Enhanced Channels Access Methods in HetBands for Single and Multi-RAT Femtocell Networks

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***Abstract*—**To handle the huge traffic in cellular networks and increase the offered bandwidth for User Equipment (UE), we proposed two enhanced methods to simultaneously access the channels in Heterogeneous Bands (HetBands). The Enhanced Dual Band Femtocell (EDBF) is utilized in single Radio Access Technology (RAT) that comprises Long Term Evolution (LTE) only, while Enhanced Integrated Femto Wi-Fi (EIFW) cell can be used for multi-RAT network (LTE and Wi-Fi). Using the unlicensed band as a supplementary band that usually occupied by Wi-Fi devices (wDevices), a fair sharing can be achieved, and however it may result in reduced network throughput. This work proposes a novel framework to enhance the overall Base Station (BS) performance of both methods in unlicensed band, thus attaining optimal throughput and fair sharing. Firstly, we proposed a channel access scheme for each enhanced method adopts our new procedure that effectively use the scheme parameters ($T_{attempt}$, $T_{trans.}$, and T_{sense}) to enhance the BS performance. Secondly, two new approaches are proposed in our analytic model to obtain the channel and manage coexistence in unlicensed band based on the channel states and scheme's parameters. Thirdly, a new formulation is proposed in our dynamic algorithm to obtain the optimal fraction of channel time in unlicensed band (t_f^*), using the optimal power in licensed band ($P_f^{*(s)}$). We validated our analysis in terms of fair sharing using simulation. Results show that our proposed framework substantially enhance the overall performance of both enhanced methods in terms of throughput, fraction of channel sharing time, and traffic balancing, which make EDBF and EIFW attractive small cells to be used (one type or both) in the deployments of current and future cellular networks.

***Index Terms*—**Aggregation technologies, channel access scheme, dual band femtocell, heterogeneous bands, integrated femto Wi-Fi, listen-before-talk technique

I. INTRODUCTION

A femtocell is a low power cellular BS, or a mini cell tower that provides cellular carriers for residential, enterprise, or metropolitan spaces. It is usually used to increase the network coverage and its capacity, when the cellular signal is nonexistent. This small cell carries cellular voice and data over the internet. Therefore, internet connection via Digital Subscriber Line (DSL) or conventional cable is needed. The cellular phone calls and internet services using femtocell as a private network provide an ease for the cellular carriers. The cellular phone can get better data rates with less power, longer battery life, and better voice quality with a femtocell.

Mobile Network Operators (MNOs) have been offloading the data traffic of macrocell to femtocells in licensed bands [1], [2], and to other small cells called cellular Wi-Fi hotspots in unlicensed bands [2]-[5]. The cellular Wi-Fi hotspot is a device that converts the available cellular signal to Wi-Fi signal and vice versa. Thus, it creates a local Wi-Fi hotspot for number of Wi-Fi devices (wDevices) and smart devices (sDevices) within its coverage area, to access the internet [4].

Although femtocells increase the network capacity through offloading the huge amount of data, it cannot be considered as a complete solution since both femtocells and macrocell share the limited licensed band, hence additional spectrum is necessary. There is a remarkable amount of unlicensed spectrum available around the world, for example the unlicensed Industrial, Scientific, and Medical bands (ISM) [6]. One most used ISM frequency band for short range radio transmissions is the 5GHz band, known as the Unlicensed National Information Infrastructure (U-NII) [7].

The paper investigates into two enhanced methods that access the channels in licensed and unlicensed bands. According to the adopted RAT in femtocell network, the methods are as follows:

A. *Enhanced Dual Band Femtocell (EDBF) for the Cellular Network with Single RAT*

The EDBF method is based on enabling femtocell to access the channel in unlicensed band in addition to the licensed band, both using LTE air interface. Therefore, the designed scheme must utilize the Licensed-Assisted Access using LTE (LTE-LAA) [6], [8], as a 3GPP standard for cellular transmission in 5GHz unlicensed frequency band [9]. This scheme obtains the channel in unlicensed band after channel sensing using Listen-Before-Talk (LBT) technique, before transmission to ensure the channel is idle [10]. The scheme procedure to obtain the channel and align with LTE frame structure will be explained in Section III. The BS needs to apply the Dynamic Spectrum Access (DSA) in unlicensed band to share it with other wDevices. Consequently, EDBF simultaneously access the channels in both licensed and unlicensed bands using LTE air interface. Then, the scheme aggregates carriers based on Carrier Aggregation (CA) approach introduced by LTE-LAA to combine multiple LTE carriers [6]-[8], Fig. 1.

Manuscript received May 2, 2020; revised November 12, 2020.
doi:10.12720/jcm.15.12.849-865

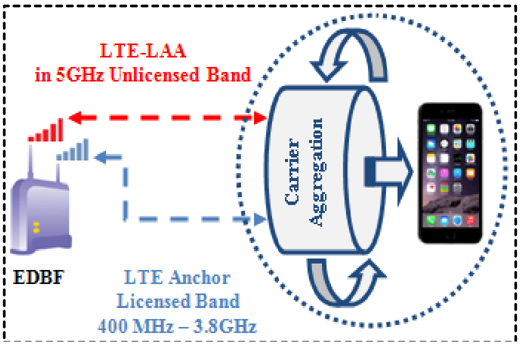


Fig. 1. Enhanced Dual Band Femtocell (EDBF).

The EDBF channel access scheme for unlicensed band with Centralized-Radio Access Network (C-RAN) architecture of the cellular BS splits the data at the BS's MAC layer, and then combines it in the mobile device or User Equipment (UE) at the same layer, Fig. 2. The C-RAN splits the BS electronics into centralized baseband units (BBUs) and conveys data via Common Public Radio Interface (CPRI) to two LTE Remote Radio Heads (RRHs) for the transmissions. In the UE, the data combines with each other at MAC layer by CA approach.

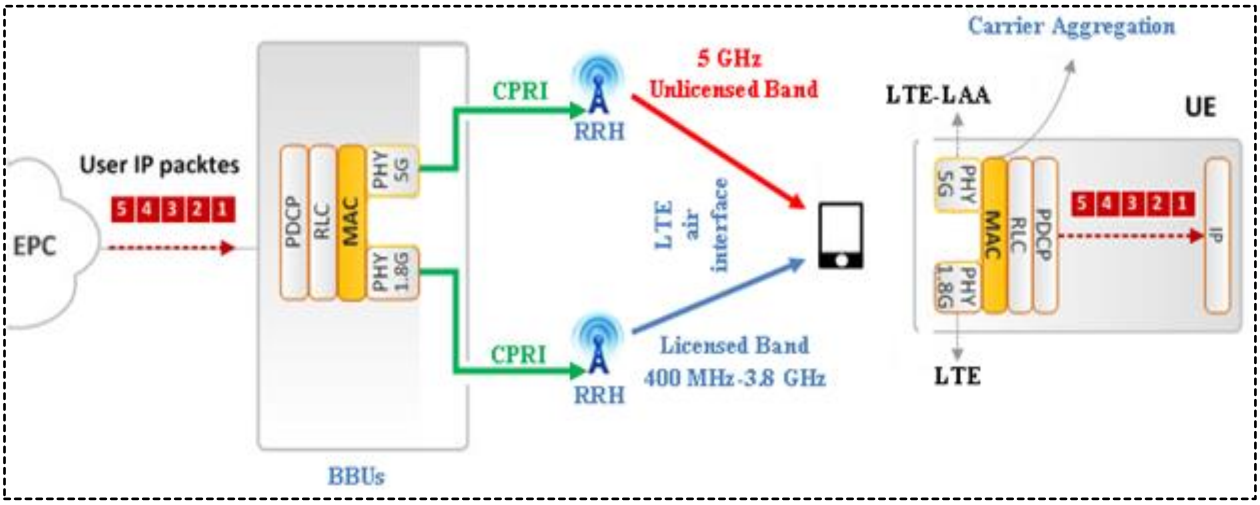


Fig. 2. Carrier Aggregation (CA) approach [11].

B. *Enhanced Integrated Femto Wi-Fi (EIFW) Cellular Small Cell for the Cellular Network with Multi-RAT*

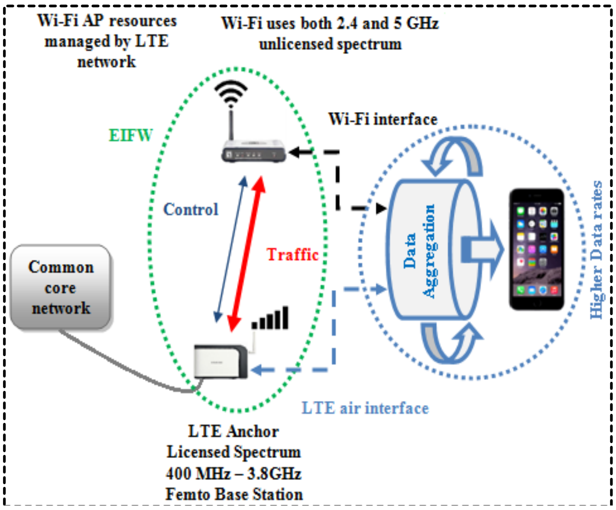


Fig. 3. Enhanced Integrated Femto Wi-Fi (EIFW).

In the cellular network with multi-RAT, the femto BS and cellular Wi-Fi AP are installed together but in isolation from each other. Unlike the first method (EDBF), the EIFW method uses both LTE air interface and Wi-Fi interface. Hence, the EIFW is based on the convergence between LTE and Wi-Fi technologies at high layers. The dual band Wi-Fi (2.4 and 5GHz) is used to get the advantages of 5GHz band that provides 20MHz channel width [7], [12]. Integration femto and Wi-Fi small cells allow to manage the access to Wi-Fi AP via LTE network Fig. 3, starting from the channel sensing using LBT technique before transmission to ensure that the channel is idle. The integration requires control the plane interworking between LTE and Wi-Fi, which permit more dynamic and reliable control of Wi-Fi offloading. Using Radio Access Network (RAN) leads to best decisions for offloading, supported by devices reports. Thus, Wi-Fi will be exactly as another carrier managed by LTE network to transfer traffic.

In the UE, aggregating LTE and Wi-Fi technologies at the RAN level specifically PDCP layer, is called LTE – Wi-Fi link Aggregation (LWA) Fig. 4, which provides utility to all applications and give MNOs more control capability. Consequently, this aggregation technology enables the users to simultaneously connect with both technologies above, which leads to improve the user experience and dynamically balance the loads between two networks (LTE and Wi-Fi). PDCP supported by a link exists between the BS and Wi-Fi AP, in order to report the information by AP to BS, for example loading and MCS. Hence, for ideal performance, the latency of this link should be in minimum.

As illustrated in Fig. 4 above, the data splits in the BS at PDCP layer and combine in the mobile device or UE at the same layer. The C-RAN as a cellular network splits the BS electronics into BBUs and conveys data via CPRI to LTE RRH, and by Gigabit Ethernet interface (GE) to Wi-Fi AP. The C-RAN is also called Cloud-Radio Access Network [13]. In UE the data from two networks (LTE and Wi-Fi) combines with each other at PDCP layer by link aggregation approach. Hence, ideal backhaul is necessary to maintain latency in BS at the minimum when combining cellular and Wi-Fi data.

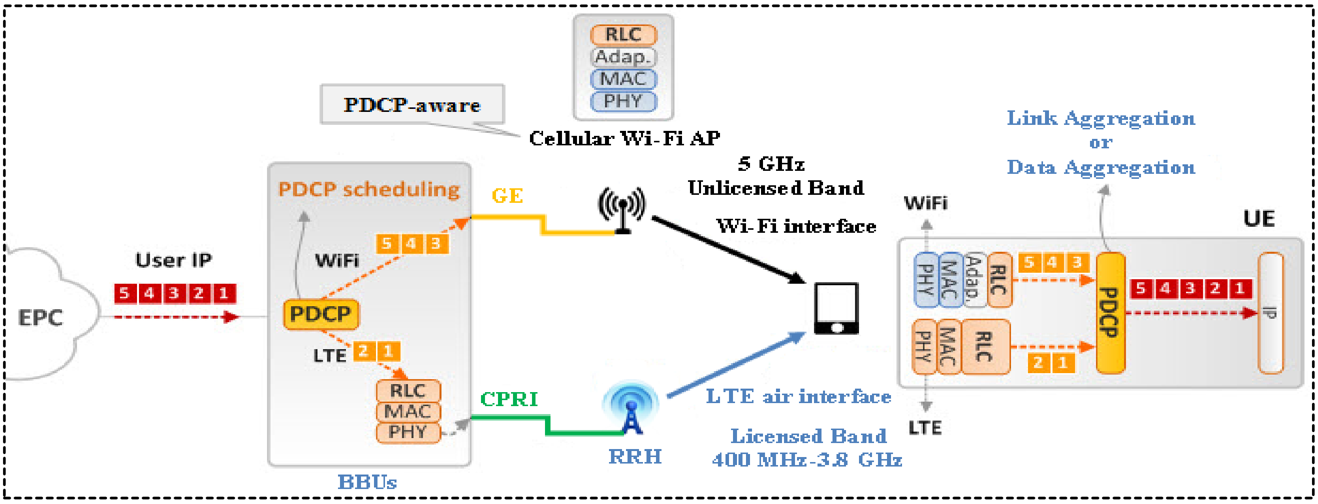


Fig. 4. LTE – Wi-Fi link Aggregation (LWA) approach [11].

According to all above, The EDBF small cells can be employed for the cellular network with single RAT, where their BSs are often installed alongside non-cellular WLAN APs. Thus, sharing the 5GHz unlicensed frequency band using LTE-LAA via LTE air interface consider an efficient method to increase the provided bandwidth to UEs in single RAT networks. On the other hand, in the cellular network with multi-RAT both femto BSs and cellular Wi-Fi APs are already used, but in separated way. This help to consider EIFW small cells the agreeable solution as an alternative method to EDBF, to increase the overall bandwidth and improve the throughput.

II. System Model

The paper investigates into two enhanced methods to simultaneously access the channels in Heterogeneous Bands (HetBands), licensed and unlicensed. The two enhanced methods are based on two types of small cells namely EDBF for the single RAT network (LTE only), and EIFW for multi-RAT network (LTE and Wi-Fi). Each type has been considered as a small cell with closed access accessible only by registered UEs. Both enhanced methods adopt the power control in licensed band, due to use LTE air interface which divides the spectrum into sub-channels. In addition, the channel time usage control is used in unlicensed band.

The paper seeks to enhance the performance of both EDBF and EIFW as cellular small cells, through developing their BSs which conduct all activities in order to offer large bandwidth to the UEs within their cells using licensed and unlicensed bands simultaneously. Our system model considers that the small cells (EDBF or EIFW) deploy within macro BS coverage area, with the existing of WLAN (non-cellular Wi-Fi) only in case of EDBF. Each small cell shares licensed band with macrocell, and unlicensed band with wDevices in case of EIFW, while with WLAN in case of EDBF. We allocate the resources for macrocell, small cells, and WLANs. Within the small cell, we do not consider the licensed band resources allocation to multi-UE [14], because it is out of the scope of our paper.

In the first method, we consider EDBF small cells and WLANs within the macrocell. Each EDBF BS connects with one UE, and the nearest WLAN AP serves one wDevice, while macro BS serves number of mUEs. In the second method, we consider EIFW small cells within the macrocell. Each EIFW BS connects with one UE and one wDevice, while macro BS serves number of mUEs. For both methods, our analysis considers the total throughput of several wDevices (whole Wi-Fi network throughput).Using the assumptions above, our paper seeks to enhance the overall performance of both proposed methods (EDBF and EIFW), to achieve the optimal in terms of the total throughput at UE and fair sharing in unlicensed band. The worth mentioning, that both DBF and IFW as conventional methods have been used in [15], to maximize the total user utility, but both reduced the UE throughput.

The control messages in each small cell (EDBF or EIFW) during both phases (channel access and data transmission) should only exchange through the control channel in licensed band, due to its reliability in comparison with the unlicensed band. Hence, the obtained unlicensed band will be used to transfer the data traffic. The unlicensed band can be used either in downlink (DL) or in uplink (UL). Also, it can be shared by both DL and UL using either Frequency Division Duplex (FDD) mode or Time Division Duplex (TDD) mode. Taking into account that LTE air interface support both modes, while Wi-Fi interface support only TDD mode.

The unlicensed band is used via LTE air interface in EDBF, and via Wi-Fi interface in EIFW. Since both interfaces support TDD mode, we will adopt it in unlicensed band to transfer the data traffic only in DL for UE in both enhanced methods. Only DL transmissions are considered in the licensed band within the small cell, and macrocell for mUEs. In Wi-Fi network, the unlicensed band is randomly accessed to deliver the loads, therefore the transmissions in both DL and UL are considered. Also, we assume the same data rate for wDevice in its DL and UL due to adopt the channel reciprocity.

The unlicensed band is accessed by the small cell BS (EDBF or EIFW) using LBT technique, while the Distributed Coordination Function (DCF) as a mandatory technique is used to access the channel in IEEE 802.11-based WLAN standard (Wi-Fi network), where Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) is used [16]. Thus, all nodes can sense each other and the unlicensed band will be used by only one user at any time, except the time of collisions. Sharing different nodes the unlicensed band using the time mean that the unlicensed band usage is the fraction of channel time occupied by small cell BS or wDevice, and refer to the performance.

The licensed band is simultaneously used by the small cells and macrocell, when the small cells deploy on the existing macro cellular system. It is accessed in OFDMA, due to use LTE air interface which divides the licensed spectrum into sub-channels. The paper consider that small cell BSs adjust the licensed band use not macro BS, in order to control the interference which usually happen from small cell BSs to mUEs. Each small cell achieves this working using the power control, when BS allocates the power in each sub-channel of the licensed band.

In our system model, the unlicensed band will be used via either LTE air interface for EDBF, or Wi-Fi interface in case of EIFW. Each interface has several modulation and coding schemes (MCSs), which use in the adaption to instantaneous SINRs. We will consider the rate function in unlicensed band ($R_{U(f)}$) in unit bits/sec/Hz. According to the type of small cell (EDBF or EIFW), the $R_{U(f)}$will be equal to the rate function of LTE ($R_{L(f)}$) in case of EDBF, while in EIFW case the $R_{U(f)}$ will be equal to the rate function of Wi-Fi network ($R_{W(f)}$), and the used standard of Wi-Fi will determine its actual value [17]. The rate function depends on the used unlicensed channel bandwidth and the adopted MCS.

We assume that EDBF BS and adjacent WLAN use the same unlicensed channel. Also, EIFW BS uses the same unlicensed channel for both UE and wDevice within its coverage area. Although this assumption considers the worst, but it is enabling us to experiment how to coexist and get the benefits from one available channel, which may happen when other channels suffer from high interference in case of the dense deployments. Thus, we can simulate the last case although we deploy the small cells and WLANs in a way prevent the outdoor interference.

Since both EDBF and EIFW share the unlicensed band with other devices in time not frequency, and because we assumed that no outdoor interference, we will consider the instantaneous signal-to-noise ratio (SNR), which has an effect on the number of bit errors in this unlicensed band. Thus, the data rate will be determined by the instantaneous SNR and the rate function. We assume that both SINR and SNR at UE in licensed and unlicensed band respectively, are known for the BS by UE feedback.

In the unlicensed band, we assume that the transmissions of Wi-Fi network fail when the collisions happen with other transmissions from this network's nodes or from the small cell BS. Also, to clearly discover and understand how the BS affect on Wi-Fi network's throughput when both of them share the unlicensed band. We assume that no errors in Wi-Fi transmissions, as long as Wi-Fi interface adapt its MCS to the instantaneous SNR for the Wi-Fi data rate [17].

Both methods access the unlicensed band as a supplementary band using a scheme adopts spectrum sharing techniques to share this band with wDevices on the concept of DSA, as proposed in Section III. The small cell BS with this scheme can conduct all activities in order to obtain the unlicensed channel and use it in a way ensure the fair sharing with other devices.

III. Channel Access Scheme for Unlicensed Band

The paper carefully investigates into both EDBF and EIFW as methods to access and share 5GHz band with other unlicensed band devices. Each method needs to create a scheme can exactly determine the access opportunities, accurately sense the unlicensed band, and align with LTE frame structure for the transmission. The proposed schemes are as follows:

A. *EDBF Channel Access Scheme for Unlicensed Band via LTE Interface*

In the cellular air interface, both technologies (LTE and LTE-A) have been designed for restricted spectrum. Hence, both are not suitable in unlicensed band which is accessible by devices operate using different air interfaces. Therefore, Qualcomm has designed the LTE-Unlicensed (LTE-U) as a cellular technology in 5GHz unlicensed band for the transmission and coexisting with Wi-Fi operating in this band. This LTE-U technology has been re-branded to be Licensed Assisted Access (LAA) using LTE (LTE-LAA), which is a 3GPP standardized version for the cellular transmission in the 5GHz unlicensed band, as part of Release-13.

The EDBF small cell is fully managed by MNOs, using LTE air interface with the licensed and unlicensed bands. It is certainly cannot use the unlicensed channel access schemes already offered by IEEE 802.11 such as Distributed Coordination Function (DCF) or Point Coordination Function (PCF), due to two reasons: 1) Both schemes are not designed for LTE air interface, 2) Cannot align with the LTE frame structure. The EDBF channel access scheme adopts CA approach to combine multiple carriers at the MAC layer.

B. EIFW Channel Access Scheme for Unlicensed Band via Wi-Fi Interface

In the EIFW small cell, femto BS is physically integrated with the cellular Wi-Fi AP which is already designed with adapter to convert the available cellular signal to Wi-Fi signal and vice versa. The dual band Wi-Fi (2.4 and 5GHz) is used in our EIFW. The cellular Wi-Fi AP resources are managed by LTE network through a link exists between the BS and Wi-Fi AP, to transfer data and receive the reported information by AP such as loading and MCS.

Since the network uses multi-RAT (LTE and Wi-Fi), and because each technology utilizes own air interface, our EIFW channel access scheme adopts link aggregation approach to combine multiple carriers at the PDCP layer. This procedure helps to control the plane interworking between LTE and Wi-Fi that will be exactly as another carrier to only transfer data traffic. Consequently, the proposed scheme performs all activities including the alignment with the LTE frame structure, which cannot be made by both DCF and PCF schemes.

To access the channel in unlicensed band, each of the two proposed schemes above need to complete the processes below.

a) The small cell BS senses the unlicensed channel using LBT technique before transmission to obviate the interference with the current transmissions from other unlicensed band devices.
b) After obtaining the channel, the channel access scheme aligns with LTE frame structure.
c) Then, the small cell BS informs UE via the control channel in licensed band, to turn on its unlicensed band radio and operate on the assigned channel.

The LTE frame structure means that LTE transmissions are organized in periodic sub-frames in time, and can start just at the beginning of the sub-frames. Hence, the channel access attempts in unlicensed band must take a fit place before the start time of sub-frames, because even when the channel is idle, BS cannot transmit until the start time of next sub-frame, as long as the channel access scheme aligns with LTE frame structure for the transmission and adheres with its structure. Thus, the BS may lose the transmission opportunity immediately when another device finds this channel jobless and use it.

As in Fig. 5, the BS attempts to access the channel at just the pre-assigned periodic time instants which are called access opportunities, and the interval time between each access opportunity and other is $T_{attempt}$. When the access opportunity arrives, the BS directly senses the unlicensed channel for T_{sense} as it is pre-defined. Depending on the discovered energy (under or above the threshold), if the unlicensed channel is jobless during the sensing time, the BS accesses the channel and use it for a determined duration $T_{trans.}$, else the BS is forced to wait the next access opportunity (when the sensing result that the channel is occupied during the sensing duration). Reference [15] has already suggested that the BS should not keep the channel for a long time, and cannot directly access the channel after use it. In detail, when the transmission finish exactly at a new access opportunity or between two of an access opportunities, the BS must skip the new access opportunity and leaves the unlicensed channel at least $T_{attempt}$ from the end of transmission before use it again, in order to allow other devices to use this channel and transmit data. The above concepts are already used as a conventional procedure when use LBT technique.

In an innovative way, for fair sharing the proposed channel access schemes adopt our new procedure that always ensure $T_{trans.}$ less than or equal to $T_{attempt}$, as it can be seen in Fig. 5. This is because the key parameter in our proposed channel access schemes is $T_{attempt}$.

C. New Procedure to Access and Use Unlicensed Band

The proposed channel access scheme for each enhanced method (EDBF or EIFW) adopts our new procedure that effectively use the scheme parameters ($T_{attempt}$, $T_{trans.}$, and T_{sense}) to enhance the BS performance. In our procedure, if the sensing result that the channel is busy, the BS attempts again at the next access opportunity after 1ms (sub-frame time duration). When the sensing result that the channel is idle, the BS accesses the channel and uses it for $T_{trans.}$. The BS determines $T_{attempt}$ depending on the last $T_{trans.}$ that correspond with the optimal fraction of channel time (t_f^*). In detail, the determined $T_{attempt}$ in our proposed channel access schemes must be equal to the last $T_{trans.}$ if it is integer. Otherwise, $T_{attempt}$ equal to the smallest integer that is no less than the last $T_{trans.}$. This procedure insure that $T_{trans.}$ always less than or equal to $T_{attempt}$ which is the required time duration to leave the channel before use it again, as an efficient way to share the unlicensed band and optimally utilize it.

D. Alignment with LTE Frame Structure

Since the channel access scheme (EDBF and EIFW) aligns with LTE frame structure, the matching and coordination between the scheme and the periodic structure of LTE sub-frames are required, and can achieve by making $T_{attempt}$ equal to LTE sub-frame duration which is 1ms, or its integer multiples. Usually, $T_{attempt}$ starts at just the access opportunity which is T_{sense} before the start time of LTE sub-frame, to finish the sensing at the boundary of sub-frame exactly. In this moment and if the channel is idle, the BS can transmit for a determined duration $T_{trans.}$. Thus, three parameters control the proposed channel access scheme of each enhanced method, as follows:

- $T_{attempt}$-The interval time. It determines when will be the next access opportunity, and the required minimum time duration to leave the unlicensed channel between two successive transmissions, to permit other devices using this channel.

- $T_{trans.}$ - The transmission duration. It is the determined duration to use the channel in unlicensed band after obtaining it. The scheme uses this parameter to prevent BS from keeping the channel for a long time, as long as other devices wait to use the same unlicensed channel.
- T_{sense} - Channel sensing duration. It is the pre-determined duration to sense the unlicensed channel at the access opportunity, when the BS attempts to access the channel.

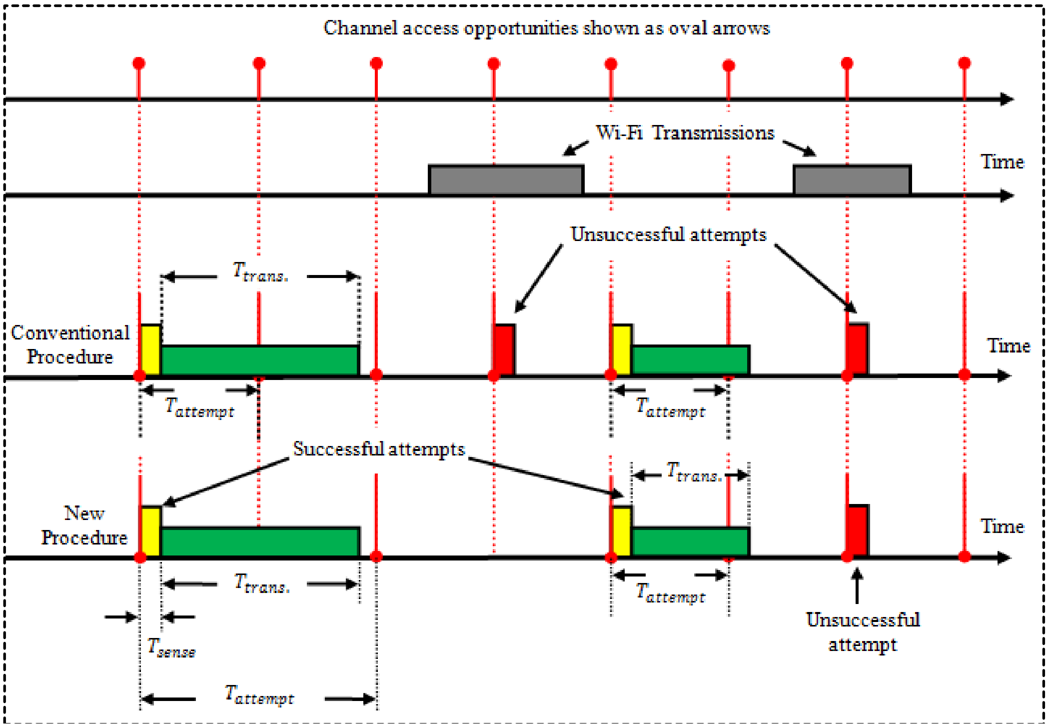


Fig. 5. The adopted new procedure by channel access schemes for both EDBF and EIFW, in comparison with the conventional procedure.

The paper plans to present two novel approaches to enhance the proposed channel access schemes. In Section IV-A, we will propose the first approach that enables the BS to do its attempt to access the channel at a successful access opportunity as possible. In the second approach (Section IV-B), we need to achieve the fair sharing in unlicensed channel through a novel formulation apply the condition of our new procedure ($T_{trans.}$less than or equal to $T_{attempt}$), to obtain the fraction of channel time occupied by BS (t_f). In both EDBF and EIFW, we need to improve the total throughput at UE that come from using licensed and unlicensed bands. In the dynamic algorithm (Section V), we will focus our efforts to formulate a novel equation to obtain the optimal fraction of channel time in unlicensed band (t_f^*), using the optimal power in licensed band ($P_f^{*(s)}$) that already solved in [15] and [18]. We seek to achieve the optimal in terms of throughput, fair sharing, and traffic balancing through the data traffic control according to the traffic load amount.

IV. OBTAININGTHE UNLICENSED CHANNEL AND COEXISTING WITH WI-FI NETWORK

A. Estimation the Successful Attempt Probability

The attempts of BS to obtain the channel in unlicensed band happen at just access opportunities, each attempt starts by sensing the channel for T_{sense}, if the channel state is idle during the sensing duration, the attempt will be successful and BS can utilize the channel for$T_{trans.}$, otherwise the attempt is unsuccessful and BS need to try again at the next access opportunity.

The paper proposes a novel approach to estimate the successful attempt probability to obtain the channel in unlicensed band. The concept based on that the successful attempt happen after successfully passing two conditions. First, the attempt time which begins with sensing the channel is located within a period when Wi-Fi AP and its devices are idle. P_{st} denote to the probability of the first condition success. Second, the channel state must continue idle during the whole sensing duration (T_{sense}). P_{nd} denote to the probability of the second condition success, taking into account that the second condition is based on the success of the first condition. To obtain the successful attempt probability ($P_{succ.att.}$), we need to derive $P_{st}$and P_{nd}, respectively.

Usually, Wi-Fi AP and its devices randomly access the channel in unlicensed band, which lead to the random in channel state at any instant of time, and may be one of three states (successful transmission, collision, or idle). Thus, P_{st} is equal to the fraction which represent the duration of time in which the channel is idle, divided by the whole channel time. Each of the channel states occupies duration of time, and can represent it as a fraction of the whole channel time. These time fractions are determined by Wi-Fi backoff window size (large backoff window size, lead to long time duration of the idle state), traffic load, and the number of Wi-Fi nodes.

When BS share the unlicensed band with Wi-Fi AP and its devices, the BS occupy a fraction of the whole channel time, and the rest can be used by Wi-Fi network. Thus, the paper considers that the Wi-Fi network's fractions of time for channel states (successful transmission, collision, and idle) will be changed to deliver their loads, according to the fraction of channel time occupied by the BS (t_f), which affect on the Wi-Fi network performance.

The time slot concept is adopted in our analytical model to analyze and determine the Wi-Fi time durations of the channel states which can be observed by BS, and as follows:

- $T_{successful}$: Time duration of a successful transmission state.
- $T_{collision}$: Time duration of a collision state.
- T_{idle}: Time duration of an idle state.

According to above, the probability of the first condition success ($P_{.st}$) is equal to the fraction which represent the duration of time in which the channel is idle (T_{idle}), divided by the sum of the Wi-Fi time durations of the channel states [19].

The probability of each channel state represents the time duration of the intended state, divided by the sum of the Wi-Fi time durations of the channel states. In the same context, [19] has already obtained the probabilities of channel states, when they used the 2D Markov Chain modeling to present their model which evaluated the channel access probabilities.

In our system model, we assume that all nodes in both networks (cellular small cell and Wi-Fi) always have data, and contend with each other to transmit its data. Also, the Wi-Fi network transmissions fail when the collision happens with other transmissions from Wi-Fi or cellular small cell. In order to better estimate the probability of the first condition success ($P_{.st}$) and easily determine the unlicensed channel state, the paper consider that the channel has two states are idle state and busy state. Thus, the BS can observe only two time durations. The $P_{.st}$ can be obtained from the formulation below.

$$P_{.st} = \frac{T_{idle}}{T_{busy} + T_{idle}}, \tag{1}$$

where T_{busy} is the time duration of a busy state.

The probability of each channel state represents the time duration of the intended state, divided by the sum of the two time durations above ($T_{busy}$and T_{idle}). The two probabilities are:

- P_{busy}: The probability of a busy state.
- P_{idle}: The probability of an idle state.

The $P_{.st}$ can be obtained using the above two probabilities and the formulation can be written as:

$$P_{.st} = \frac{P_{idle}}{P_{busy} + P_{idle}} \tag{2}$$

The time duration of an idle state (T_{idle}) consist of a number of an idle time slots (N), which must be integer (N = 1, 2…). To increase the probability of the second condition success ($P_{.nd}$), and to somewhat ensure that the channel is continued in idle state during the whole sensing duration (T_{sense}) till the end, we adjust the channel sensing duration (T_{sense}) to be equal to the idle slot time (*st*). As we assumed in our novel approach, the second condition is based on the success of the first condition when the access attempt time is within a period when Wi-Fi AP and its devices are idle. Then, the probability of the second condition success is

$$P_{.nd} = \frac{T_{idle} - T_{sense}}{T_{idle}}, \tag{3}$$

here the $P_{.nd}$may be one of two cases, as follows:

- $P_{.nd}$ = 0, when the T_{idle}= T_{sense}, and happen if N = 1. In this case, the BS fails, and need to wait and try again at the next access opportunity.
- $P_{.nd}$> 0, when the T_{idle}>T_{sense}, and happen if N > 1. In this case, the probability of the second condition success ($P_{.nd}$) will be equal to a fraction which represent this probability.

From (2) and (3), the successful attempt probability to obtain the channel in unlicensed band is

$$P_{succ.att.} = P_{.st} \cdot P_{.nd}. \tag{4}$$

The BS contends with other unlicensed band devices to access and utilize the channel in this band. The proposed channel access schemes for both EDBF and EIFW depend on three parameters. The first parameter is used at just the access opportunity to sense the channel for T_{sense} before the start time of the LTE sub-frame. If the channel is idle during the whole sensing duration, the attempt will be successful and the BS can access the channel and transmit the data for determined time duration $T_{trans.}$. Otherwise, the BS needs to wait the next access opportunity which is located after $T_{attempt}$ from the previous one. The successful attempt probability ($P_{succ.att.}$) can be used to determine the number of attempts which BS needs to obtain the channel, which are on average $1/P_{succ.att.}$.

B. Fair Sharing Management in Unlicensed Channel

For fairly coexisting with WLAN AP and its devices in case of EDBF, and fair usage for unlicensed band in case of EIFW, the fraction of channel time occupied by BS in unlicensed band can be obtained by the novel formulation below.

$$t_f = \frac{T_{trans.}}{(1/P_{succ.att.}) \cdot T_{attempt} - T_{attempt} + T_{trans.}}, \tag{5}$$

on condition of

$$T_{trans.} \leq T_{attempt}. \quad (6)$$

The novel formulation above enables us to adjust the fraction of channel time occupied by BS in unlicensed band (t_f), by controlling in two of the channel access scheme parameters ($T_{trans.}$ and $T_{attempt}$), while the formulation condition ensures fair coexistence with other unlicensed band devices.

The unlicensed band may be accessed by the small cell BS (EDBF or EIFW) at each attempt using channel access scheme which use LBT technique to sense the channel, and depending on the sensing result the BS may obtain the channel or not. Therefore, the maximum fraction of channel time that the channel can be used is t_{max}< 1 as a reasonable assumption, because t_{max}= 1 means that the channel always busy and no any device can obtain it.

According to above, the BS occupies the unlicensed channel for $t_f$which will be a fraction of the maximum fraction of channel time (t_{max}). Thus, we need to rewrite (5) to be

$$t_f = \left(\frac{T_{trans.}}{(1/P_{succ.att.}) \cdot T_{attempt} - T_{attempt} + T_{trans.}}\right) \cdot t_{max}, \quad (7)$$

the rest will be for Wi-Fi devices to deliver their loads in both DL and UL, and can be written as in

$$t_w = t_{max} - t_f, \quad (8)$$

and when BS apply the condition (6), we can see that

$$t_w \geq t_f. \quad (9)$$

V. BS's Performance Enhancement

Recall our system model in Section II, the BS in both of EDBF and EIFW cellular small cells shares the licensed band with macrocell and unlicensed band with WLAN in case of EDBF, while with wDevices in case of EIFW. The unlicensed band is used in TDD mode and its usage can be characterized by the fraction of channel time. In both EDBF and EIFW, the coexisted wDevices' buffer status (full buffer or not) does not depend on only their aggregated traffic loads, but also on the fraction of channel time (t_f) occupied by small cell BS (EDBF or EIFW). When the BS always have data need to transmit it as assumed, in addition to apply the optimal power control and optimal control of channel's time usage in the licensed and unlicensed bands respectively, the wDevices' status will be always full buffer, like WLAN in full buffer status when it alone use the unlicensed band [19].

For both methods (EDBF and EIFW), we derive the total throughput of Wi-Fi network, which will be applicable to one coexisted wDevice or more. We consider that the fraction of channel time occupied by wDevice$j$ (j = 1, 2, 3...) isf_j. The total throughput can be written as in

$$W_{thr.} = \sum_j R_W f_j. \quad (10)$$

Since we assumed that wDevice has the same data rate in its DL and UL, also considering that the transmissions of all Wi-Fi network's nodes have the same data rate, R_W is the instantaneous data rate which depend on the rate function of Wi-Fi network $R_{W(f)}$, and the instantaneous SNR.

The fraction of channel time occupied by all wDevices is

$$t_w = \sum_j f_j, \quad (11)$$

then recall (8), we can obtain on

$$t_{max} - t_f = \sum_j f_j. \quad (12)$$

We can rewrite (10) to be

$$W_{thr.} = R_W(t_{max} - t_f). \quad (13)$$

The throughput at UE in both EDBF and EIFW cellular small cells come from using licensed and unlicensed bands simultaneously. Since the licensed band is shared between the small cell and macrocell, the small cell BS adjusts the licensed band usage through power control when it allocates the power $P_f^{(s)}$ in each sub-channel s (s = 1, 2, 3...), as long as BS knows the SINR at UE in each sub-channel by UE feedback. Also, the power control keeps the interference from small cell BS to mUEs below the predefined threshold. In the unlicensed band, BS shares this band with WLAN in case of EDBF, while with wDevices in case of EIFW. The BS uses the time to control the unlicensed channel usage, through adjusting its fraction of the channel time (t_f).

Thus, the total throughput at UE using the licensed and unlicensed bands is

$$UE_{thr.} = B \sum_s R_{Lic.(f)}\left(P_f^{(s)} E_f^{(s)}\right) + t_f R_U, \quad (14)$$

for the first part of equation above, B is the licensed bandwidth and $R_{Lic.(f)}$ is the rate function of LTE measured by bits/sec/Hz, which depends on the used licensed channel bandwidth and the adopted MCS. We need to multiply $R_{Lic.(f)}$by B to get the LTE data rate. $P_f^{(s)}$ is the transmitting power in sub-channel s as previously mentioned, and $E_f^{(s)}$ is the path loss of the transmitted signal divided by the sum of noise and interference in sub-channel s, which can be written as in

$$E_f^{(s)} = \frac{\left|g_{ff}^{(s)}\right|^2}{P_m^{(s)} \left|g_{mf}^{(s)}\right|^2 + N_f^{(s)}}, \quad (15)$$

where in sub-channel s the $g_{ff}^{(s)}$, $g_{mf}^{(s)}$, $P_m^{(s)}$, and $N_f^{(s)}$ are the gain of small cell BS to its UE, the gain of mBS to small cell UE, the transmitting power of mBS, and the noise power, respectively.

The obtained throughput at UE in through licensed band is

$$B \sum_{s} R_{Lic.(f)}\left(P_f^{(s)} E_f^{(s)}\right), \tag{16}$$

and when using the power control, it will be subject to

$$\sum_{s} P_f^{(s)} \leq P_{Total}, \tag{17}$$

$$P_f^{(s)} \geq 0, \tag{18}$$

$$P_f^{(s)} \left|g_{fm}^{(s)}\right|^2 < I_s. \tag{19}$$

The restriction (17) ensures that the sum of all transmitting powers allocated by the BS in all sub-channels is less than or equal to the allowed and determined total transmitting power (P_{Total}) to be used by the BS within its area. The restriction (19) is necessary to ensure that the interference power from small cell BS to the near mUE when both use the same sub-channel s, is below the threshold which is already predefined (I_s), and the $g_{fm}^{(s)}$ is the gain of small cell BS to mUE in sub-channel s.

Based on Shannon capacity, the instantaneous rate function of LTE in (16) is

$$\sum_{s} R_{Lic.(f)}\left(P_f^{(s)} E_f^{(s)}\right) = log_2\left(1 + \sum_{s} P_f^{(s)} E_f^{(s)}\right). \tag{20}$$

The obtained throughput at UE in through unlicensed band is

$$t_f R_U, \tag{21}$$

where t_f is the fraction of channel time occupied by small cell BS (EDBF or EIFW) as previously mentioned, and R_U is the instantaneous data rate in unlicensed band which depend on either the rate function of LTE ($R_{L(f)}$) in case of EDBF, or the rate function of Wi-Fi network ($R_{W(f)}$) in case of EIFW, in addition to the instantaneous SNR.

In our dynamic algorithm, the unlicensed band is a supplementary band to increase the overall bandwidth offered to UE and improve the throughput. Thus, we seek to improve the obtained throughput in through this band, which leads to improve the total throughput at the UE. Hence, we need to formulate a novel equation to obtain the optimal fraction of channel time in unlicensed band (t_f^*) that achieve the optimal in terms of the throughput and sharing.

Reference [15] and [18] have already obtained the optimal power ($P_f^{*(s)}$) in licensed sub-channel, when they applied the Karush-Kuhn-Tucker (KKT) conditions [20], to solve the problem of (16)-(19). Using the instantaneous $R_{Lic.(f)}$ that has been defined in (20), the optimal power is

$$P_f^{*(s)} = min\left(max\left(\frac{1}{v} - \frac{1}{E_f^{(s)}}, 0\right), \frac{I_s}{\left|g_{fm}^{(s)}\right|^2}\right), \tag{22}$$

where v is the chosen power which with the equality satisfy (17). Equation (22) is numerically solvable using the algorithm of modified water-filling adopted in [21], [22], in which the power can be allocated into sub-channels in the same way of usual water-filling, on condition of that the allocated power in sub-channel s is satisfy (19).

To enhance the BS performance in unlicensed band, the optimal control of channel's time usage is required to determine the optimal fraction of channel time (t_f^*) that can be occupied by BS to achieve the optimal throughput in this band, and fair sharing with wDevices. To solve this problem, the paper proposes a novel formulation uses the obtained $P_f^{*(s)}$ from (22) above. Thus, the optimal fraction of channel time can be formulated as in

$$t_f^* = \begin{cases} 0, & if \;\; T_L \leq R_{Lic.max}/2 \\ t_{max}\left(min\left(0.5, \left(\dfrac{T_L - \sum_s R_{Lic.max}\left(P_f^{*(s)} E_f^{(s)}\right)}{R_{Umax}}\right)\right)\right), & otherwise, \end{cases} \tag{23}$$

where T_L is the small cell downlink traffic load, $R_{Lic.max}$ is the maximum LTE data rate in licensed band and equal to the maximum LTE rate function (when using the highest modulation order) multiplied by the bandwidth, and R_{Umax} is the maximum unlicensed data rate and equal to either the maximum LTE data rate (R_{Lmax}) in case of EDBF, or the maximum Wi-Fi data rate (R_{Wmax}) in case of EIFW, taking into account that both R_{Lmax} and R_{Wmax} depend on the unlicensed channel bandwidth. Consequently, using the unlicensed band is dependent on the amount of traffic load (T_L), as shown in (23).

Finally, using both of $P_f^{*(s)}$ and t_f^* obtained from (22) and (23) respectively, the optimal total throughput at UE using the licensed and unlicensed bands can be written as in

$$UE_{thr.}^* = B \sum_{s} R_{Lic.(f)}\left(P_f^{*(s)} E_f^{(s)}\right) + t_f^* R_U. \tag{24}$$

According to equation above and in case of high traffic load, the BS achieves part of this traffic load using the optimal power $P_f^{*(s)}$ in licensed band, while try to convey the rest of traffic load using the optimal fraction of channel time t_f^* in unlicensed band. Thus, $UE_{thr.}^*$ comes from using licensed and unlicensed bands simultaneously.

Practically, we can consider a closed-form expression in the approximation of instantaneous $R_{Lic.(f)}$ instead of using the Shannon capacity, and as it is already proposed in [23] for LTE cellular networks. Three parameters can be used in this approximation are k_{bw}, k_c, and k_{sinr}, where the first parameter value can be obtained from LTE protocol's parameters, and represent the system efficiency related to the overheads which take into account non-use the whole bandwidth, estimation the channel using a pilot signal, and cyclic prefix. Usually, the LTE air interface adapt its MCSs to the instantaneous SINR, and to achieve the efficient adaption, it is useful adjusting the values of both k_c and k_{sinr} together, which should be corresponded with the curve of data rate plotted from the simulation at the link level. Our analysis in Section IV can be closer to reality using the parameters above when we consider the instantaneous $R_{Lic.(f)}$. Thus, we can rewrite (20) to be

$$\sum_s R_{Lic.(f)}\left(P_f^{(s)} E_f^{(s)}\right) \approx$$

$$k_{bw} \cdot k_c \cdot log_2\left(1 + \left(\sum_s P_f^{(s)} E_f^{(s)}\right) \Big/ k_{sinr}\right). \quad (25)$$

The approximation of instantaneous $R_{Lic.(f)}$ will be considered in the simulations for SISO LTE-Advanced using the above three parameters in (25), where k_{bw}=0.6726, k_c=0.75, and k_{sinr}=1.

According to our proposed algorithm, the small cell (EDBF or EIFW) needs to keep the interference from its BS to the near mUE below the predefined threshold, which require knowing the channel gain of small cell BS to mUE in sub-channel s ($g_{fm}^{(s)}$) and as mentioned in the restriction (19). For the cellular networks, this implementation problem can be solved using one of the mechanisms which have been designed to achieve the coordination between the macrocell and femtocells. As an example, mBS can inform femtocells existed within its coverage area about the locations of mUEs and their used resources, which enable each femtocell to estimate the $g_{fm}^{(s)}$ depending on the distance between its BS and mUE. Our simulations will consider that the BS knows $g_{fm}^{(s)}$ in each sub-channel.

VI. Analysis Validation

In this section, we validate our analysis which concluded to a novel formulation (usable for both EDBF and EIFW) to determine the fraction of channel time occupied by the BS in unlicensed band (t_f). Also, we verify the role of channel access scheme parameters ($T_{trans.}$ and $T_{attempt}$) in adjusting t_f in order to achieve fairly coexisting with WLAN AP and its devices in case of EDBF, and fair usage for the unlicensed band in case of EIFW. The same assumed concepts in Section IV-B have been considered in our simulation, with assumption that the data traffic is only in DL for UE, while the transmissions at the same data rate are in both DL and UL for wDevices. The performed simulation has considered that the small cell BS connect to one UE and three wDevices in case of EIFW, while WLAN AP serves these three wDevices in case of EDBF. We focus on the performance of both networks (cellular small cell and Wi-Fi) in the unlicensed band represented by t_f and t_w respectively.

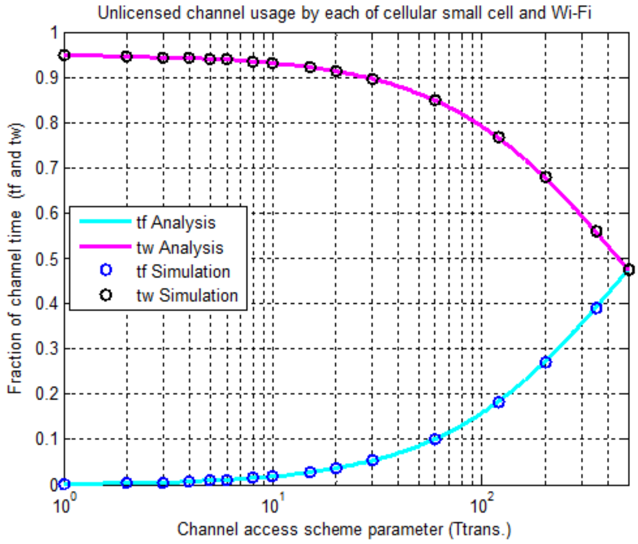


Fig. 6. Analysis validation of unlicensed channel usage by each of cellular small cell and Wi-Fi.

TABLE I: PARAMETERS USED IN SIMULATIONS

Licensed channel bandwidth: 20MHz Unlicensed channel bandwidth: 20MHz I_s: -100dBm Unlicensed channel sensing threshold: -62dBm Noise power: -95dBm (over licensed/unlicensed channel) Small cell refer to DBF, IFW, EDBF, or EIFW	
Transmit Power	
mBS: 23dBm Small cell BS: 15dBm Wi-Fi (WLAN) AP: 15dBm	
Channel Access Scheme for Unlicensed Band	
T_{sense}: 18 µs(used in both DBF and IFW) T_{sense}: 9 µs (used in both EDBF and EIFW) t_{max}: 0.95	
Wi-Fi (IEEE 802.11n) uses DCF technique in 5GHz unlicensed band	
Idle slot time (st): 9 µs	
SIFS: 16 µs	DIFS: 34 µs
CWMin: 15	CWMax: 1023
RTS/CTS: Enabled	IP Packet Size: 1500 Bytes
Path Loss (PL) Models	
R: the distance in meter L_{ow}: the penetration loss of outer wall in dB	
Small cell BS ↔ its associated UE Wi-Fi AP ↔ its associated wDevice PL = 38.46 + 20 $\log_{10}(R)$ + 0.7 R	

Small cell BS ↔ its associated wDevice (only in case of IFW & EIFW) PL = 15.3 + 37.6 $\log_{10}(R)$ + L_{ow}, L_{ow} = 20dB
mBS ↔ mUE PL = 15.3 + 37.6 $\log_{10}(R)$
mBS ↔ Small cell UE Small cell BS ↔ mUE PL = 15.3 + 37.6$\log_{10}(R)$ + L_{ow}, L_{ow} = 10dB

The used parameters in both analytic model and simulation are included in Table I, with assumption that all nodes always have data and contend with each other to transmit its data. To study the effect of channel access scheme parameters on the performance of cellular small cell (t_f), which affect on the Wi-Fi performance (t_w), we change the transmission duration ($T_{trans.}$) from 1ms to 500ms, while keep the interval time between each access opportunity and other ($T_{attempt}$) constant at 500ms. As shown in Fig. 6, our simulation result match the analytic result obtained using (7) and (8) very well. Thus, our simulation has proved the rightness of (7) which already predicted that the small cell performance (t_f) increase by increasing $T_{trans.}$, which lead to degrade the performance of Wi-Fi (t_w).

Also, we verified that the adjusting of both $T_{trans.}$ and $T_{attempt}$ according to (6), ensure fair usage for the unlicensed band and fairly coexistence between both networks (cellular small cell and Wi-Fi).

VII. Performance Evaluation

In this section, we evaluate our proposed framework for both methods (EDBF and EIFW), through evaluation the proposed channel access schemes for the unlicensed band including our new procedure, the novel approaches to obtain the channel and manage the coexisting with wDevices, and the novel formulation in our dynamic algorithm to enhance BS's performance in the unlicensed band. We considered the practical deployments for macrocell, small cells, and Wi-Fi networks in our extended simulations using matlab as a programming platform, to study their interactions and activities in order to understand the performance in terms of the throughput and coexisting.

A suburban scenario has been considered in the network topology. The mBS is located at the macrocell center with the radius of 300m, and within its coverage area 36 mUEs are randomly distributed in locations, some of which are very close to the small cell BSs. We assumed that 48 houses are placed within macrocell in uniform distribution, with the distance of 70m from the center of each house to other.

The type of small cell BS (EDBF or EIFW) used inside the house determines the considered method Fig. 7, as follows:

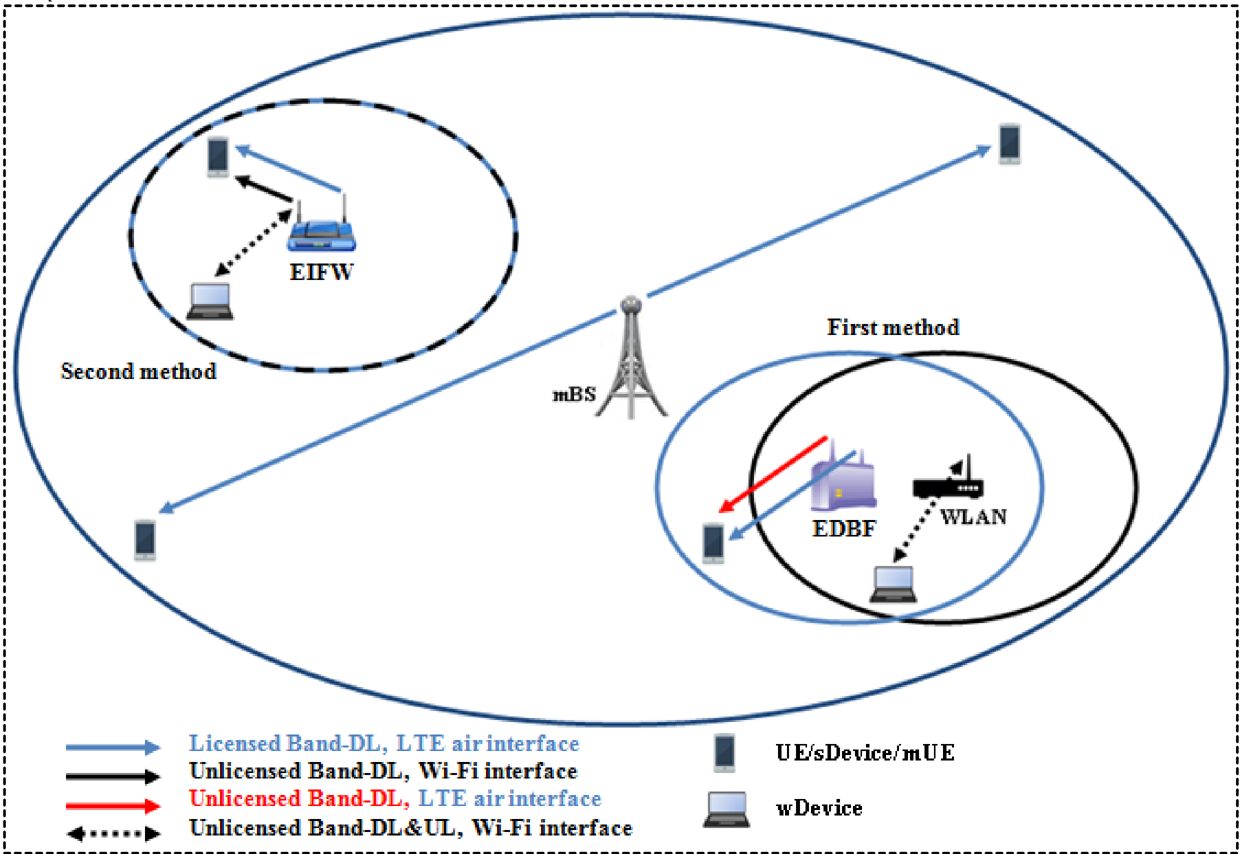


Fig. 7. The network topology for both enhanced methods (EDBF and EIFW).

- Case 1: For the first method, the EDBF BS is utilized in each house with one UE within a radius of 20m. This BS accesses both licensed and unlicensed bands using only the LTE air interface. Hence, one Wi-Fi AP (WLAN) is installed within a distance of 10m from the EDBF BS, with one wDevice within a radius of 20m. Thus, the EDBF BS requires Wi-Fi AP (non-cellular WLAN) near from it, to serve both UE and wDevice.
- Case 2: For the second method, the EIFW BS is utilized in each house with one UE and one wDevice, which are placed within a radius of 20m. The EIFW BS accesses both licensed and unlicensed bands using LTE air interface and Wi-Fi interface, respectively. Thus, it can be used by both UE and wDevice. Additional Wi-Fi AP (WLAN) is not required, and no necessity to use it.

According to the network topology above, the interference among the houses is very low, where each house is isolated from the other houses. The worth mentioning, that the dynamic algorithm in Section V is applicable to our network topology, as long as this algorithm did not assume the interference among the houses. Nevertheless, this algorithm has considered the interference in licensed band to compute the required SINR in the procedures for the optimal traffic balancing.

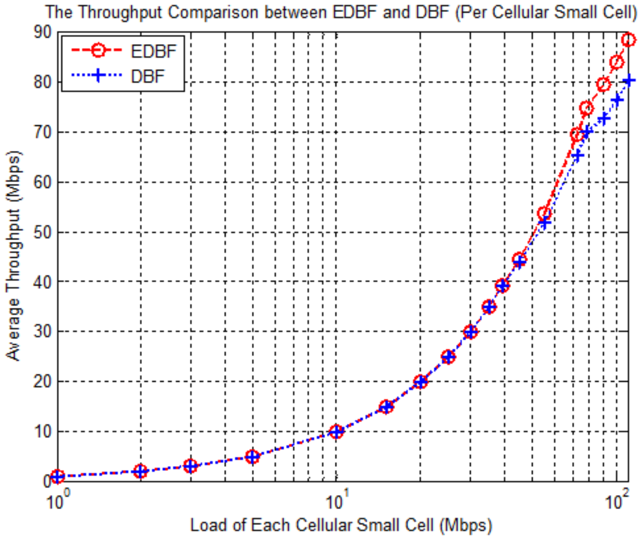
The channel bandwidth is 20MHz in each licensed and unlicensed band. LTE-A and 802.11n (Wi-Fi frame aggregation level of 64k Bytes) are adopted for the cellular air interface and Wi-Fi air interface, respectively. Our simulations considered that the maximum physical layer net data rates are 78Mbps in LTE-A and 72.2Mbps in Wi-Fi, by assumption that the channel bandwidth is fully utilized and considering diverse overheads. The simulations parameters and the used path loss models are summarized in Table I, where PL is the path loss measured by dB, R is the distance in meter, and L_{ow} is the penetration loss of outer wall. The path loss models are according to those in Small Cell Forum whitepaper [24], and [25]. The described approximation in Section V is considered for the instantaneous rate function of LTE in our simulations.

For both methods, we considered the optimal power control in licensed band, and fixed the used parameters values of channel access scheme in the unlicensed band, where T_{sense}= 18 µs, $T_{trans.}$= 20ms, and $T_{attempt}$= 1ms. Our simulations according to above represent the conventional DBF and IFW small cells.

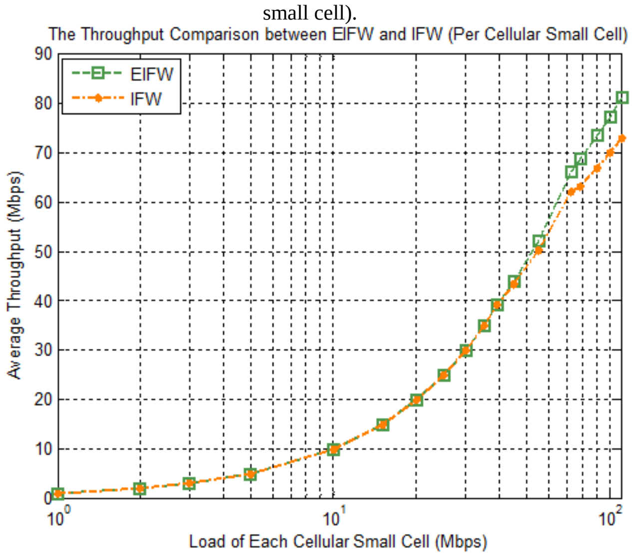
Then, we concentrated our efforts in the unlicensed band to enhance the performance of both enhanced methods in terms of the throughput and coexisting. We followed the novel approach described in Section IV-A to estimate the successful attempt probability to obtain the channel, and the same concepts in Section IV-B to ensure the fair coexistence in this band. Also, we applied the dynamic algorithm for the optimal traffic balancing over licensed and unlicensed bands, which is described in Section V. Hence, both EDBF and EIFW have been considered enhanced methods. All the channel access schemes in unlicensed band follow the illustrated procedures in Section III.

Although the simulations settings are different according to the method (EDBF or EIFW) and whether it enhanced or not, but we consider the same traffic loads for each cellular small cell in all simulations. For wDevice, we assume the aggregated load of both DL and UL is 42.5Mbps. We can obtain the following observations from the simulations results.

The maximum achievable throughput at MAC layer of LTE and Wi-Fi are 75Mbps and 61Mbps, respectively. This is due to the centralized MAC layer of LTE, in which the resources are scheduled by the network for each UE, while the channel access scheme at MAC layer of Wi-Fi is a distributed scheme, which cause many overheads (randomly access the channel).



(a) The throughput comparison between EDBF and DBF (per cellular small cell).



(b) The throughput comparison between EIFW and IFW (per cellular small cell).

Fig. 8. The throughput comparison between enhanced and conventional methods.

As we can see in Fig. 8(a), various traffic loads are considered for each cellular small cell. Under high small cell traffic loads, the total throughput at UE from the licensed and unlicensed bands in EDBF outperforms that in DBF. This is due to our proposed framework to enhance the performance in the unlicensed band. The throughput results are the same in both EDBF and DBF under the low and median small cell traffic loads, where both apply the optimal power control in licensed band. The same observations can be obtained when we compare the throughput results of EIFW with those from IFW, as shown in Fig. 8(b).

Fig. 9 illustrates the performance in terms of the throughput of both EDBF and EIFW small cells, which adopt the proposed framework. Also, the effect of each small cell mentioned above on the performance of macrocell. Under high traffic loads, we can observe that EDBF small cell has higher total throughput at the UE (from licensed and unlicensed bands) than EIFW small cell. This is because EDBF adopts LTE air interface in the unlicensed band, while Wi-Fi air interface is adopted by EIFW in this band, hence EDBF has higher efficiency at the MAC layer than EIFW [26]. When the traffic load of small cell is median or low, the small cell BS (EDBF or EIFW) usually uses only licensed band according to our dynamic algorithm (no need to use the unlicensed band in this case). Both enhanced methods apply the optimal power control in this licensed band and can achieve the same throughput under the same conditions, as shown in our simulations results.

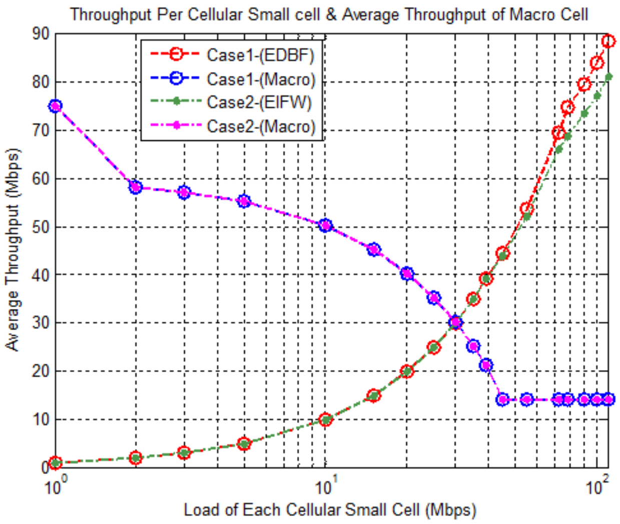


Fig. 9. Throughput per small cell and average throughput of macrocell.

In the same context, Fig. 9 shows how each small cell (EDBF or EIFW) affects the macrocell performance, when both of them share the same licensed band. We can observe the throughput degradation of macrocell, as a result to share its licensed band by small cell which adopt the optimal power control to keep the interference from small cell BS to mUEs below the predefined threshold. Under high traffic loads, the proposed dynamic algorithm enable small cell BS to perform the maximum achievable of traffic load in licensed band, taking into account that the interference is always below the predefined threshold. The rest can be achieved in unlicensed band using the optimal fraction of channel time. Thus, we can understand why the macrocell performance does not continue to decrease.

The licensed band is simultaneously shared by both macrocell and small cell (EDBF or EIFW) using OFDMA as an access technique. Thus, both macro and small cell BSs can transmit in the same sub-channels, but using different sub-carriers. The leaked interference from adjacent sub-carriers which are used by small cell BS [27], [28], and the increased overheads in each sub-channel leads to reduce the maximum achievable throughput in licensed band. This interprets the macrocell throughput degradation once the small cell BS share licensed band. In our system model, the small cell BS uses the power control to adjust the licensed band usage and control the interference that usually happens to mUEs. Thus, the small cell BS can achieve its traffic load when it allocates the power in each sub-channel of licensed band. In each of small cell and macrocell, the equally throughput happens when the small cell BS uses only licensed band and the achieved throughput at small cell UE is half of the maximum obtainable throughput from this band when sharing it with macrocell. Hence, we can see the same throughput in each of small cell and macrocell, as shown in Fig. 9.

Fig. 10, illustrates that the throughput per Wi-Fi (WLAN) and per EIFW small cell for its associated wDevice, are the same. This is because both enhanced methods (EDBF and EIFW) have applied the same proposed framework, in spite of the differences in their configurations. We can observe that the throughput degradation start when the traffic load amount of small cell require using unlicensed band in addition to the licensed band, as it is proposed in our dynamic algorithm for the optimal traffic balancing. In unlicensed band, the small cell BS adopts the optimal control of channel's time usage to adjust its fraction of the channel time (t_f) for fairly sharing in this band.

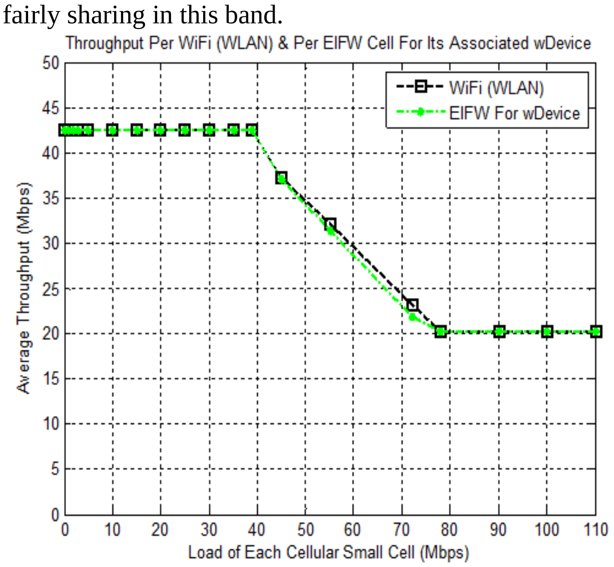
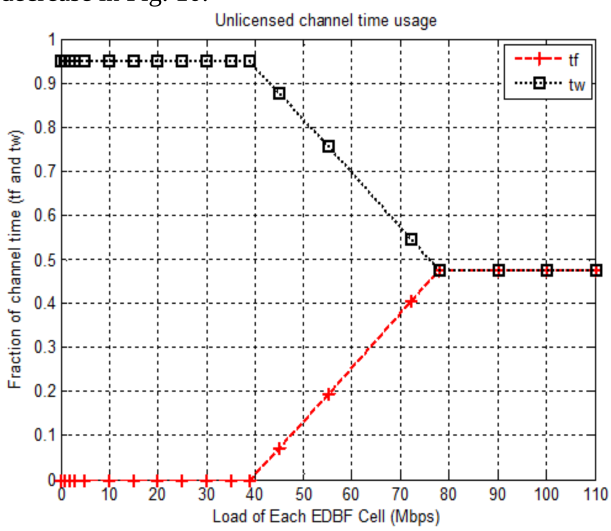


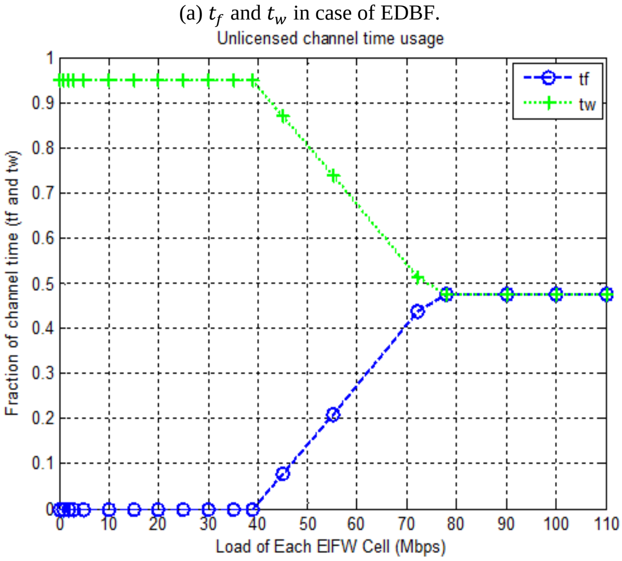
Fig. 10. Throughput per Wi-Fi (WLAN) and per EIFW cell for its associated wDevice.

This interprets the throughput stability of Wi-Fi network afterward in our simulations results, in spite of increasing small cell traffic load. The obtained results prove the effectiveness of our proposed framework in term of the fair coexistence in unlicensed band.

The Wi-Fi throughput decreases when the BS (EDBF or EIFW) starts to use the unlicensed band and occupies a fraction of channel time (t_f), which affect on the Wi-Fi performance represented by t_w. According to (9) and for fair sharing, the t_f should not be more than the half of the maximum fraction of channel time that the channel can be used (t_{max}), as shown in Fig. 11 (a) and (b) which interpret why the Wi-Fi throughput does not continue to decrease in Fig. 10.



(a) t_f and t_w in case of EDBF.



(b) t_f and t_w in case of EIFW.

Fig. 11. Unlicensed channel time usage (t_f and t_w) in both enhanced methods (EDBF and EIFW).

In the same context, Fig. 11(a) shows the fraction of channel time (t_f) occupied by EDBF BS in the unlicensed band, (t_f = 0, when BS uses only licensed band in case of the low and median traffic loads, because the BS try to achieve the largest possible amount of traffic load in licensed band using the optimal power). As we can see, in the unlicensed band the BS effectively control in its t_f , which affect the non-cellular Wi-Fi (WLAN) performance represented by t_w. This is due to adopt dynamic algorithm include the optimal control of channel's time usage, which significantly achieve the fairness in this band, as shown in our simulation results, where $t_f \leq t_w$ and its maximum value in case of equality with t_w slightly less than 0.5, because t_{max}< 1. The same observations can be obtained about t_f occupied by EIFW BS in the unlicensed band, and its effect on t_w which can be occupied by wDevice to deliver its loads in both DL and UL, as shown in Fig. 11(b).

Finally, for both enhanced methods (EDBF and EIFW), Fig. 12 shows the total throughput from both cellular and non-cellular networks. Under high traffic loads, the obtained total throughput of the first method higher than those from the second method. We expected that, because EDBF small cell adopts LTE air interface when using the unlicensed band, while Wi-Fi air interface is adopted by EIFW small cell in this band. This leads to, higher efficiency with EDBF that schedule the network resources for each UE using the centralized MAC layer of LTE in comparison with EIFW where the channel access scheme at MAC layer of Wi-Fi is a distributed scheme and cause many overheads (randomly access the channel). When the traffic loads are median or low, the both enhanced methods usually operate only in licensed band according to our proposed dynamic algorithm. Hence, under the same conditions, the same total throughput can be obtained from each enhanced method.

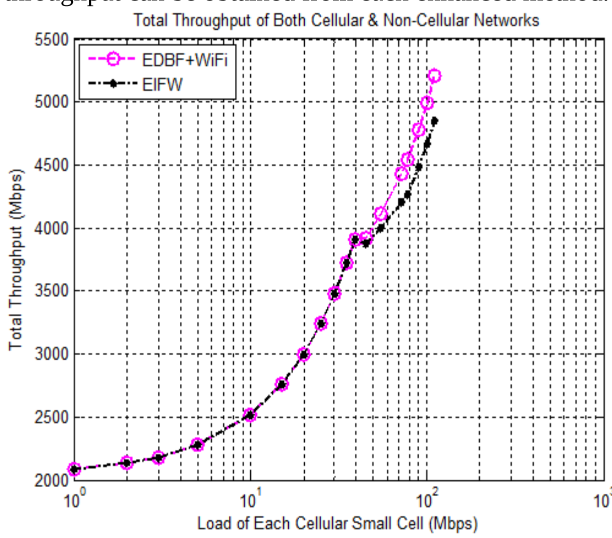


Fig. 12. Total throughput of both cellular and non-cellular networks.

For more clarity in this section, the paper findings can be summarized as follows:

- The throughput comparison between enhanced methods and conventional methods proves the effectiveness of the proposed framework to enhance BS's performance in unlicensed band.
- The EDBF small cell has higher total throughput at the UE (from licensed and unlicensed bands) than EIFW small cell, under high traffic loads. This

superiority confirms the efficiency of LTE air interface in the unlicensed band in comparison with Wi-Fi interface.

- Both enhanced methods (EDBF and EIFW) have the same influence on the macrocell throughput, since both adopt the proposed dynamic algorithm. The results reveal the efficient role of dynamic algorithm through the data traffic control according to the traffic load amount.
- The macrocell throughput does not continue to decrease, because the BS perform part of traffic load in licensed band, while try to convey the rest through the unlicensed band as a supplementary band.
- The leaked interference from adjacent sub-carriers which are used by small cell BS and the increased overheads in each sub-channel leads to reduce the maximum achievable throughput in the shared licensed band.
- Both enhanced methods (EDBF and EIFW) have the same influence on the Wi-Fi network throughput, since both adopt the same proposed framework. The Wi-Fi throughput results reveal the achieved fairness in unlicensed band due to apply the optimal control of channel's time usage, where the optimal fraction of channel time (t_f^*) is determined by BS to enhance its performance in unlicensed band for fair coexistence with wDevices and to get the optimal throughput from this band for UE.
- The optimal traffic balancing was significantly implemented, where Wi-Fi throughput decreases when the BS (EDBF or EIFW) starts to use unlicensed band as a supplementary band in addition to the licensed band.
- The simulation results about unlicensed channel time usage (t_f and t_w) reveal that the BS effectively control in its t_f in order to achieve the fairness in this band, where $t_f \leq t_w$and its maximum value in case of equality with t_w slightly less than 0.5, because t_{max}< 1.
- The simulations results of both enhanced methods (EDBF and EIFW) under high traffic loads reveal that the first method (EDBF) outperforms the second method (EIFW) in terms of the total throughput from both cellular and non-cellular networks (whole system).

VIII. Conclusion

This work has proposed a novel framework enable femtocell BS to simultaneously access and optimally exploit the channels in HetBands (licensed and unlicensed). The proposed channel access scheme for each enhanced method (EDBF or EIFW) has been designed to access the unlicensed band as a supplementary band and utilize it on the concept of DSA. Although the differences between both methods according to the used air interface in unlicensed band (LTE or Wi-Fi), but we assigned three important parameters (usable for both enhanced methods) each one has its own defined role. The validated novel approaches confirmed the effectiveness of scheme's parameters in obtaining the channel and ensuring fair coexisting in unlicensed band. Thus, Listen-Before-Talk (LBT) technique is needed to share channel with other devices, while control scheme's parameters can achieve the fair sharing. The formulated dynamic algorithm that has been verified via simulations has significantly enhanced the BS performance in unlicensed band in terms of the throughput and coexisting. In addition, this algorithm has implemented the optimal traffic balancing over licensed and unlicensed bands, as an efficient strategy. Our dynamic algorithm suggested using both bands only when the traffic load amount of small cell require unlicensed band as a supplementary band in addition to the licensed band.

Our results illustrate that the total throughput at UE (from licensed and unlicensed bands) in each enhanced method (EDBF or EIFW) outperforms that in the conventional method of the same small cell type. With our proposed framework, EDBF small cell has higher total throughput at the UE than EIFW, where LTE-LAA uses the unlicensed spectrum better than Wi-Fi. Both enhanced methods have the same effect on macrocell's performance (throughput) in licensed band, since both methods adopt the optimal power control in this band. The fair coexistence in unlicensed band with Wi-Fi network is illustrated through Wi-Fi network's throughput which decrease then fairness named by throughput stability, as long as EDBF and EIFW adopt the optimal control of channel's time usage in this band as it is modeled in our algorithm. The channel time usage results of each enhanced method illustrate the relation between t_f and t_w, also how the BS effectively achieves the fairness in this band. At last, the results of total throughput from both cellular and non-cellular networks (all small cell and Wi-Fi networks) illustrate that the first method (EDBF) outperforms the second method (EIFW) under the same conditions. Consequently, our proposed framework substantially enhance the overall performance of both enhanced methods in terms of throughput, fair sharing, and traffic balancing through the data traffic control according to the traffic load amount, which make EDBF and EIFW attractive small cells in the deployments of cellular networks.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

The first author conducted the research and wrote the paper under the second author supervision. The authors contributed together to analyze the data. All authors had approved the final version.

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