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WiFi in Licensed Band (WiFi-Lic)

*Shahid Mumtaz, †Anwer Al-Dulaimi, *Kazi Mohammed Saidul Huq, *Firooz B. Saghezchi, *Jonathan Rodriguez
*Instituto de Telecomunicações, Aveiro, Portugal; †University of Toronto, Toronto, Canada.
E-mail: *{smumtaz, kazi.saidul, firooz, jonathan}@av.it.pt; †anwer.aldulaimi@utoronto.ca

***Abstract*—This letter proposes a novel idea targeting WiFi users operating in the LTE licensed band, which we refer to as WiFi-Lic. Recently, LTE-U has been proposed as a vehicle for accommodating LTE users on unlicensed WiFi in order to provide access to additional spectrum on demand using carrier aggregation techniques. However, this creates new challenges in terms of coexistence with native WiFi users. This letter aims to address the coexistence challenge, by considering a scenario where WiFi users are able to exploit licensed LTE uplink band. We introduce new system characterization parameters and decision metrics for so called WiFi-Lic users that not only overcome the coexistence concerns between WiFi and LTE-U (LTE-Unlicensed) operating in the same (5GHz) band, but also potentially reduces the WiFi busy time to almost zero. To the best of the authors knowledge no works have been proposed that consider WiFi/LTE coexistence using LTE white spaces.**

***Index Terms*—Licensed, LTE-U, Unlicensed, WiFi**

I. Introduction

In recent years, mobile data usage has grown by 70%-200% per annum. The main reason for this exponential increase in mobile traffic is the new mobile applications in smartphones, which consumes almost all the available free radio resources. These applications, such as high definition video streaming, real-time interactive games, wearable mobile devices, ubiquitous health care, do not only demand higher data rates but also require an improved Quality of Experience (QoE). To meet such high data rate and QoE requirements, three main solutions are proposed [1]: a) addition of more radio spectrum for mobile services (increase in MHz); b) deployment of small cells (increase in bit/Hz/km^2); and c) efficient spectrum utilization (increase in bit/second/Hz/km^2). For mobile operators, efficient spectrum utilization is the most essential resource in this pursuit. Therefore, mobile operators consider integrating the WiFi within its infrastructure as an additional supplementary downlink for offloading more data traffic [2]. The utilization of the WiFi unlicensed band offers a significant extension for mobile operators resources to meet mobile traffic requirements. In a 3GPP RAN plenary standards meeting in December 2013, the proponents, formally proposed "LTE-Unlicensed" (LTE-U) to utilize unlicensed spectrum to carry data traffic for mobile services with initial focus on the 5725-5850 MHz band for this use [3, 4].

The Federal Communications Commission (FCC) pioneered unused TV spectrum for "Super WiFi" hotspots with highly-efficient characteristics, many of which are owing to the comparatively low carrier frequencies of TV bands [5–7]. LTE-U stretches out LTE to the unlicensed spectrum and incorporate the unlicensed spectrum with the licensed spectrum based on existing Carrier aggregation technology continuous seamless data flow between licensed and unlicensed spectrum via a single Evolved Packet Core (EPC) network. For operators, the presence of LTE-U means synchronized integrated network management, same authentication procedures, more efficient resource utilization, all of which leading towards lower operational costs. For mobile users, LTE-U implies improved quality of experience, i.e., more data rates, uninterrupted service provisioning between licensed and unlicensed bands, ubiquitous mobility and improved reliability. However, it is observed that the coexistence of LTE-U and WiFi in the same frequency bands causes a significant degradation on the system performance. Currently, Wi-Fi systems adopt a contention based medium access control (MAC) protocol with random backoff mechanism [7]. If left unrestrained, unlicensed LTE transmissions can actively and aggressively occupy the channel (i.e. 5GHz) and make the medium busy most of the time. This will generate continuous interference to Wi-Fi systems, resulting in Busy Time Period (BTP) of Wi-Fi nodes. This will not only degrade the Wi-Fi devices throughput, but also the overall throughput of the system.

To overcome the above constraint, we propose a novel WiFi-Lic solution that can sense and access the spectrum hole of the LTE band during channel busy period. This solution not only solves the coexistence challenges between WiFi and LTE-U, but also reduces the WiFi BTP of the channel to zero and efficiently uses the underutilized spectrum of LTE [7–9]. Finally, WiFi-Lic is a complementary technology to LTE-U rather than being a competing technology, which further enhances the overall system throughput. To the best of the authors knowledge no work has been done similar to this topic.

II. LTE-U

The main objective of LTE-U is to aggregate carriers between licensed and unlicensed band. There are two types of carriers, those are: principal component carrier (PCC) in licensed band and secondary component carrier (SCC) in unlicensed band. Any LTE-U user is configuredto access one PCC and several SCCs. PCC is responsible for control-plane and Layer 1 control signaling, while user-plane data is carried through either PCC or SCC. The Listen-Before-Talk (LBT) technology [1, 5] is the enabler for friendly coexistence between WiFi systems in unlicensed band. As of late, researchers have studied WiFi and LTE coexistence considering TV white spaces. Several studies, such as [10], propose Carrier Sense Multiple Access with Collision Avoidance (CSMA)/sensing based modifications in LTE with features like Listen-Before-Talk. In other studies, to enable WiFi/LTE coexistence, solutions like blank LTE subframes/LTE muting [10], carrier sensing adaptive transmission and interference aware power control in LTE. All of the above proposals explain how LTE-U can access the unlicensed band or coexist with WiFi. In contrast, no work has been proposed to allow WiFi access to the licensed band.

III. WiFi in licensed band (WiFi-Lic)

Figure 1 shows a high-level system design of WiFi-Lic technology. It consists of operator deployed WiFi and LTE Small Cell (SC) Access Points (AP) operating on the 5GHz unlicensed and 2.6GHz licensed bands, respectively. Moreover, there exist one LTE and one WiFi devices, which consist of three SDR radios (i.e. LTE, LTE-U and WiFi), with the WiFi device being retrofitted with the cognitive radio functionality. Among various possible LTE-U deployment options, this letter focuses on Supplemental Downlink (SDL) deployment in unlicensed band. In an SDL mode, the unlicensed spectrum is used to provide an additional bandwidth to be aggregated with the licensed downlink bandwidth in order to improve the overall downloading rate for the mobile users. For this letter, we specifically consider a deployment that targets the regions without LBT requirements such as the US. During the transmission interval, LTE users can access the licensed and unlicensed component carriers (PCC and SCC), simultaneously. However, the system configuration information including the SCC access is only exchanged using the PCC carriers. The initial attach, authentications and security are performed on the

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PCC. All other time/jitter-sensitive applications can be supported on PCC that has more predictable availability and QoS.

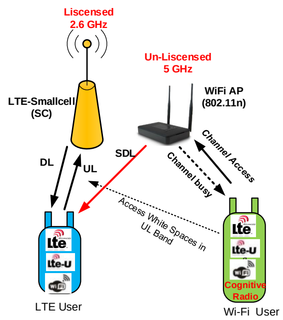

Fig. 1. System Model of WiFi-Licensed spectrum

The unlicensed SCC bands are used only for data transmissions due to the fact that data can be buffered when there is no free channel. In contrast, control signals cannot be delayed due to the Physical Resource Block (PRB) allocations and therefore have to be sent immediately over PCC. In our proposed scheme, once a WiFi channel becomes available, the small cell exchanges information with the LTE end user over PCC. Upon reception, LTE end user switches on its LTE-U interface to the assigned SDL channel. On the other hand, when the WiFi user tries to access the channel (assume all channels are currently occupied by LTE-U), it senses the medium and postpones the transmission upon the detection of co-channel LTE-U. This can degrade the WiFi users throughput and increase the BTP. The main reason for this disproportionate drop in the WiFi throughput is due to the fact that LTE does not sense the medium before transmitting. In contrast, Wi-Fi is designed to coexist with other networks and it senses the channel before any transmission.

In our proposed model, as soon as the WiFi user senses the medium busy, it configures the cognitive radio to access the white spaces in the licensed band. This solution can increase the WiFi throughput, as well as reducing the BTP to virtually zero. As WiFi-Lic is operated by the same LTE operator, synchronization of the carrier frequency between the WiFi-Lic devices and the AP (in the licensed band) can first be initiated by some assistance from the LTE network, e.g., by advertising the new channel's carrier frequency exploiting LTEs regular control signaling. Then, the WiFi-Lic AP can start sending beacons at this new channel, updating the Direct Sequence (DS) Parameter Set information element of the beacon frame which indicates the current WiFi channel, accordingly. Meanwhile a WiFi-Lic user device, being aware of this shift of the carrier frequency (from 5GHz band to 2.6GHz), can start scanning the licensed band to detect the new beacons to synchronize its carrier frequency and to associate itself to the WiFi-Lic AP.

A. Channel selection for LTE-U

Prior to data transmission, LTE small cells scan the unlicensed band for the identification of the vacant channels and inform the users of data transmission via cross-carrier scheduling. The measurements are performed at both the initial power-up stage and later periodically at the SDL operation stage. If any interference is found in the operating channel and there is another channel available, the SDL transmission will be switched to a new channel using LTE Rel 10/11 procedure. If there is no channel available, the LTE-U can share the channel with WiFi AP or another LTE-U system using Carrier-Sensing Adaptive Transmission (CSAT) [11]. For this letter, we assume that there is always a vacant channel available for LTE-U.

1) Channel selection for WiFi-Lic: The WiFi-Lic channel access mechanism is depicted in Fig. 2. For the sake of simplicity, the mechanism of WiFi-Lic operation is divided into four steps as given below.

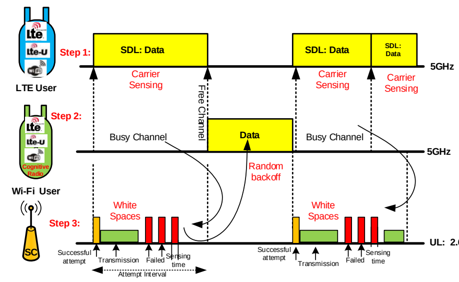

Fig. 2. Channel access mechanism of WiFi-Lic

Step 1: During this step, LTE-U user accesses the 5GHz band (for example, IEEE 802.11n channels) using SDL. SDL data can vary from channel to channel according to traffic demand and have a time duration of 1ms. Moreover, we assume that there is always a vacant channel available for LTE-U in 5GHz (no WiFi transmission).

Step 2: In this step, WiFi user tries to access one of the channels that are currently in use by LTE-U. Hence, a WiFi user starts sensing all of the channels and finds that none of them are free. BTP will automatically turn "on" the cognitive radio interface of WiFi for duration of SDL data (1ms).

Step 3: During cognitive radio activation, WiFi-Lic user attempts to access the LTE channel. The WiFi-Lic conducts channel assessment only at preassigned periodic time intervals compatible to the LTE PRBs; we refer to these intervals as "WiFi-Lic access opportunities". We denote the WiFi-Lic predefined period time as T_{sensing} (μs). Once the WiFi-Lic identifies an access opportunity, transmission starts for a fixed transmission duration $T_{\mathbf{WiFi-Lic_{Tx}}}$ (μs); otherwise, the WiFi-Lic user starts sensing again, unless the channel is idle.

Step 4: **Step 2** and **Step 3** have occurred for the duration of 1ms, which we called "attempt interval ($T_{\mathbf{WiFi-Lic_{attempt}}}$)". As soon as attempt interval finishes, WiFi-Lic automatically switches off cognitive radio interface and switches on its WiFi interface to sense the carrier again. The WiFi performs the normal channel assessment and starts transmitting if a channel becomes available or backs off by a random number of time slots and then resumes transmission attempts. Otherwise, it goes to **Step 3**. We assume that LTE uplink band is vacant for 1ms, which we call attempt interval for WiFi-Lic users and it keeps the channel for 3ms after a successful channel access attempt, for we consider that WiFi transmits three MPDUs at the PHY as one Aggregated-MPDU transmission (see simulation parameter in Table 1). This will give enough opportunity to WiFi-Lic to finish its transmission, while licensed users do not starve, as they are the primary users of the LTE band.

We identify three key performance metrics to model the WiFi-Lic proposed channel access mechanism are as follows:

Attempt Interval $\left(T_{\mathbf{WiFi-Lic_{attempt}}}\right)$ is the period of access opportunities in LTE band. $T_{\mathbf{WiFi-Lic_{attempt}}}$ is used to control how frequent WiFi-Lic accesses licensed band and duration of 1ms.

Transmission duration $(T_{\mathbf{WiFi-Lic_{TX}}})$ is the maximum duration that a WiFi-Lic can occupy the channel during transmission period. At the end of $T_{\mathbf{WiFi-Lic_{TX}}}$, the WiFi-Lic user has to move to the next available channel assuming that the licensed user returns to access this channel. So licensed users do not starve, as they are the primary users of LTE band.

Channel Sensing Duration (T_{sensing}) is the predefined time interval during which the WiFi-Lic examines a selected licensed channel for a potential transmission attempt.

IV. Performance Metrics

The WiFi nodes are assumed to employ the clear channel assessment (CCA) mechanism to evaluate the channels availability [1, 5].

To this end, all WiFi nodes are considered to be able to detect surrounding nodes to avoid any collision in transmissions due to simultaneous channel access attempts. In LTE-U model, the WiFi considers a channel to be busy if energy level (ε_c) exceeds a certain threshold (CCA_T). Thus, the CCA mechanism is a key parameter to access the white spaces in LTE band. We assume transmit powers are denoted as p_i $(i \in \{\omega, \lambda\})$ where ω and λ indices are to denote WiFi-Lic and LTE links respectively. We note that the maximum transmission power of an LTE small cell is comparable to that of the WiFi-Lic, and thus is consistent with regulations of unlicensed bands. The power received from transmitter j at a receiver i is given by $p_j \xi_{i,j}$ where $\xi_{i,j} \geq 0$ represents a channel gain which is inversely proportional to $\delta_{i,j}^{\gamma}$ where $\delta_{i,j}$ is the distance between i and j , and γ is the path loss exponent. $\xi_{i,j}$ may also include antenna gain, cable loss and wall loss. SINR (Γ) of link i is given as

$$\Gamma_i = \frac{p_i \xi_{i,i}}{p_j \xi_{i,j} + \sigma_i}, i, j \in \{\omega, \lambda\}, i \neq j \quad (1)$$

where σ_i is noise power for receiver i. For the case of single WiFi-Lic and LTE, if i represents the WiFi-Lic links, then j is the LTE link, and vice versa.

A. SINR of WiFi Link

Therefore, SINR of WiFi link, $i, i \in \omega$, in the presence of LTE and no LTE is shown as

$$\Gamma_i = \begin{cases} \frac{p_i \xi_{i,i}}{\sigma_0} \text{ if no LTE,} \\ \frac{p_i \xi_{i,i}}{\sum\limits_{j \in \lambda} p_j \xi_{i,j} + \sigma_0} \text{ if LTE,} \end{cases} \quad (2)$$

where term $\sum\limits_{j \in \lambda} p_j \xi_{i,j}$ is the interference from all LTE networks at WiFi link i.

B. Throughput of WiFi Link

Firstly, for single WiFi link (in this case BoE model [1, 11]), CCA mechanism is initiated as

$$R_\omega = \begin{cases} 0, \text{ if } \varepsilon_c \geq CCA_T; \text{ (WiFi operation)} \\ f\left(\Gamma_{\omega(p)}\right), \text{ if } \varepsilon_c \geq CCA_T; \text{ (WiFi-Lic operation)} \\ f\left(\Gamma\right), \text{ if } \varepsilon_c < CCA_T; \text{ (Normal operation)} \end{cases}$$

and, if $\varepsilon_c < CCA_T$, the throughput is formulated as follows:

$$\begin{aligned} &T_S = f\left(R_\omega\right), \ \Lambda = f\left(R_\omega\right), \\ &\mathbb{E}[S] = T_E + T_S + T_C, \eta_E = \tfrac{T_E}{\mathbb{E}[S]}, \\ &\eta_S = \tfrac{T_S}{\mathbb{E}[S]}, \ \eta_C = \tfrac{T_C}{\mathbb{E}[S]}, \Gamma = \tfrac{P(S)\Lambda}{\mathbb{E}[S]}, \end{aligned} \quad (3)$$

where $\mathbb{E}[S]$ is the WiFi-Lic expected time per packet transmission; T_E, T_S, T_C are the average times per $\mathbb{E}[S]$ that the channel is empty due to random backoff, or busy due to successful transmission or packet collision (for multiple WiFi in the CSMA range), respectively. $P(S)$ is the AP-successful-probability of transmitting a packet in a given time slot. Λ is the average time spent transmitting the payload data.

If $\varepsilon_c \geq CCA_T$ (WiFi-Lic), the throughput is expressed as follows:

$$\begin{aligned} &T_{LTE} = f\left(R_\omega\right), \ \Lambda = f\left(R_\omega\right), \\ &\mathbb{E}[S] = T_{sensing} + T_{\mathbf{WiFi-Lic_{Tx}}}, \\ &\eta_{sensing} = \tfrac{T_{sensing}}{\mathbb{E}[S]}, \\ &\eta_{\mathbf{WiFi-Lic_{Tx}}} = \tfrac{T_{\mathbf{WiFi-Lic_{Tx}}}}{\mathbb{E}[S]}, \\ &\Gamma = \tfrac{P(RB)\Lambda}{\mathbb{E}[S]} \end{aligned} \quad (4)$$

$P(RB)$ is the successful probability of AP to transmit in a given resource block of LTE. Other parameter definitions can found in section III-A1.

C. SINR of LTE Link

The SINR of LTE link, $i, \forall i$, in the presence of WiFi and no WiFi is shown as

$$\Gamma_i = \begin{cases} \frac{p_i \xi_{i,i}}{\sum\limits_{j \in \lambda, j \neq i} p_j \xi_{i,j} + \sigma_0}, \text{ if no WiFi;} \\ \frac{p_i \xi_{i,i}}{\sum\limits_{j \in \lambda, j \neq i} p_j \xi_{i,j} + \sum\limits_{\tau \in \omega} \alpha_\tau p_\tau \xi_{i,,\tau} + \sigma_0}, \text{ if WiFi;} \end{cases} \quad (5)$$

where the terms $\sum\limits_{j \in \lambda, j \neq i} p_j \xi_{i,j}$ and $\sum\limits_{\tau \in \omega} \alpha_\tau p_\tau \xi_{i,,\tau}$ indicate the interference contribution from other LTE links and WiFi links, (assuming all links in ω are active). For the τ^{th} WiFi link, $\forall \tau$, the interference is reduced by a factor α_τ to capture the fact that the τ^{th} WiFi is active approximately for only α_τ fraction of time due to the CSMA/CA protocol at WiFi.

D. Throughput of LTE Link

We are considering LTE TDD downlink mode. LTE channel quality index (CQI) is used to calculate the peak throughout $\left(T_{LTE_{peak}}\right)$ of LTE which resembles to be eNB→User SINR. Moreover, CQI define the modulation method (bits/symbol→B_S and coding rate→C_R)for data transmission. Hence, we have

$$\begin{aligned} &CQI = f(\Gamma); \\ &B_S = f(CQI), \ C_R = f(CQI), \\ &T_{LTE_{peak}}(bps) = \Psi(R_E B_S C_R), \end{aligned} \quad (6)$$

where R_E is the number of resource elements for a given bandwidth and Ψ is the LTE control and signaling overheard.

V. Simulation results and discussions

To check the validity of our proposed approach, we have performed computer simulation. We considered the system design as described in section III coupled with the following parameters as shown in Table I.

TABLE I
SIMULATION PARAMETERS
(a) LTE parameters

Parameter	Value
Layout	21 cell Marco layout
Inter-site distance	500 m
System bandwidth	2×20 MHz (For adjacent 20 MHz carriers are assumed for LTE-U and one 40 MHz carrier for WiFi)
Carrier Frequency on unlicensed	5 GHz
Tx Power on unlicensed for LTE small cell and WiFi AP	24 and 30 dBm outdoor
UE noise figure	9 dB
Distance-dependent pathloss/Shadowing/Fading	Outdoor: (Smallcell-to- UE: ITU UMi) (WiFi-to- UE: ITU UMi) (UE-to- UE: 3GPP TR 36.843)
Number of Small cell	5
Number of users	10
Traffic model	3GPP Traffic-2 (0.5 MB for small cell with unlicensed layer, 0.025 MB for other users)
UE speed	3 km/h
Scheduling	Proportional Fairness
SINR w.r.t CQI	(1.95, 4, 6, 8, 11, 14, 17, 19, 21, 23, 25, 27, 29)
Frame	TDD (4UL:4DL)

(b) Operator WiFi parameters

Parameter	Value
WiFi Type	802.11n
Number of WiFi AP	10
Number of users	5
MPDU	1500B and 1ms duration
MAC	DCF Contention window: 15 slot, Max:1023 slot Detection: Energy detection
CCA Threshold	-62 dBm
Channel rate	(13, 26, 39, 52, 78, 104, 117, 130) Mpbs
Required SINR	(5, 7, 9, 13, 17, 20, 22, 23) dB
ACK frame rate	Max(6.5, 13, 26) Mbps
WiFi user Tx Power	18 dBm
ACK	16 Bytes

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In our simulation, we consider an SDL mode in a two-tier cellular network similar to [11]. The network consists of macrocells and outdoor picocells that share a bandwidth of 20MHz in the licensed band. The inter-site distance between macrocells is set as 500m. In each macrocell domain, we employ 5 picocells and 10 operator-deployed WiFi APs. We are considering the TDD frame with fixed 4UL:4DL slots. We assume that WiFi-Lic users can randomly choose from two available LTE UL slots (white space) and the other 2 UL slots are currently in use by LTE. Capacity of WiFi-Lic users depends upon the availability of these empty UL slots. For realistic simulation we focus on 40MHz channel for WiFi and 20MHz for LTE. When there are access opportunities available in LTE Uplink band, the WiFi-Lic can access the licensed band assuming that there is no opportunity available in the unlicensed band. If WiFi-Lic users (40MHz) access the LTE band (20MHz), then we add few null WiFi subcarriers in the remaining portion of the band to align with LTE bandwidth. We may lose some portion of WiFi-Lic bandwidth, but the loss is not so effective for best effort traffic. The spectrum gained through this operation is more valuable than the unutilized portion. We examine different network scenarios, e.g. cellular/WiFi internetworking and conventional heterogeneous network (HetNet), only with licensed access. In the former, WiFi replaces the picocells, while in the latter, there is no WiFi and the network operates only in the licensed band.

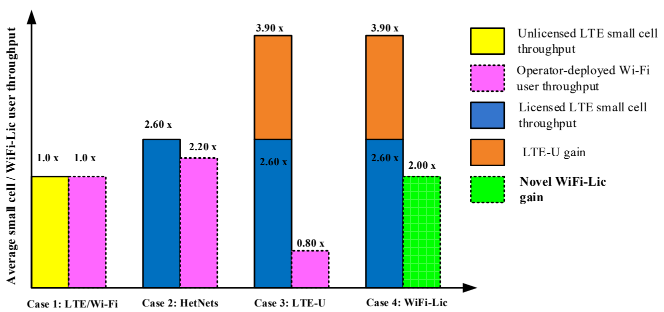

Fig. 3. WiFi-Lic Throughput Performance

Figure 3 shows the results in terms of average user throughput of licensed, unlicensed and WiFi-Lic for LTE small cells. The actual user throughput of operator deployed scenario in *case 1* is 4.526Mbps.The other throughput values are all normalized according to *case 1* baseline value. The figure shows the performance of our scheme against the state of the art schemes and it consists of four cases. **Case 1:** the throughput of both networks (LTE & Wi-Fi) are the same and this is due to the fact that both networks are using unlicensed band, equal number of users and access nodes densities. **Case 2:** the throughput for HetNets is enhanced almost double than *case 1*. This is due to the fact that users from the small cell access the licensed spectrum of LTE using centralized MAC, which is more spectrally efficient than DCF. Eventually the WiFi user throughput is increased by a factor of 2 since LTE small cells use orthogonal spectrum with WiFi, which causes no interference from LTE to WiFi users. **Case 3:** instead of deploying HetNets small cell in licensed spectrum as in *case 2* (blue bar), the introduction of LTE-U (small cell in 5GHz unlicensed band) proves to be a better throughput enhancement solution (brown bar) for the future Fifth-Generation (5G) systems. However, this solution degraded operator deployed WiFi throughput severely (0.80x) as shown in *case 3*, without any coexistence mechanism. **Case 4:** When we apply our novel solution, WiFi-Lic throughput increases to 2.00x. This is due to the fact that during busy times WiFi-Lic will access the white space in LTE band, according to the procedure explained in section III. Moreover, it is important to note that we need to do down conversion of WiFi 5GHz carrier frequency to LTE 2.6GHz. WiFi may lose some part of bandwidth but that loss is not so effective for best effort traffic.

Figure 4 shows the performance of WiFi-Lic during a busy period (LTE access the 5GHz and no channel is available). WiFi-Lic performance is much better than the normal WiFi mode during busy time. Normal WiFi waiting period varies randomly during channel busy time, as compared to WiFi-Lic solution which access the LTE white spaces during busy time and spends much less time in busy mode, which directly translates into higher overall throughput of the system.

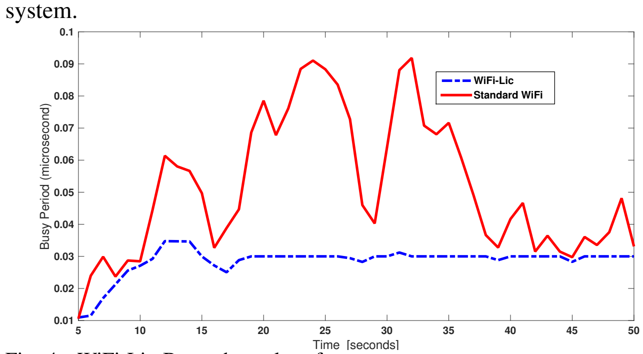

Fig. 4. WiFi-Lic Busy channel performance

VI. CONCLUSIONS

This letter addressed a new idea of operating WiFi in the licensed band. This solution not only increases the system throughput, but also decreases the busy period time of a WiFi node. For the future work, we plan to test this solution in a testbed using different metrics to verify our simulation. Details of our sensing mechanism will be provided in coming papers.

ACKNOWLEDGMENTS

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