

# Modeling and Analysis of MAC Protocol for LTE-U Co-existing with Wi-Fi

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**Abstract**—In this paper, a new MAC protocol for LTE over unlicensed spectrum (LTE-U) is presented that allows friendly co-existence of LTE-U with other unlicensed wireless networks, including Wi-Fi. Specifically, in a time-slotted LTE-U system, LTE-U users can transmit continuously for a period after a successful channel reservation during the spectrum sensing period. Following each LTE transmission period, a certain duration is reserved for asynchronous Wi-Fi transmissions. By adaptively adjusting the periods of LTE transmissions, Wi-Fi transmissions, and spectrum sensing, different levels of Wi-Fi protection can be achieved. Based on the proposed MAC, an analytical model is developed to study the throughput performance of both LTE-U and Wi-Fi, considering the asynchronous transmission nature of Wi-Fi within the time-slotted MAC structure. Impacts of the protocol parameters, i.e., the periods of LTE/Wi-Fi transmissions and spectrum sensing, on the throughput performance of LTE-U and Wi-Fi are also investigated. Extensive simulation results are provided to validate the analysis.

**Index Terms**—LTE-Unlicensed, MAC, LTE/Wi-Fi co-existence, performance analysis.

## I. INTRODUCTION

The mobile communication industry continues to scale rapidly in recent years. As such, the main objective of the next generation 5G networks is to excavate more network capacity to meet the ever-growing mobile traffic demand. In 2014, the Federal Communication Committee (FCC) opened a spectrum of 295 MHz in the 5 GHz spectrum for unlicensed commercial use, which motivates new research activities [1] to exploit the unlicensed bands along with the licensed bands to provide complementary capacity in Long Term Evaluation (LTE) network based on the existing LTE network architecture. LTE is originally designed to operate in licensed bands to achieve the maximum spectral efficiency and optimize the QoS performance of subscribers [2]. Unlike licensed spectrum which is exclusive for the licensed users, unlicensed spectrum is usually shared by multiple unlicensed systems given the regulation requirements are met. Therefore, the foremost issue in unlicensed network is to achieve friendly co-existence among multiple unlicensed systems. For instance, the most successful unlicensed network, Wi-Fi, uses a “listen before talk” (LBT) based medium access control (MAC) protocol, namely, carrier sensing multiple access with collision avoidance (CSMA/CA), to ensure long term fairness among different users. Thus, to implement LTE over unlicensed band (LTE-U), it is essential for LTE-U to co-exist in a fair manner with other unlicensed networks especially Wi-Fi. It is likely that LBT-based techniques will be introduced in Release 13 to allow friendly LTE-U unlicensed sharing. However, LTE and Wi-Fi adopt different

MAC protocols that are fundamentally different, i.e., LTE uses scheduling-based MAC for synchronous transmissions while Wi-Fi implements contention-based MAC for asynchronous transmissions. How to allow efficient and friendly co-existence between synchronous LTE-U and asynchronous Wi-Fi and how to analyze the performance of each co-existing network still remain open and beckon for further investigation.

There are several MAC proposals for LTE-U in the literature. In [3] [4], an on/off transmission cycle is introduced where the on period is used for LTE-U transmissions and the off period for Wi-Fi transmissions. The off duration can be randomly selected [3] or dynamically adjusted according to the collected statistics of Wi-Fi activities [4]. For these mechanisms, the LTE-U transmission is not hinged on the instantaneous channel availability and thus may interrupt the ongoing Wi-Fi transmissions. To improve the co-existence performance, the LBT feature is introduced in the MAC design of LTE-U such that the LTE-U node can transmit only if the channel is sensed idle for a certain duration [5] [6]. In [5], an LTE-U node can transmit for a maximum time ratio in one cycle if the channel is sensed idle; or keep silent for the whole cycle, otherwise. An analytical performance study of the duty cycle based protocol is provided in [6]. With a duty cycle based mechanism, LTE-U senses the channel at the specific time in each duty cycle, which makes it difficult for LTE-U to retrieve the channel access due to the elastic feature of Wi-Fi transmissions. Therefore, it is hard to ensure the coexistence performance of the LTE-U system. As such, it is desirable to design a more fair MAC protocol to achieve high performance of LTE-U while ensuring a certain level of Wi-Fi protection.

In this paper, we propose a MAC protocol for LTE-U and analyze the performance of the co-existed LTE-U and Wi-Fi networks. The main contributions are three folds. First, we propose an LBT-based LTE-U MAC protocol to achieve harmonious co-existence with Wi-Fi systems. Specifically, the MAC timing is divided into variable cycles, each composed of variable periods for LTE-U transmissions, Wi-Fi transmissions, and channel sensing. By adjusting the ratio between the transmission periods of LTE-U and Wi-Fi adaptively, performance balance between the LTE-U and Wi-Fi can be ensured and the desired Wi-Fi protection levels can be achieved. Second, based on the proposed MAC, we develop an analytical model to study the network performance of LTE-U and Wi-Fi, capturing the asynchronous nature of Wi-Fi in a synchronous MAC frame structure of LTE-U. We analyze the average duration of channel sensing in each cycle for LTE-U to retrieve the channel access, and derive the average throughput of both

LTE-U and Wi-Fi networks. Finally, extensive simulations are conducted to validate the throughput analysis under different sensing configurations and Wi-Fi protection levels, which provides important guidance for the optimal MAC setting in an LTE-U/Wi-Fi co-existing system.

The remainder of this paper is organized as follows. Section II introduces the system model. Section III presents a MAC protocol that allows friendly co-existence of LTE-U and other unlicensed networks, followed by an analytical study in Section IV. Simulation results are shown in Section V to validate the analysis, followed by concluding remarks in Section VI.

## II. SYSTEM MODEL

### A. Co-existence Scenario

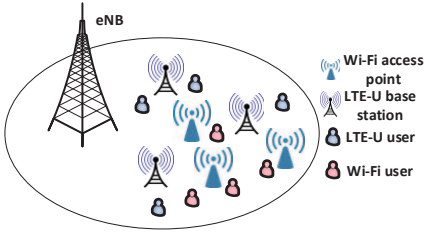


Fig. 1: Coexistence scenario between LTE-U and Wi-Fi.

Fig. 1 shows a network with co-existed LTE-U and Wi-Fi operating on the same unlicensed spectrum band. Due to the unlicensed transmission power limitations [5], the LTE-U technology will be mainly used for small cells, yet the small cells may operate on both licensed and unlicensed bands. Data with high reliability and QoS requirements, e.g., control signaling, is transmitted over the licensed bands; while other supplemental data can be transmitted over the unlicensed bands [1]. In a dense deployment, it is possible that more than two different access networks, e.g., LTE-U small cells or Wi-Fi networks, select the same channel, and cause inter-system interference. Unlike the traditional LTE system where macro- and micro-cells are managed by one operator for efficient coordination, coordination is difficult for unlicensed networks of different operators or Wi-Fi owners. Therefore, it is critical to design a co-existence mechanism to allow efficient spectrum sharing between LTE-U and Wi-Fi.

### B. LTE and Wi-Fi MAC/PHY Features

The LTE and Wi-Fi have different PHY and MAC features. LTE employs orthogonal frequency division multiple access (OFDMA) in the PHY layer. The whole bandwidth is divided into a set of orthogonal physical resource blocks (PRBs). Different PRBs can be scheduled to different users in the same subframe, thus achieving multi-user diversity gain. Wi-Fi adopts orthogonal frequency division multiplexing (OFDM) in the PHY layer, but only one user can access the channel at one time. For the MAC protocols, LTE adopts a centralized and synchronous MAC to schedule transmissions in each subframe of 1 ms. Wi-Fi uses a distributed asynchronous MAC based on CSMA/CA [7]. That is, before transmission, the Wi-Fi node

first listens to the intended channel. If the channel is busy, the Wi-Fi node will backoff for a random time to reduce collision probability. Due to these differences, MAC design for LTE-U should be based on the synchronous structure of LTE for easy integration and compatibility, yet should also be efficient and adaptive to the asynchronous Wi-Fi transmissions.

## III. THE PROPOSED LBT-BASED MAC FOR LTE-U

The basic principle of the LBT-based MAC is that LTE-U nodes need to sense the channel for a period before transmission. If the channel is sensed busy, the LTE-U node should remain silent and sense the channel periodically in the following subframes till the channel is idle for a certain duration. In 3GPP meetings, it is generally accepted that alternating channel reservation periods for LTE-U and Wi-Fi should be adopted in the LTE-U MAC [8]. Based on these principles [8], we propose a detailed LTE-U MAC protocol to coordinate the unlicensed spectrum sharing with Wi-Fi systems, as illustrated in Fig. 2. Parameters of the MAC protocol play a critical role in the performance of coexisted networks, and will be analytically studied in Section IV.

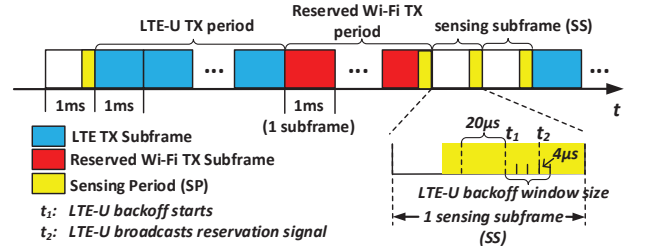


Fig. 2: LBT-based MAC protocol of LTE-U.

Timing in LTE-U is slotted into subframes of 1ms, as shown in Fig. 2. Several subframes are reserved for LTE-U and Wi-Fi transmissions, respectively, i.e., the LTE-U transmission period (LTX, the blue period) and the Wi-Fi transmission period (WTX, the red region). Both LTX and WTX can be adjusted according to the desired performance of either system. In the last subframe of WTX, the LTE-U node can start channel sensing. The subframes where sensing is performed are called sensing subframes (SSs), and the duration of sensing in each SS is called one sensing period (SP) as marked in yellow at the end of each SS. If the channel is sensed idle for a duration, the LTE-U node broadcasts a reservation signal to reserve the next few subframes for LTX; otherwise, the node will sense in every following SS until the channel is sensed idle. The LTE-U node can only transmit at the beginning of the subframe following the reservation signals, while Wi-Fi can transmit at any time during a subframe. Due to the asynchronous Wi-Fi transmissions, there may be a variable number of SSs before LTX starts. The duration of the SPs affects the network throughput of both LTE-U and Wi-Fi.

The sensing procedure is illustrated in Fig. 2. The SP has a minimum duration of  $20\mu s$ . In one SP, if the channel is sensed idle for  $T_{thre}\mu s$ , the LTE-U node adds a random backoff time to avoid reservation collisions with different LTE-U nodes. The

backoff timer elapses when the channel is sensed idle. When the backoff timer reaches 0, the LTE-U node immediately broadcasts a reservation signal. If a new Wi-Fi transmission or a reservation signal from another LTE-U occurs during the backoff, the reservation fails and the above process has to be repeated till a successful reservation is launched.

It is also interesting to point out that LBT sensing may make it difficult for LTE-U to retrieve the channel access from Wi-Fi. Unlike the Wi-Fi nodes that can sense the channel continuously, the channel sensing of LTE-U is usually performed at specific time in one SS. When the Wi-Fi traffic load is medium or high, it is with high probability that there are ongoing Wi-Fi transmissions covering the SP due to the elastic and asynchronous channel access nature. Consequently, the channel will be sensed busy with high probability, resulting failure of the LTE-U system to retrieve the channel access. In such case, LTE-U may achieve a low throughput while Wi-Fi is well protected. Therefore, the duration of SP can significantly affect the LTE-U success probability for channel retrieval, and further affect the throughput performance of both systems.

In the proposed LTE-U MAC, we set  $T_{thre} = 20\mu s$ , and the maximum LTE-U backoff timer is 3 slots with a slot duration of  $4\mu s$ . Notice that a DCF interframe space (DIFS) duration is  $34\mu s$ , i.e., a Wi-Fi transmission can be initiated after the channel is sensed idle for at least  $34\mu s$ . By allowing an LTE-U node to reserve LTX transmissions after a maximum of  $20\mu s + 3 * 4\mu s = 32\mu s$ , LTE-U node has a higher priority for channel access compared with Wi-Fi nodes during the SP so that LTE-U can easily retrieve the channel access after the WTX completes. This can ensure the throughput efficiency of LTE-U while providing the satisfactory Wi-Fi performance via WTX reservations. The main notations of the proposed protocol are summarized in Table I.

#### IV. PERFORMANCE ANALYSIS FOR LTE-U LBT-BASED COEXISTENCE MECHANISM

This section presents throughput analysis for the network with one LTE-U small cell co-existed with Wi-Fi networks. Firstly, the average number of SPs taken by LTE-U to retrieve the channel access is derived. Then, the average system throughput is derived for both LTE-U and Wi-Fi systems. Finally, discussions are provided on how to tune the MAC parameters according to the desired Wi-Fi protection level.

##### A. Average Number of SPs to Retrieve the Channel Access

Denote the average number of SPs needed by the LTE-U to retrieve the channel access as  $\overline{N_{SP}}$ .  $\overline{N_{SP}}$  is closely dependent on the position of the first Wi-Fi transmission that overlaps with the first SS of LTE-U. Such Wi-Fi transmissions are referred to as *first overlapping (FO) transmissions* in this paper. There are two types of FO transmissions: i) those that start before the first SS and stretch into the SSs, and ii) those that start in the first SS but their respective previous Wi-Fi transmission ends before the first SS.

As specified in 802.11 standard [9], when one Wi-Fi transmission ends, other nodes first sense the channel for a DIFS

TABLE I: Notation Table

Notations	Physical Meanings
$T_s$	The duration of one LTE subframe, $1ms^*$
$LTX$	The reserved period for LTE transmissions in one cycle
$WTX$	The reserved period for Wi-Fi transmissions in one cycle
$\overline{WTX_{tot}}$	Average total period that the Wi-Fi system can transmit consecutively
$T_{SP}$	Channel sensing period in one sensing subframe (SS)**
$\overline{T_{int}}$	The time interval between two consecutive Wi-Fi transmissions
$T_{DIFS}$	The duration of DIFS in Wi-Fi MAC protocol*
$T_{W,Win}$	The maximum contention window size of Wi-Fi**
$T_{L,Win}$	The maximum backoff window size of one LTE-U node**
$T_{thre}$	The minimum sensing time threshold to determine whether channel is idle, i.e., $20\mu s^*$
$APWT$	The average period per Wi-Fi transmission**
$\overline{R_L}$	The average cell throughput of one LTE-U system
$\overline{R_W}$	The average sum throughput of the Wi-Fi system
$N_{SP}$	The average number of SPs needed for LTE-U to get the channel access back
<b>Remarks</b>	The variables marked with * are constants. The variables marked with ** are configurable parameters.

duration (denoted as  $T_{DIFS}$ ) and transmit only when the backoff timer reaches 0. Thus the average interval between two consecutive Wi-Fi transmissions, denoted as  $\overline{T_{int}}$ , is

$$\overline{T_{int}} = T_{DIFS} + T_{W,Win}/2, \quad (1)$$

where  $T_{W,Win}$  is the maximum random backoff window size in  $\mu s$ . Thus, the average range where the second-type FO transmissions start is  $\overline{T_{int}}$ . Therefore, the total range where FO transmissions start is

$$T_{range} = APWT + \overline{T_{int}}, \quad (2)$$

where  $APWT$  is the average period per Wi-Fi transmission. Meanwhile, to retrieve the channel access, one LTE-U node needs to first sense channel for a  $T_{thre}$  period plus backoff time in SP before broadcasting the reservation signal. Thus, the average period from the instance when the channel is sensed idle to the instance when the reservation signal is broadcast is

$$T' = T_{thre} + T_{L,Win}/2. \quad (3)$$

where  $T_{L,Win}$  denotes the maximum backoff window size for one LTE-U node in  $\mu s$ .

For FO transmissions, different positions where the transmission completes can lead to different channel sensing results and different numbers of following SSs. Thus, we study the four cases with different positions of the FO transmissions, as illustrated in Fig. 3. To simplify the analysis, we consider that  $APWT$  is a multiple of milliseconds.

**Case 1:** If the Wi-Fi transmission ends no earlier than  $(\overline{T_{int}} - T')$   $\mu s$  before SP begins and no later than  $T_{thre}$   $\mu s$  before SP ends, the LTE-U node, e.g., LTE-U base station (BS), is able to detect a  $T_{thre}$  idle period and broadcast the reservation signal before another Wi-Fi transmission starts. In this case, no more SPs are needed and LTE can start transmission in the beginning of the next subframe.

**Case 2:** If the Wi-Fi transmission ends more than  $(\overline{T_{int}} -$

$T')$   $\mu s$  before the SP starts, the LTE-U node cannot detect a  $T_{thre}$   $\mu s$  idle period in the current SS or has no enough time to broadcast the reservation signal. In this case, a new Wi-Fi transmission may start and the LTE-U node has to sense at least another  $APWT/T_s$  SSs to retrieve the channel access.

**Case 3:** If the Wi-Fi transmission ends later than  $T_{thre}$   $\mu s$  before the SP ends, the LTE-U node cannot detect a  $T_{thre}$   $\mu s$  idle period in the current SS. In this case, the LTE-U node has to sense at least another  $APWT/T_s + 1$  subframes to get the channel access back.

**Case 4:** Case 4 is different from the above ones in the sense that it corresponds to the second type of FO transmissions. In this case, the LTE-U node cannot detect any idle period in the first SS in an average sense and has to sense at least  $APWT/T_s + 1$  subframes before transmitting.

In the following, we will calculate the average number of SPs before an LTX can be launched, i.e.,  $\overline{N_{SP}}$ , for different cases. Denote  $\overline{N_{SP}}$  for case  $c$  as  $\overline{N_{SP_c}}, c \in \{1, 2, 3, 4\}$ . We assume that the arrival of the FO transmissions follows a uniform distribution within  $T_{range}$ .

1) *Case 1:* In a single subframe, the probability that one FO transmission belongs to case 1 is calculated as

$$p_1 = [(T_{SP} - T_{thre}) + (\overline{T_{int}} - T')]/T_{range}. \quad (4)$$

If one FO transmission corresponding to case 1 starts within the  $i$ th subframe of the first APWT duration in  $T_{range}$ , as one transmission lasts for APWT duration on average, the average number of SPs needed to find the transmission end is  $i$ . Thus  $\overline{N_{SP_1}}$  can be calculated as

$$\begin{aligned} \overline{N_{SP_1}} &= \sum_{i=1}^{APWT/T_s} p_1 \cdot i \\ &= \frac{\overline{T_{int}} - T' + T_{SP} - T_{thre}}{T_{range}} \cdot \frac{(1 + \frac{APWT}{T_s}) APWT}{2T_s} \end{aligned} \quad (5)$$

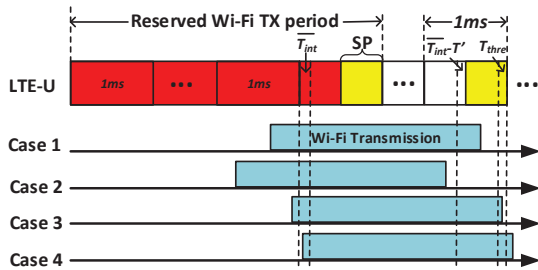


Fig. 3: Illustration of four cases for FO transmissions.

2) *Case 2:* In one subframe, the probability that one FO transmission belongs to case 2 is given by

$$p_2 = [(T_s - T_{SP}) - (\overline{T_{int}} - T')]/T_{range}. \quad (6)$$

In this case, the LTE-U node cannot detect an idle period of  $T_{thre}$   $\mu s$  or cannot finish the backoff to broadcast a reservation signal. Only Wi-Fi transmissions may start and last for APWT on average until a new Wi-Fi transmission completes in the region corresponding to case 1. Thus according to the number of new transmissions that will occur, the region corresponding

to case 2 in one SS is divided into  $N_{sr}$  sub-regions, where

$$N_{sr} = \left\lceil \frac{T_{C_2}}{\overline{T_{int}}} \right\rceil, T_{C_2} = (T_s - T_{SP}) - (\overline{T_{int}} - T_{thre}). \quad (7)$$

The conditional probability that the transmission ends in the first sub-region given that it belongs to case 2 is

$$p(\text{first sub-region}|C_2) = (T_{C_2} - N_{sr} \cdot \overline{T_{int}})/T_{C_2}. \quad (8)$$

The conditional probability that the transmission ends in one of the other sub-regions given that it belongs to case 2 is

$$p(\text{another sub-region}|C_2) = \overline{T_{int}}/T_{C_2}. \quad (9)$$

Eq. (8) and (9) are different because the first sub-region may be less than  $\overline{T_{int}}$ . For the  $j$ th sub-region, the LTE-U node needs to sense  $(N_{sr} + 1 - j)APWT/T_s$  more SPs before transmitting. Thus, the average number of extra SPs due to new Wi-Fi transmissions, denoted as  $\overline{N_{SP_2}^{new}}$ , is calculated as

$$\begin{aligned} \overline{N_{SP_2}^{new}} &= \frac{APWT}{T_s} [p(\text{first sub-region}|C_2)N_{sr} \\ &+ \sum_{j=2}^{N_{sr}} p(\text{another sub-region}|C_2)(N_{sr} + 1 - j)]. \end{aligned} \quad (10)$$

Then, the average total number of SPs needed due to both current and new Wi-Fi transmissions is calculated as

$$\overline{N_{SP_2}} = \sum_{i=1}^{APWT/T_s} p_2 \cdot (i + \overline{N_{SP_2}^{new}}). \quad (11)$$

3) *Case 3:* The way of calculation for case 3 is similar to that of case 2, i.e., exploiting sub-regions to calculate the average number of extra SPs due to new Wi-Fi transmissions. We divide the combined region, i.e., the region corresponding to case 2 in the current SS and the region corresponding to case 3 in the next SS, into  $N'_{sr}$  sub-regions, i.e.,

$$N'_{sr} = \left\lceil \frac{T_{C_2} + T_{thre}}{\overline{T_{int}}} \right\rceil, \quad (12)$$

where  $T_{R_2}$  is given in Eq. (7). The region corresponding to case 3 may belong to the same sub-region or two sub-regions. If  $(N'_{sr} - 1)\overline{T_{int}} \leq T_{C_2}$ , the entire region of case 3 in one single subframe belongs to the 1st sub-region, otherwise the region stretches across the 1st and 2nd sub-regions. Therefore, the average number of SPs due to new Wi-Fi transmissions, denoted as  $\overline{N_{SP_3}^{new}}$ , is calculated as

$$\begin{aligned} \overline{N_{SP_3}^{new}} &= 1 + APWT/T_s \\ &\cdot \begin{cases} N'_{sr}, & \text{if } (N'_{sr} - 1)\overline{T_{int}} \leq T_{C_2}; \\ \frac{T_{C_2} + T_{thre} - (N'_{sr} - 1)\overline{T_{int}}}{T_{thre}} N'_{sr} \\ + \frac{(N'_{sr} - 1)\overline{T_{int}} - T_{C_2}}{T_{thre}} (N'_{sr} - 1), & \text{otherwise.} \end{cases} \end{aligned} \quad (13)$$

Thus the average total number of SPs due to both current Wi-Fi transmissions and new Wi-Fi transmissions is

$$\overline{N_{SP_3}} = \sum_{i=1}^{APWT/T_s} \frac{T_{thre}}{T_{range}} \cdot (i + \overline{N_{SP_3}^{new}}). \quad (14)$$

4) *Case 4:* Similarly, we can divide the sub-regions in case 4. Divide  $T_{C_2}$  by  $\overline{T_{int}}$  and the duration of the region for case

4 is  $\overline{T_{int}}$ . The region for case 4 must stretch across the 1st and 2nd sub-regions. Thus the average number of SPs needed in case 4, i.e.,  $\overline{N_{SP_4}}$ , is calculated as

$$\overline{N_{SP_4}} = 1 + \frac{APWT \cdot \overline{T_{int}}}{T_{range}} \cdot \left[ \frac{T_{C2} - (N_{sr} - 1)\overline{T_{int}}}{\overline{T_{int}}} (N_{sr} + 1) + \frac{N_{sr}\overline{T_{int}} - T_{C2}}{\overline{T_{int}}} N_{sr} \right]. \quad (15)$$

Therefore, combining Eq. (5)(11)(14)(15), the average number of SPs needed before a LTX is

$$\overline{N_{SP}} = \sum_{c=1}^4 \overline{N_{SP_c}}. \quad (16)$$

#### B. Average System Throughput for LTE-U and Wi-Fi Systems

After obtaining the average number of SPs needed for an LTE-U node to retrieve the channel access, i.e.,  $\overline{N_{SP}}$ , we then derive the network throughput of the coexisted LTE-U and Wi-Fi. During the WTX and the SSs, LTE-U cannot launch a transmission, while Wi-Fi transmissions could happen in all SSs. Denote the total average duration of the period that LTE-U cannot transmit (or Wi-Fi can transmit) as  $\overline{WTX_{tot}}$ ,

$$\overline{WTX_{tot}} = WTX - T_s + \overline{N_{SP}} \cdot T_s. \quad (17)$$

One " $T_s$ " in Eq. (17) is reduced because the first SP starts in the last subframe of WTX.

Given  $LTX$  and  $\overline{WTX_{tot}}$ , the system throughput for LTE-U and Wi-Fi can be derived. Following [10], the average throughput of an LTE cell when proportional-fair MAC scheduling and adaptive power allocation are adopted is

$$\overline{R_{LTE}} = \frac{N_{LTE} N_{PRB}}{\sum_{i=1}^{N_{LTE}} R_i^{-1}}, \quad (18)$$

where  $R_i = W_{PRB} \log_2 \left[ 1 + \frac{\Gamma \cdot 10^{(\alpha-1)L_i/10}}{N_0} \right]$ ,  
 $\Gamma = 10^{(P_0-30)/10}$ ,

where  $N_{LTE}$  denotes the number of LTE users,  $N_{PRB}$  the number of PRBs in one channel,  $W_{PRB}$  the bandwidth of one PRB,  $L_i$  the pass loss of user  $i$ ,  $N_0$  the noise power per PRB, and  $(\alpha, P_0)$  the frequency-specified power control parameters. Due to time sharing, the actual average throughput of LTE-U in coexisted scenario is

$$\overline{R_L} = \overline{R_{LTE}} \frac{LTX}{LTX + \overline{WTX_{tot}}}. \quad (19)$$

For a Wi-Fi system, as given in [11], the aggregate network throughput can be derived as

$$\overline{R_W} = \beta \cdot \frac{P_{suc} S_{pay}}{P_{idle} T_{W,Win}/2 + P_{suc} APWT + P_{col} T_{col}}, \quad (20)$$

and  $\beta = \frac{\overline{WTX_{tot}}}{LTX + \overline{WTX_{tot}}}$ ,

where  $S_{pay}$  denotes the average number of bits per Wi-Fi transmission,  $T_{col}$  denotes the average duration of a collision period,  $P_{suc}$ ,  $P_{idle}$  and  $P_{col}$  are the probabilities of a successful transmission, an idle slot, and a collision, which are determined by the analytical framework in [11].

From Eq. (19)(20), the Wi-Fi protection level is closely related to the ratio  $\beta$ , which depends on  $WTX$  and  $T_{SP}$ . Thus, Proposition 1 is provided to show how to tune  $WTX$

based on  $LTX$ ,  $T_{SP}$  and the required Wi-Fi protection level.

**Proposition 1:** Given the  $T_{SP}$  and  $LTX$ , to protect  $\eta$  percent of Wi-Fi system throughput,  $WTX$  should be set that the following condition is satisfied,

$$\frac{\overline{WTX_{tot}}}{LTX + \overline{WTX_{tot}}} \geq \eta\% \quad (21)$$

As the corresponding equality of Eq. (21) is a transcendental equation without an analytical solution, numerical results are presented in next section to show how  $WTX$  changes with different  $\eta$  and  $T_{SP}$  values.

#### V. SIMULATION RESULTS

In this section, simulation results are provided to validate our analysis and demonstrate the performance of the proposed LTE-U MAC. We simulate the coexistence network scenario presented in Fig. 1, where one LTE-U small cell coexists with a set of Wi-Fi access points (APs) on a 20MHz unlicensed channel. The simulation runtime is 100s. For the LTE-U system, two LTE-U users are uniformly located within the cell with a radius of 40m for downlink transmissions. For the Wi-Fi system, all the APs and users are uniformly distributed within the LTE-U cell. All the nodes carry saturated traffic. The main simulation parameters are shown in Table II.

TABLE II: Main Simulation Parameters

LTE-U Parameters	Values
Path Loss Factor	3
Shadowing Statistics	$\mu = 0 \text{ dB}, \sigma = 8 \text{ dB}$
Noise Power per RB, $N_0$	-90dBm
$[\alpha, P_0]$	[0.5, -58dBm]
Power allocation for user $i$ (dBm)	$P_0 + 10 \log(N_{PRB}) + \alpha L_i$
Number of PRBs in the channel	100
Bandwidth per PRB	180kHz
MAC scheduling method	Proportional Fair
LTX	5ms
Default sensing period $T_{SP}$	200μs
Channel idle time threshold $T_{thre}$	20μs
Maximum Backoff window size	3 slots
Backoff time slot duration	4μs
Wi-Fi Parameters	Values
Default WTX	5ms
DIFS duration $T_{DIFS}$	34μs
Maximum contention window size	31 slots
Backoff time slot duration	9μs
Packet size $S_{pay}$	6750 bytes

We first investigate the probability that the LTE-U BS fails to reserve the channel in the first SS under different  $T_{SP}$  in Fig. 4. It can be seen that when  $T_{SP}$  is very small, i.e., 20μs, the failure probability can be as high as 0.82. This is because unlike the Wi-Fi system that can sense the channel continuously, the LTE-U BS senses the channel at specific time, i.e., at the last 20μs in one SS. As a result, the probability that the BS can detect a 20μs idle period and broadcast the reservation signal is very small for a lower  $T_{SP}$ . When  $T_{SP}$  increases, the failure probability is reduced since the BS is more likely to detect a 20μs idle period and launch a successful reservation with a larger SP duration.

The analytical and simulated results of average system throughput are shown in Fig. 5 for both LTE-U and Wi-Fi

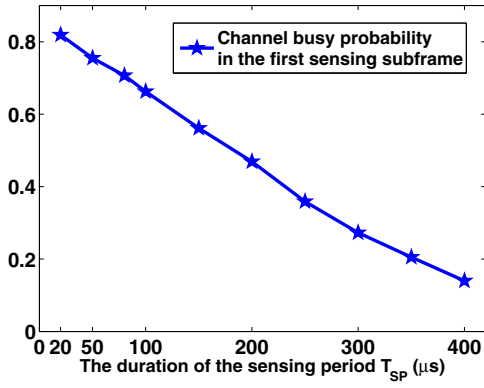


Fig. 4: The probability that the LTE-U BS fails to reserve the channel in one subframe. WTX = 5ms.

systems. It can be observed that when  $T_{SP}$  increases, the average Wi-Fi throughput decreases while that of the LTE-U system increases. Meanwhile, the protection level of the Wi-Fi performance reduces when  $T_{SP}$  increases. The reason is as follows. When  $T_{SP}$  increases, the probability that the LTE-U BS can successfully reserve the channel in one SS becomes larger. Consequently, the average number of SSs for the LTE-U BS to retrieve the channel is smaller. As Wi-Fi can still transmit in the SS, the reduced number of SSs will result in reduced time ratio of the Wi-Fi transmission in the whole simulation period. Thus, the Wi-Fi throughput decreases and the LTE-U throughput increases. Besides, the analytical results match well with the simulation results. The gap between the analysis and simulation is slightly larger when  $T_{SP}$  is smaller. This is because the analysis assumes that the end of the Wi-Fi transmissions belonging to case 1 follows a uniform distribution. When  $T_{SP}$  is smaller, the assumption becomes less accurate, resulting a larger gap.

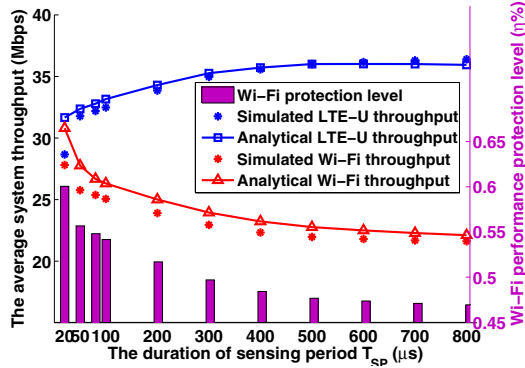


Fig. 5: The average system throughput for LTE-U and Wi-Fi and the corresponding Wi-Fi protection level. WTX = 5ms.

Finally, we show that given  $LTX$  and  $T_{SP}$ , how to adjust WTX according to different Wi-Fi protection levels in Fig. 6. For a given  $T_{SP}$ , the average number of SSs needed by LTE-U to retrieve the channel can be determined. Thus, to increase the Wi-Fi protection level is equivalent to increase the time ratio of Wi-Fi transmissions in one cycle. As shown in the figure, the average Wi-Fi throughput increases with a larger  $\eta$  at the

expense of the decreased average LTE-U throughput because a smaller ratio of time is allocated for LTE-U transmissions.

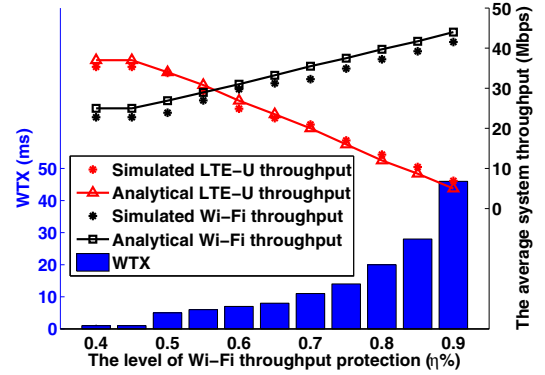


Fig. 6: WTX adaptation according to different Wi-Fi protection levels.  $T_{SP} = 200\mu s$ .

## VI. CONCLUSION

In this paper, we have presented a new MAC protocol design for LTE-U networks. An analytical model has been developed to study the MAC throughput performance of co-existed LTE-U and Wi-Fi networks, considering the asynchronous WiFi transmissions in a time slotted MAC structure of LTE-U. It has been shown that a certain level of Wi-Fi protection can be achieved by adaptively adjusting the MAC parameters. In our future work, we will extend our performance study by considering multiple co-existed small cells and Wi-Fi networks operating in multiple unlicensed channels.

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