Study of CR Based U-LTE Co-existence Under Varying Wi-Fi Standards

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Abstract. Long Term Evolution in unlicensed band extends the benefits of Long Term Evolution and Long Term Evolution - Advanced to deploy in 5 GHz unlicensed spectrum, enabling mobile operators to offload data traffic onto unlicensed frequencies. The License Assisted Access with Long Term Evolution allows co-existence with Wi-Fi through carrier aggregation. The recently evolved intelligent technology viz. Cognitive radio which supports the efficient spectrum utilization is applied in the proposed system model to detect the white spaces in 5 GHz band to accomplish Listen-Before-Talk regulatory requirement of radio communication in Long Term Evolution - unlicensed band. Another major goal of Long Term Evolution - unlicensed to co-existence along with Wi-Fi/Internet of Things users in a non-interference style is also accomplished by the use of Cognitive radio. Simulation results demonstrate their coexistence along with effectiveness of resource allocation in a varying 5 GHz compatible 802.11 wireless local area networks environment.

Keywords: LTE · U-LTE · Cognitive radio · Carrier aggregation
Coexistence issues · Wi-Fi/IoT in 5 GHz band

1 Introduction

1.1 LTE in Unlicensed Spectrum

Fourth Generation (4G) Long Term Evolution (LTE) is one of the several competing 4G standards along with Ultra Mobile Broadband and WiMax (IEEE 802.16). The main goal of LTE is to provide a high data rate, low latency and packet optimized radio-access technology, supporting flexible bandwidth deployments. LTE networks carries large amount of data. In spite of efficient cell management, large spectrum is required to handle such huge data. To address these issues, Long Term Evolution in unlicensed (LTE – U) is considered as the best innovations to meet the high performance and seamless user experience. Since LTE radio technology is based on state of the art technology, it can achieve both high data rates and at the same time high spectral efficiency in the unlicensed arena. Known in (3rd Generation Partnership Project) 3GPP

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as LTE License Assisted Access (LTE-LAA) or more generally as LTE-U, it enables access to unlicensed spectrum especially in the 5 GHz (Industrial, Scientific and Medical) ISM band.

Qualcomm, Huawei and Ericsson requested the 3GPP standards committee to allow LTE service to run on the 5 GHz band. The 5 GHz spectrum offers a large amount of bandwidth and is one of the two unlicensed bands that are typically used by Wi-Fi service. It has a shorter communication range due to higher path loss but has wider available bandwidth [1].

The 802.11 standard defines 23 20 MHz wide channels in the 5 GHz spectrum. Each channel is spaced 20 MHz apart and separated into three Unlicensed National Information Infrastructure (UNII) bands. Wireless devices specified as 802.11a/n/ac are capable of operating within these bands. In the United States, UNII-1 (5.150 to 5.250 GHz) containing channels 36, 40, 44, and 48 and UNII-3 (5.725–5.825) containing channels 149, 153, 157, 161 are permitted. UNII-2 (5.250–5.350 GHz and 5.470–5.725 GHz) which contains channels 52, 56, 60, 64, 100, 104, 108, 112, 116, 120, 124, 128, 132, 136, and 140 are permitted in the United States, but shared with radar systems.

1.2 Coexistence of U-LTE with Wi-Fi/IoT

Due to non-exclusive usage nature of unlicensed spectrum by U-LTE, there are two main challenges. The foremost challenge of design of U-LTE is its coexistence with Wi-Fi/IoT systems on a fair and friendly basis. The Wi-Fi/IoT systems are the user-deployed systems and they are the incumbent users or primary users of the unlicensed band. The PHY/MAC implementation differences between LTE transmissions and Wi-Fi/IoT, hinders the direct implementation of U-LTE transmissions as it can generate continuous interference to Wi-Fi/IoT systems.

Second is the coexistence of two or more different U-LTE operators in the same unlicensed band. The operation in unlicensed band also needs to factor in the regulatory requirements of a given region. In some markets, like Europe, Japan and India, a specific waveform requirement on supporting Listen-Before-Talk (LBT) at milliseconds scale is required which would need changes in LTE air interface. In other markets, like US, Korea and China, there are no such requirements. In these countries, with carefully designed coexistence mechanisms realizable by software to ensure peaceful coexistence with Wi-Fi/IoT, operators can deploy LTE in unlicensed bands that are compatible with Rel. 10/11 3GPP LTE standards. In markets where LBT is required, LTE in unlicensed operation can be further optimized through air interface enhancement with the introduction of LBT feature potentially in 3GPP Release 13 [2, 3].

1.3 Usage 5 GHz Band and Wi-Fi/IoT Usage

The Internet of Things (IoT) or Machine-to-Machine (M2M) communications is one of the most exciting and fastest growing technologies across the globe today. It employs the embedded technology with sensors and actuators, connects to other devices or to cloud, and automatically transmits information. There are many standards and proprietary solutions used for connecting devices to each other or to cloud such as Wi-Fi, Bluetooth, ZigBee, Active RFID, loWPAN, EtherCAT, NFC, RFID, etc. Wi-Fi has been the most successful among these technologies listed above due its adaptability, scalability, ease of use and cost. As the 2.4 GHz band is meant for unlicensed users, it is presently heavily crowded and hence, the IoT device communication and Wi-Fi are shifting to less crowd 5 GHz band.

In this work, IEEE 802.11a, 802.11n and 802.11ac standards of 5 GHz band are considered. 802.11a uses an orthogonal frequency division multiplexing encoding scheme and provides up to 54-Mbps. With multiple-input multiple-output (MIMO), the real speed of 802.11n would be 100-Mbps. The 802.11ac specification operates only in the 5 GHz frequency range and features support for wider channels (80 MHz and 160 MHz) to deliver data rates of 433Mbps per spatial stream, or 1.3 Gbps in a three-antenna (three streams) design.

1.4 Cognitive Radio and 5 GHz Band

The Federal Communication Commission (FCC) defined CR as the radio that can change its transmission parameters based on interaction with the environment in which it operates [4]. The Wireless communication has been increased along with the increase in high data rate requirements. The licensed spectrum space remains idle at most of the times [5] due to the inefficient allocation of frequencies whereas the cellular bands are overloaded. For effective utilization of spectrum and also to meet the spectrum demands, FCC revisited the problem of spectrum management [6] and this leads to CR invention. The IEEE 802.22 is the standard for cognitive wireless regional area networks (WRANs). The main goal of CR is to identify the unused licensed spectrum for secondary users (SU) without interfering Primary Users (PU) and this method of sharing is often called as Dynamic Spectrum Access (DSA) [7].

The flexibility in the hardware and its feasibility to program for a band or mode enables CR to adapt over to an ISM band or up to an IEEE band and even to unlicensed 5 GHz bands. CR dynamically monitors certain bands of the 5 GHz unlicensed spectrum to identify the idle spectrum and uses them as needed [8].

1.5 CR Applications in U-LTE

In authors' previous work [9], a system was so modeled to utilize the attributes of the CR to optimally operate U-LTE in 5 GHz band. Figure 1 depicts the architecture of U-LTE in 5 GHz band. User Equipment (UEs) and IoT devices, communicates with Wi-Fi Access Point (AP) using the unlicensed spectrum, form a femto cell and become primary users. During their communications with eNodeB (eNB), UEs form a small cell and try to utilize the unlicensed spectrum and become secondary users.

U-LTE operates in two modes: Supplemental Downlink (SDL) and Time Division Duplex (TDD). In SDL mode, the unlicensed spectrum is used only for the downlink traffic, thereby eNB performs most of the necessary operations to ensure the reliable communications, including checking whether the intended unlicensed channel is free from other use [10]. For TDD mode, the unlicensed spectrum is used for uplink and downlink, resulting additional implementation complexity in UEs for LBT feature. Latest release of 3GPP LTE standard Rel.13 supports usage of unlicensed spectrum in both operating modes [3].

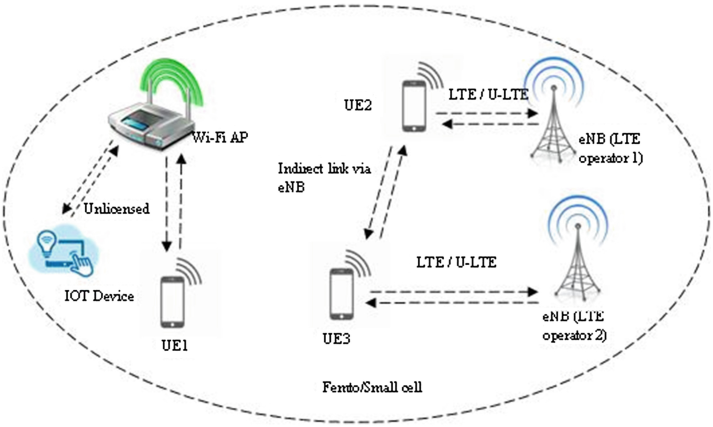

Fig. 1. U-LTE architecture in 5 GHz band

Considering the SDL mode, the eNB equipped with CR realizes the LBT feature with an efficient mechanism to share the unlicensed spectrum with Wi-Fi, the primary users of the specified band in a non-interference basis and also paving the way for the currently evolving IoT or M2M communications.

Channel and traffic model was formulated to optimize the functionality of U-LTE in terms of clean channel searching and co-existence of secondary users with primary users and presented in the previous work [9]. The same work is extended to study the data traffic and resource allocation for eNB/Wi-Fi nodes in SDL mode for IEEE 802.11a and 802.11n standards and presented in this paper.

The mathematical theory formulation for resource allocation in 23 channels of 5 GHz band is explained in Sect. 2. Simulation and performance analysis of U-LTE in 802.11a and 802.11n 5 GHz bands is presented in Sect. 3 and concluded in Sect. 4.

2 Problem Formulation

Considering the U-LTE architecture in 5 GHz band as shown in Fig. 1, the Wi-Fi access points are the primary users and eNBs are secondary users equipped with CRs. The network is considered to be operates in time slots t, t + 1, t + 2 etc. The time slot for U-LTE is defined by the ETSI standards [11] as Channel Occupancy Time (CCT) for 10 ms. The downlink U-LTE traffic (in bps) is enqueued in the eNBs and then transmitted to UEs using packet-scheduling procedure as detailed in LTE standard [12]. Based on the resource allocation procedures [13] and queuing theory [14, 15], the following notations are used in sequel:

1. $Q_i^L(t)$ and $Q_i^w(t)$ denotes the queue size (in bits) at eNB node and Wi-Fi/IoT access point at the beginning of the time slot t at i^{th} channel.
2. $S_i^L(t)$ and $S_i^w(t)$ denotes the service rate (in bps) at the time slot t at i^{th} channel for eNB node and Wi-Fi/IoT access point.

3. $D_i^L(t)$ and $D_i^w(t)$ denotes the amount of data (in bps) generated during the time slot t at ith channel for eNB node and Wi-Fi/IoT access point.
4. C_i is the capacity (data rate) of the channel.
5. $Q_i^L(t+1)$ and $Q_i^w(t+1)$ denotes the queue size (in bits) at eNB node and Wi-Fi/IoT access point at the next time slot.

The total number of bits served by the channel cannot exceed its maximum serving capacity

$$S_i^L(t) \leq C_i,\ S_i^w(t) \leq C_i\ \forall i \in l, \boldsymbol{l} = \{1, 2, \ldots\ldots.23\} \tag{1}$$

Here $\boldsymbol{l}$ denotes the 23 non-overlapping channels of 5 GHz band.

By applying Lindley's equation, $Q_i^L(t+1)$ and $Q_i^w(t+1)$ can be estimated as

$$Q_i^L(t+1) = [Q_i^L(t) + D_i^L(t) - S_i^L(t)]^+, \forall i \in l \tag{2}$$

$$Q_i^w(t+1) = [Q_i^w(t) + D_i^w(t) - S_i^w(t)]^+, \forall i \in l \tag{3}$$

Where

$$[\mathrm{x}]^+ = \max[0, \mathrm{x}] \tag{4}$$

By using Eq. (2), the queue length for n time slots is determined. The resource can be allocated as continuous time slots not exceeding the channel capacity can be shown as

$$\sum_{t=1}^{n} S_i^L(t) \leq C_i, \forall i \in l,\ \boldsymbol{l} = \{1, 2, \ldots\ldots.23\} \tag{5}$$

The application of Eq. (5) is considered for U-LTE (secondary users) alone whereas the resource allocation and data transmission for primary or the Wi-Fi/IoT users are assumed to be taken care by its own MAC protocol.

3 Simulation

3.1 System Model

The system model is simulated in compliance to Rel. 13 3GPP LTE standards using MATLAB showing the coexistence of U-LTE and Wi-Fi/IoT in 5 GHz band ranging from 5.0 to 5.8 GHz (U-NII 1/2/2e), 23 channels each with assumed bandwidth of 20/40/80 MHz's. The general simulation parameters are listed in Table 1. Table 2 lists the simulation parameters of U-LTE under different Wi-Fi standards.

The block diagram for simulating the coexistence of U-LTE with Wi-Fi/IoT with LBT using CR is shown in Fig. 2. The simulation system consists of two separate

Table 1. General simulation parameters

Parameters	Values
No. of channels (*l*)	23
Time slot (t)	10 ms
Aggregated time slots	10/20/50/100 ms
Wi-Fi band	5 GHz (UNII –1,2 & 2e)
No. of users	10 to 500
Energy of Wi-Fi signal	–60 dBm to –30 dBm
Energy of LTE signal	–80 dBm to –65 dBm
CCA threshold	20 µs and < –80 dbm

Table 2. U-LTE simulation parameters under different Wi-Fi standards

Type of Wi-Fi	Bandwidth	$S_i^L(t)$	C_i	$D_i^L(t)$	$Q_i^L(t)$
Case 1: 802.11a	20 MHz	540 Kbits	54 Mbps (max)	100/200/500/1000 Mbps	50/100/200/500 Mbps
Case 2: 802.11n	20 MHz	700 Kbits	72 Mbps (max)	100/200/500/1000 Mbps	50/100/200/500 Mbps
Case 3: 802.11n	40 MHz	30 Mbits	600 Mbps (max) 300 Mbps (avg)	100/200/500/1000 Mbps	50/100/200/500 Mbps

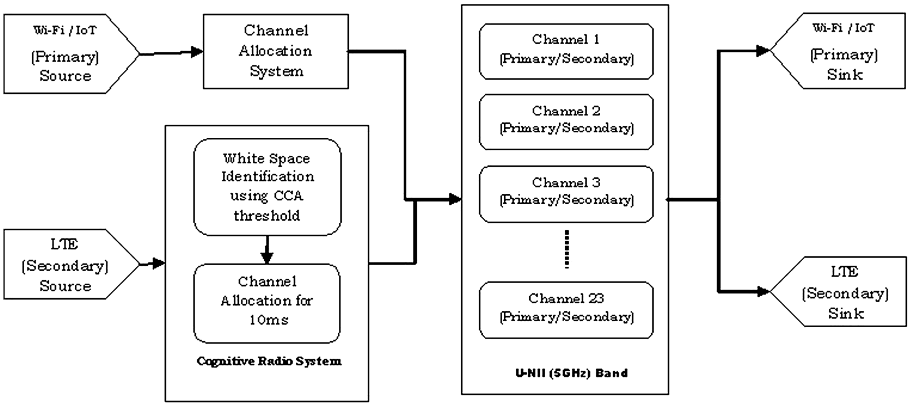

Fig. 2. Block diagram of channel allocation in LBT scenario with application of cognitive radio

sources, one for LTE and other for Wi-Fi/IoT generating multiple signals in random fashion with respective energy and transmission time. Due to the application of CR in this system model, Wi-Fi/IoT systems are considered as the primary users and U-LTE systems as secondary users. Incoming signals from Wi-Fi/IoT sources occupy the channels by following their own MAC protocol by means of Channel allocation system. Whereas, U-LTE signals, in order to accomplish LBT feature, they follows the ETSI standards [10] for channel occupancy through CR system. The channel and the traffic model are formulated based on the state transition model and queuing theory [16] in our previous work and the same is utilized in this system.

The CR system at the LTE eNB node, on getting a transmission request from LTE source, identifies the white space (free channel) in U-NII band and estimates the Clear Channel Assessment (CCA) threshold. CCA threshold is estimated by measuring the energy level of the free channel for a listening period of 20 μs.

If the energy level in the channel is below –80 dBm for the listening period of 20 μs, considering it as low interference level in the channel and assumed to be free. The Channel is then allocated for the U-LTE signal transmissions for the duration equal to Channel Occupancy Time of 10 ms. Later, if LTE source wishes to continue its transmission, it repeats the white space detection and CCA process for channel allocation. On every channel request and allocation process, the Channel Occupancy time for LTE source is maximum 10 ms. Therefore, the above process is repeated until LTE source completes its transmission. On every cycle, the channel allocated for LTE transmissions is different or same based on the free channel availability. The two scenarios depicting coexistence of U-LTE with Wi-Fi/IoT with LBT using CR at different continuous instances of time for 100 users are shown in Figs. 3 and 4.

In Fig. 3, the channel occupancy status during the initial time span of 100 ms is shown. During that time, 13 channels out of 23 are occupied by Wi-Fi/IoT signals and the remaining 10 channels are occupied by U-LTE signals. Therefore, channels of U-NII band have been occupied almost fairly by U-LTE and Wi-Fi/IoT systems during the initial phase of channel allocation.

Figure 4 depicts the channel occupancy status at later time after 200 ms. Here, Wi-Fi/IoT signals occupy 15 channels and 8 by U-LTE signals. The channel occupancy measure of Wi-Fi/IoT systems is almost same as that of in earlier time span. Maintaining almost the same channel occupancy status even after the later time span depicts the fair and friendly sharing of channels between Wi-Fi/IoT and U-LTE signals. This leads to the reduced back off rate of Wi-Fi/IoT systems.

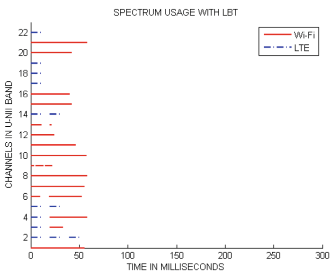

Fig. 3. Scenario 1: initial channel occupancy

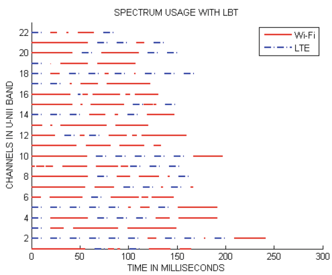

Fig. 4. Scenario 2: channel occupancy status after 200 ms

3.2 Performance Analysis

Considering the channel capacity C_i (data rate) of the Wi-Fi standards, timeslots are aggregated as 10, 20, 50 and 100 ms to service the U-LTE signals. For every cases depicted in Table 2, the queue size $Q_i^L(t)$ at the eNB node is varied as 50/100/200/500 Mbps at the beginning of the time slot for every channel and the behavior of the system is analyzed. Similarly, the system is analyzed for various amounts of data $D_i^L(t)$ such as 100/200/500/1000 Mbps generated during the time slot at every channel.

In case 1 (802.11a) and case 2 (802.11n 20 MHz) as shown in Figs. 5a and 6a, Wi-Fi back off rate increases. The increase in back off rate is due to the dominance usage of medium by LTE-U users due to time slot aggregation with increased data traffic. Increase in back off rate results in throughput deficiency. Figures 5b and 6b compares the throughput of Wi-Fi and LTE-U. As the medium is most utilized by LTE-U, its throughput ratio is more than Wi-Fi. The imbalance utilization of medium by LTE-U and Wi-Fi indicates the reduced chance of fair and friendly co-existence between them.

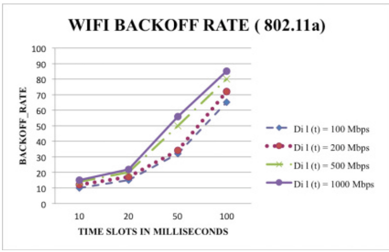

Fig. 5a. Wi-Fi Back off rate for IEEE802.11a

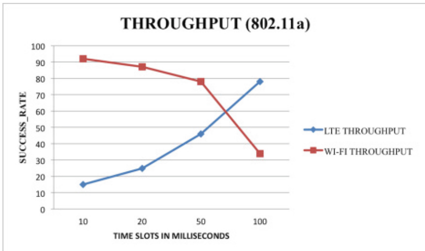

Fig. 5b. Throughput for IEEE802.11a

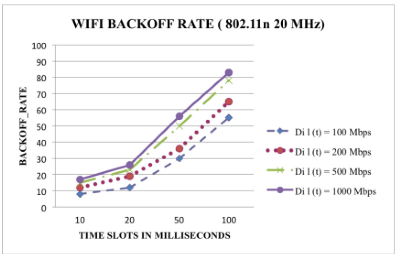

Fig. 6a. Wi-Fi Back off rate for IEEE802.11n (20 MHz)

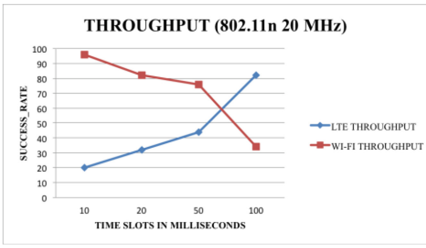

Fig. 6b. Throughput for IEEE 802.11n (20 MHz)

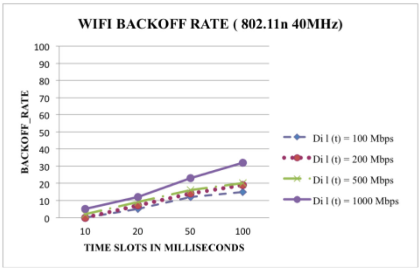

Fig. 7a. Wi-Fi Back off rate for IEEE802.11n (40 MHz)

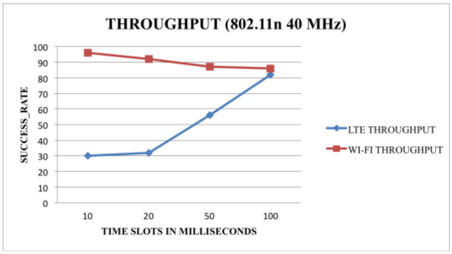

Fig. 7b. Throughput for IEEE802.11n (40 MHz)

In case 3 (802.11n 40 MHz) as shown in Fig. 7a, the Wi-Fi back off rate reduced to 50% of case1 and 2. Though the throughput of LTE-U increases with increased data traffic and time slot aggregation, Wi-Fi throughput does not falls below 80% as shown in Fig. 7b.

Based on the above observations, it can be summarized that, time slot aggregation technique of LTE-U transmissions creates reduced level of interference to incumbent Wi-Fi users in IEEE standards 802.11n (40 MHz) and 802.11a than 802.11a/n (20 MHz) paving the way for their fair and friendly coexistence. The data rate of IEEE standards 802.11n (40 MHz)/ac is a major factor that supports the fair coexistence between the two.

4 Conclusion

The spectrum utilization of radio frequencies is gaining momentum due to the invasion of wireless equipment in every field of human life. In this regard, there is a change over from licensed LTE to U-LTE in view of the evident advantages of later in terms of speed, cost etc. An improved method is proposed in this work to include CR in U-LTE for effective utilization of the white spaces in the radio spectrum. Performance of such system under varying data traffic for different IEEE standards of 5 GHz band was observed to analyze the interference level and the chances of fair and friendly coexistence of U-LTE with Wi-Fi/IoT users.

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