cell, for each AP/BS, STAs/UEs are dropped at random locations. All of them are

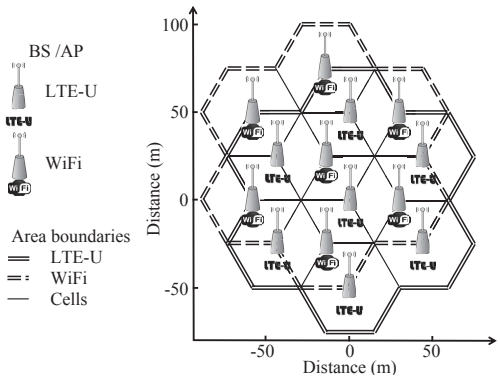


Fig. 3: Cellular coverage layout.

assumed to be uniformly distributed within the cells of their serving BSs having a mobility speed of 3 km/h. The traffic arrival rates for LTE-U and WiFi are $\lambda_{\mathrm{LTE}} = \lambda_{\mathrm{WiFi}} = 2.5$. The LTE and WiFi IEEE 802.11n medium access control (MAC) and physical (PHY) layers are modeled in which a PHY layer abstraction is used for Shannon capacity calculations of WiFi and LTE-U at the granularity of each WiFi OFDM symbol duration of 4 μs obtaining the number of successfully received bits [8]. For both technologies wireless channel is modeled according to [16], when the systems are operated in the 3.5 GHz band. Indoor Hotspot (InH) scenario is considered with path loss and shadowing parameters. FTP Traffic Model-2 [16] is employed for either WiFi and LTE-U with a noise spectral power density of -95 dBm/Hz.

In each transmission time interval (TTI), DL SINR is reported to the corresponding BS. Based on the number of LTE-U UEs waiting and requesting UL transmission during one sub frame, bandwidth is equally shared among themselves. The simulation parameters for LTE-U transmissions are summarized in TABLE I. TDD configuration 1 [12, Fig. 6.2(a)] is used for the LTE-U frames having a 50 ms total duty cycle period. Minimum required capacity level $C_j^{\min}$ is 10 Mbps and the set of power levels is $\mathcal{P}_i = \left\{p_1^i, p_2^i, \ldots, p_{|\mathcal{P}|}^i\right\} = \{8, 13, 18, 23\}$ dBm.

TABLE I: LTE MAC/PHY Parameters.

Parameter	Value
Frequency	3.5 GHz
Transmission Scheme	OFDM
Bandwidth	20 MHz
DL Tx Power	40 dBm
UL Tx Power	PL Based TPC
Frame Duration	10 ms
Scheduling	Round Robin
UL Base Power Level P_0	-106 dBm
TTI	1 ms

For WiFi, CSMA/CA with enhanced distributed channel access (EDCA) and clear channel assessment (CCA) has been implemented. All WiFi STAs with traffic in their queue will compete for channel access after receiving a beacon transmission. Without reception of a signal beacon, transmission or reception will not be initiated. The WiFi STA will sense the

channel and will transmit if it is idle. Otherwise transmission will be backed off and the next transmission will be initiated after a backoff time. Random backoff time mechanism is used for this study. All the parameters for the WiFi transmission are summarized in TABLE II.

TABLE II: WiFi MAC/PHY Parameters.

Parameter	Value
Frequency	3.5 GHz
Transmission Scheme	OFDM
Bandwidth	20 MHz
DL/UL Tx Power	15 dBm
Access category	Best Effort
MAC protocol	EDCA
CCA Channel sensing threshold	-82 dBm
CCA Energy detection threshold	-62 dBm
No of service bits in PPDU	16 bits
No of tail bits in PPDU	12 bits
Contention window size	$\mathcal{U}(0, 31)$
Noise figure	6
Beacon interval	100 ms
Beacon OFDM symbol detection threshold	10 dB
Beacon error ratio threshold	15

A comprehensive UL:DL aggregate capacity / throughput performance comparison for both LTE-U and WiFi with $\left|\mathcal{Q}_{\mathrm{L}}^{i}\right| = 10$ and $|\mathcal{Q}_{\mathrm{W}}^{w}| = 10$ is presented in Fig. 4. Capacity of WiFi transmission when there is no LTE-U service and capacity of LTE-U transmission when there is no WiFi activity are indicated by the black dashed lines. Duty cycles based transmissions for LTE-U operations are also presented. It is shown that LTE-U capacity is almost linearly increased whereas WiFi capacity is significantly decreased with the increase of duty cycle percentages (DCPs). Overall throughput is also deceased with the increase of DCP, and a clear increase in capacity is seen.

Compared to fixed DCP scenarios, with the use of MAB algorithm, overall capacities are increased. Performance of Epoch-Greedy algorithm with and without PC is presented in the same figure. No significant influence could be observed for LTE-U throughputs due to PC. Even though it is not quantified, both interference caused by LTE-U BSs and the energy consumption at the BSs are reduced due to PC mechanism. When there is a PC mechanism, a degradation in performance particularly in the WiFi activities also can be seen. Capacity reduction of WiFi is caused by the behavior of LTE-U transmissions and CSMA/CS technique. As given by Fig. 4, in all the cases a severe performance degradation of LTE-U could be seen in the presence of WiFi transmissions, when compared to the case with only LTE-U transmission. In other words, a very high sensitivity for interference is shown by LTE-U. The same behavior is shown by WiFi as well where there is a considerable throughput reduction compared to the scenario with no LTE-U transmission.

The aggregate capacity performance of LTE-U UEs and WiFi STAs under different densities is given in Fig. 5. There is a capacity improvement with reductions of users in both services. Comparatively high sensitivity could be seen when the density of STAs are changed. When the densities are reduced, particularly the STAs, a significant increase in capacity is

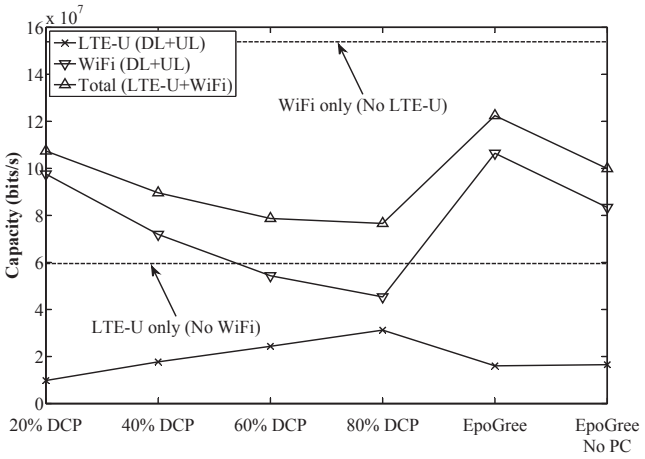


Fig. 4: LTE-U and WiFi UL/DL capacities.

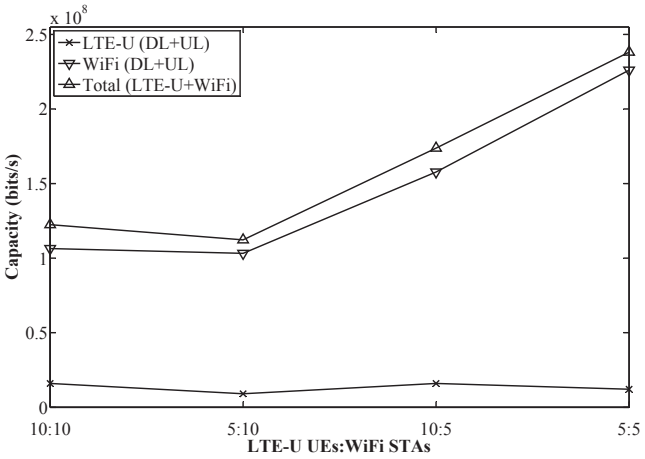


Fig. 5: Comparison of different UE and STA configurations.

achieved under reduced interference conditions. However this reduction is further contributed by the CSMA/CS mechanism as well.

Aggregate capacity of LTE-U and WiFi networks for different power control techniques with $\left|\mathcal{Q}_{\mathrm{L}}^{i}\right| = 10$ and $|\mathcal{Q}_{\mathrm{W}}^{w}| = 10$ are presented in Fig. 6. Four parameter settings are used for PC. In the fist instance, no PC is considered. In the second case, PC is used by replacing the parameters in Step 7 of the Algorithm 1 with $\frac{C_i}{p_s^i} > \frac{C_j^{\min}}{P_{\min}}$ where $P_{\min} = 8$ dBm. For the third and forth cases, parameters are replaced with $\frac{C_i}{p_s^i} > \frac{C_j^{\min}}{P_{\max}}$ and $C_i > C_j^{\min}$ where $P_{\max} = 23$ dBm. The set of power levels is defined as $\mathcal{P}_i = \left\{p_1^i, p_2^i, \ldots, p_{|\mathcal{P}|}^i\right\} = \{8, 11, 14, 17, 20, 23\}$ dBm where $P_{\min} = 8$ dBm and $P_{\max} = 23$ dBm. In the second and third cases a given level of energy efficiency is aimed at. In the last case, according to the explanation given for (9), the level is dynamically adjusted. However, in terms of capacity, the best and worst results are shown under the second and third configurations, respectively. The capacity of third configuration is even higher than 60% DCP LTE-U (DL+UL) scenario.

Different UE and STA densities are considered to evaluate

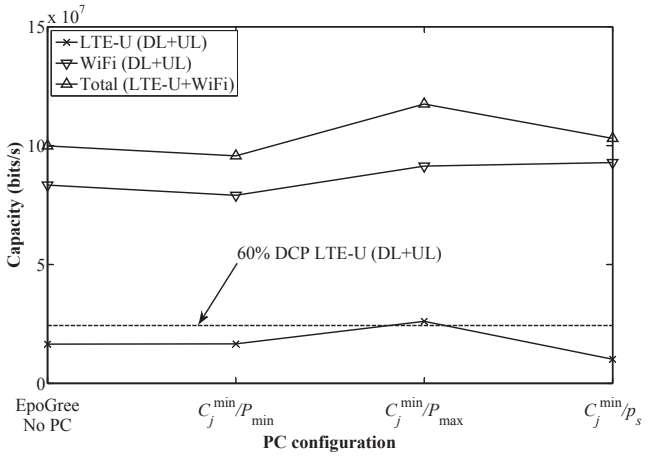


Fig. 6: Capacity of 10UEs: 10STAs case with different PC configurations.

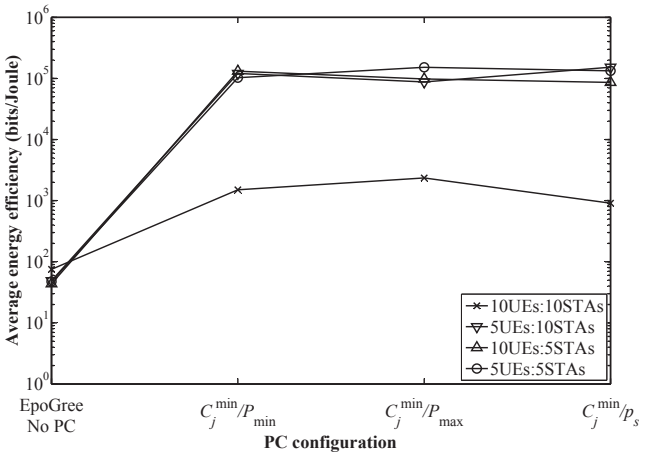


Fig. 7: Energy efficiency under different PC configurations.

energy efficiency performance in Fig. 7. For all the densities, the least efficiency is achieved with no PC. In the most dense scenario, the best efficiency can be observed under the third configuration, $\frac{C_j^{\min}}{P_{\max}}$. As it is expected with the reduction of densities, energy efficiency is increased. However after a certain average energy efficiency level, no significant improvements could be observed.

The objectives, subsequently the gains, of this study are not limited to throughput enhancements. The benefits that are achieved in different dimensions with the aid of MAB scheme and the other supporting techniques like PC can be summarized as: 1) Proper coexistence of either techniques is guaranteed increasing the aggregate capacity values than certain DCPs. Due to the application of MAB algorithm, optimal or suboptimal solutions are achieved. 2) Using DL PC higher capacity values are achieved under dense UE and STA configurations. 3) Higher energy efficiency is also achieved with PC, which always attempts to reduce the transmission power while increasing the energy efficiency. 4) With the use of learning algorithm, a high degree of overall efficiency is achieved.

V. Conclusion

A MAB based dynamic duty cycle selection method was investigated to facilitate a coexistence between WiFi and LTE-U in the same unlicensed band. Performance of the proposed algorithm was further enhanced by using a DL PC technique. Then the concept was extended to optimize energy efficiency. Considerable gains in overall throughputs could be achieved via this algorithm while ensuring a minimum capacity for LTE-U based services in the same band. Significant gains in terms of energy efficiency could be achieved where it is observed that the gains under different parameter settings with PC is much higher than those of with no PC.

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