

On the Impact of LTE-U on Wi-Fi Performance

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Abstract With the exponential growth in mobile data traffic taking place currently and projected into the future, mobile operators need cost effective ways to manage the load of their networks. Traditionally, this has been achieved by offloading mobile traffic onto Wi-Fi networks due to their low cost and increasingly ubiquitous deployment. Recently, LTE operating in the unlicensed spectrum has drawn significant interests from mobile operators due to the availability of the unlicensed spectrum. Using this technology, the unlicensed spectrum is directly utilized by LTE without the need to offload traffic to an alternative radio access technology such as Wi-Fi. However, the deployment of LTE networks in the unlicensed band poses significant challenges to the performance of current and future Wi-Fi networks. We discuss the LTE and Wi-Fi coexistence challenges and present analysis on performance degradation of the Wi-Fi networks at the presence of LTE.

Keywords Heterogeneous networks coexistence · LAA-LTE · LTE unlicensed · LTE-U · Radio spectrum management · Wi-Fi

1 Introduction

The exponential growth of mobile data traffic is driving mobile network operators (MNOs) to look into various cost effective solutions to meet the continuously increasing demand and offload traffic from the costly licensed spectrum. The low cost of Wi-Fi access points, the pervasiveness of Wi-Fi in mobile devices and the availability of unlicensed spectrum has made Wi-Fi the technology of choice for data offload. Nonetheless, the integration of Wi-Fi into the 3GPP core network remains complex despite the availability of four separate standardized methods dating back to 3GPP Release 6 [1]. Despite the numerous options, none of them were found to be satisfactory by the MNOs and thus no wide deployments of the solutions are seen.

Most recently, the 3GPP is considering extending the use of LTE into the unlicensed spectrum as another means to enable traffic offload. This new approach is dubbed LTE Unlicensed (LTE-U)¹. Compared to Wi-Fi, LTE-U offers MNOs a way to offload traffic onto the unlicensed spectrum with a technology that seamlessly integrates into their existing LTE evolved packet core (EPC) architecture. A

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¹ Since July 2014, 3GPP has been using License Assisted Access (LAA) as the official 3GPP term, and ETSI amended “Listen before talk” into LAA. By the time this paper was accepted, both FDD and TDD modes were introduced in TR36.889. Meanwhile, the LTE-U forum, formed by Verizon and a few other vendors in 2014, released an LTE supplemental downlink (SDL) coexistence specification, where an adaptive duty cycle based coexistence scheme was introduced, and the term “LTE-U” was used instead of “LAA” in the specification. Hence, there are now technical and business related differences between LTE-U and LAA. Various vendors and operators have developed positions in support of one or the other. However, since this paper focuses on duty cycle based LTE on unlicensed spectrum, we still use the short and conventional term LTE-U for convenience.

single eNB can support LTE and LTE-U for seamless integration to the MNO network. Furthermore, LTE-U promises higher throughput and spectral efficiency than Wi-Fi, with estimates ranging from $2\times$ to $5\times$ improvement over Wi-Fi [2, 3].

Three modes have been proposed for LTE-U, distinguished by the supplementary and control channel configurations as shown in Fig. 1:

- Supplemental downlink (SDL): In this mode, the unlicensed band is used to solely carry data traffic in the downlink direction, while the uplink and control channel remain in the licensed spectrum.
- Carrier aggregation TD-LTE: In this mode, the unlicensed band is used as an auxiliary TDD channel capable of carrying data traffic in the uplink and the downlink directions while the control channel remains in the licensed spectrum.
- Standalone LTE-U: In this mode, the data and the control channels of LTE-U operate in the unlicensed spectrum; thus there is no dependence on licensed spectrum availability to support LTE-U operations. This option has not been discussed in the 3GPP, but provides a option for operators that do not currently own spectrum to benefit from LTE-U capabilities.

In this paper, we consider the potential impact of LTE-U on Wi-Fi networks for the first two configurations above. No specific modification to LTE channel access is considered and the goal is to evaluate the impact of LTE transmission on Wi-Fi channel access probability. We begin with a brief review of the lower layers of LTE and Wi-Fi protocols in Sect. 3, followed by an analysis of the LTE “quiet period” in Sect. 4. We then present a probabilistic framework to determine the likelihood of Wi-Fi transmission during the LTE quiet period. Numerical results are presented in Sect. 5.

2 Prior Works

The problem of Wi-Fi and LTE coexistence and the potential impact of one network over the other have recently been studied and simulation results have been presented in a number of research and industry publications.

In [4], a paper published by Nokia Research, a simulator based system level analysis has been performed to assess the performance of LTE and Wi-Fi networks coexisting in an office environment. Single-floor and multi-floor office environments with different assumptions on the density of Wi-Fi and LTE nodes have been considered in the simulation. Although the simulation model, the assumptions on Wi-Fi and LTE system parameters and deployment environment can be improved, the results presented in [4] validate our analysis presented in this paper: in the absence of any modification to LTE channel access mechanism, channel sharing between Wi-Fi and LTE networks is significantly unfair for the Wi-Fi network, LTE only loses about 4 % of the performance when Wi-Fi is present on the same band, while Wi-Fi could lose up to 70 % performance under sparse deployment and or 90 % performance under dense deployment. In [5], the performance of LTE and WLAN in a shared frequency band was evaluated, the results shows co-existence has a negative but controllable impact on WLAN system performance.

In [3], LTE-U is described as a better neighbor to Wi-Fi than Wi-Fi to itself. It is also claimed that LTE-U provides operators substantial improvements in data throughput without any impact to Wi-Fi users when a proprietary coexistence mechanism called carrier sensing adaptive transmission (CSAT), which will be introduced in Sect. 3, is applied. While these claims are derived from simulations, the simulation models used are not available publically.

Fig. 1 LTE-U alternatives

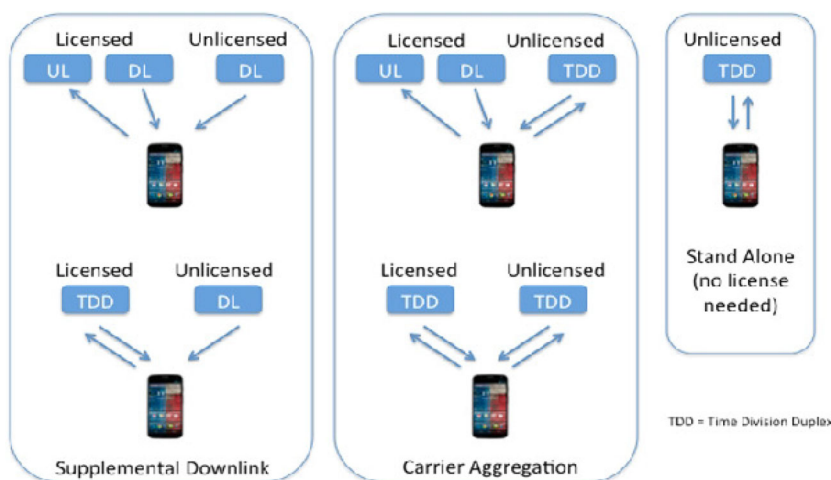


Table 1 MAC layer comparisons

	LTE	Wi-Fi
Multiple access	Multiple users served simultaneously, occupying different frequencies in channel	Absent of MU-MIMO, only one user is served at a time, takes up entire channel spectrum
Channel usage	Frames are contiguous, so channels are approximately “always on”	Channel is occupied only when packets needs to be transmitted
Channel access	Centralized scheduling on DL and UL. LTE does not contend, it simply transmits	Distributed Coordination Function (DCF), contention-based
Collision avoidance	None, b/c channel access are centrally scheduled	CSMA/CA + RTS/CTS (in principle, “sense before transmit”)
Co-existence	Has not had the need to be able to coexist with other technologies	Already coexists well with other technologies in unlicensed band, although with no common fairness mechanism

In [2], simulation results are provided on spectrum efficiency comparison between Wi-Fi and LTE in a sparse deployment scenario. It states that the simulation includes coexistence updates to LTE-U to accommodate Wi-Fi, but does not provide sufficient detail on the effectiveness of the coexistence features. The trends of interference based on traffic load appear credible, if LTE-U to LTE-U coordination is achieved or interference avoidance is deployed.

Remarkably, the recent 3GPP study item technical report document [6] has listed Listen-Before-Talk (LBT) as the required function for clear channel assessment for LTE LAA. The application of LBT may potentially enhance the coexistence behavior of Wi-Fi and LTE. Meanwhile, in the LTE-U SDL Coexistence Specifications from LTE-U forum, CSAT is officially introduced as the access mechanism.

3 A Comparison of Wi-Fi and LTE Lower Layers

All of the UEs within an LTE cell are synchronized with eNB. LTE radio architecture contains control plane for radio-specific functionality, and the user plane handles data packet traffic. Downlink (DL) and uplink (UL) transmission can proceed either simultaneously or sequentially depending on whether TDD or FDD duplex modes being selected. The usage of OFDMA technology on DL enables multiplexing of data transmission among UEs. In particular, the eNB determines the resource block allocation over frequency-time space for associated UEs according to each of their channel state information and QoS request. The UL stream is established using SC-FDMA to reduce the power consumption on end-user mobile devices. An important new feature proposed in release 10 is carrier aggregation (CA), which combines multiple carriers to support higher peak rate transmission. The LTE-U is a natural extension of CA from licensed band to unlicensed band.

Contrary to LTE MAC, Wi-Fi medium access has always been a “listen before talk” (LBT) protocol on either primary or secondary channels. CSMA/CA and RTS/CTS

are applied for clear channel assessment². The Wi-Fi physical layer (802.11n or later versions) also employs OFDM for both DL and UP, but the subcarrier spacing is sparser and granularity is longer than of LTE PHY, therefore Wi-Fi and LTE waveforms are not always orthogonal. Similar to CA of LTE, 802.11n introduced the concepts of primary and secondary channels. The beacon signal and the existence announcement will be placed on primary channel, and the secondary channels, if available, led to higher data transmission rate.

Table 1 shows that LTE MAC may be more efficient at spectrum usage compared to Wi-Fi MAC, specially when large number of users access the medium. This is primarily due to the centralized scheduling nature of the LTE protocol at the eNB. LTE will fill the airtime when the traffic load permits. The maximum sector capacity is independent of the number of UEs being served by the LTE eNB. On the other hand, as the number of users increases in the Wi-Fi network, the performance of CSMA/CA and channel utilization degrades due to the increased probability of collision [7].

4 The Coexistence Challenge

LTE-U poses significant coexistence challenges for Wi-Fi networks due to the inherent differences between channel usage and access procedures used by each technology. Wi-Fi is designed to coexist with other technologies through channel sensing and random backoff. On the other hand, LTE is designed with the assumption that one operator has exclusive control of a given spectrum; LTE traffic channels are designed to continuously transmit with minimum time gap even in the absence of data traffic. Consequently, Wi-Fi users will have little chance to sense a clear channel and deem it suitable for transmission.

² Although point coordination function is also defined in Wi-Fi, it is not widely implemented, and therefore not discussed in this paper.

LTE is an almost continuously transmitting protocol. In order for Wi-Fi users to transmit, they need to wait for a “quiet” period when LTE is not transmitting. Even when there is no data traffic present on the air interface, LTE periodically transmits a variety of control and Reference Signals. How long LTE remains truly “quiet” depends on the periodicity of these signals. We examine the control signals next.

4.1 LTE “Quiet Period”

4.1.1 LTE FDD System

As shown in Fig. 1, LTE-U has been defined with several different access modes, depending on which link is carried on the unlicensed spectrum. One realization of LTE-U is to carry one or more DL carrier(s) of a LTE FDD network on the unlicensed spectrum. The periodicity of the DL control and Reference Signals will dictate whether and when Wi-Fi may be able to leverage these quiet periods and be able to transmit.

Figure 2 shows a pair of LTE DL Resource Blocks (RBs) with Physical Downlink Control Channel (PDCCH) and Reference Signals³. The PDCCH carries UL and DL scheduling assignments, among other vital control information. The PDCCH occurs at the start of every subframe, or every 1 ms, taking between one and three OFDM symbols. The Reference Signals are present regardless of whether DL data transmissions are present, and are used for channel estimation for coherent detection. The Reference Signals are transmitted in every DL subframe at fixed locations, spanning the entire DL bandwidth.

4.1.2 TD-LTE “Quiet Period”

Another realization of LTE-U shown in Fig. 1 is to carry both the UL and DL traffic of a TD-LTE network on the unlicensed spectrum. In TD-LTE, seven UL/DL configurations are defined to allow for the adaptation of different UL–DL traffic profiles by assigning more or less subframes within a frame for UL or DL data transmission.

To enable fair access to the channel in the unlicensed spectrum, LTE-U using TD-LTE network may be designed to intentionally not schedule data transmission for X subframes during the period of every Y total subframes. For example, UL/DL configurations 0, 3, and 6 all show that a maximum of three UL subframes (or 3 ms) are scheduled together, and therefore can be intentionally muted by the eNB. This duty cycle approach to coexistence allows LTE-U to maintain the efficiency it enjoys due to the scheduled

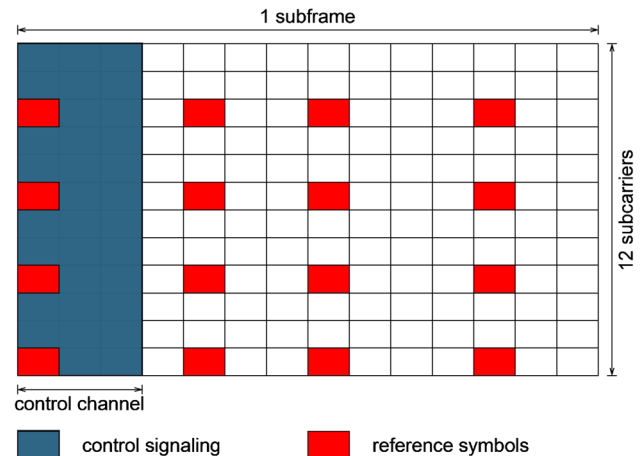


Fig. 2 LTE DL control and reference signals

nature of the LTE air interface while providing WiFi APs opportunities to access the channel.

4.2 How does LTE Quiet Period Compare to Wi-Fi?

For LTE-U, the maximum quiet period is

- Three symbols, or approximately 215 μ s, on the DL of a LTE FDD network
- Up to three subframes, or 3 ms, on a TD-LTE network

Wi-Fi AP and devices need to back off for a random period of time prior to transmission which can potentially occur outside the window of the LTE quiet period. When a transmission does occur, the burst length for a 1518 byte frame is approximately between 110 μ s and 1.8 ms, depending on the modulation and coding used.

Unless the LTE-U traffic channels are designed differently than LTE traffic channels in licensed spectrum, LTE-U will apply continuous traffic to devices in a periodic fashion. LTE-U will present significant challenges to Wi-Fi throughput and delay performances by maintaining control of a large share of the airtime.

4.3 Probability of Wi-Fi Channel Access

In Sect. 4.1, we derived the maximum “quiet” period for SDL and TD-LTE modes of LTE-U. In this section, our goal is to obtain the probability of Wi-Fi channel access, which is formulated as the probability of Wi-Fi backoff delay being less than the LTE-U quiet periods, provided the backoff procedure is initiated inside the LTE quiet period⁴ By Wi-Fi backoff delay, we mean the time elapsed

³ Only standard slot configuration is considered, i.e., normal cyclic prefix with seven symbols per slot. No MIMO configuration is considered.

⁴ Note that, even if the LTE-U quiet period is long enough that the Wi-Fi user can access the channel, its transmission may be interfered by LTE-U users, seriously degrading its throughput. This is however outside the scope of this paper.

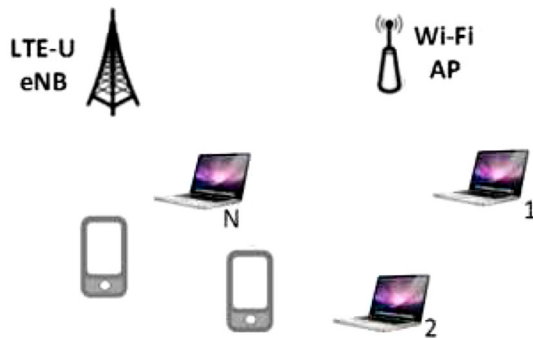


Fig. 3 LTE-U network coexisting with a Wi-Fi network with N stations

since Wi-Fi starts its backoff process until the packet is successfully transmitted. Let us define D as the random variable denoting backoff delay and variable L as the length of LTE-U quiet period. With the above notations, the probability of Wi-Fi channel access within an LTE-U quiet period is $\Pr\{D < L\}$. In what follows, we use the notation $\Pr\{\cdot\}$ for probability of event, and $p_X(x)$ (or simply $p(x)$) as the probability mass function (pmf) of random variable X .

We consider a Wi-Fi network with N stations coexisting with an LTE-U network as shown in Fig. 3, and assume that the N stations follow the DCF and backoff rules to access the channel. The N stations in the Wi-Fi network contend to access the wireless medium and the collisions of their transmitted packets increases the backoff delay. In Fig. 4, we show different components of backoff delay.

The DCF can be mathematically modeled into a two dimension Markov chain model [8] as given in Fig. 5. The i -th floor in the Markov chain stands for the random back-off process before the i -th transmission attempt, where $0 \leq i \leq M$, with contention window size $W_i = 2^i W_0$, where W_0 is the contention window size of the 0-th back-off. This Markov chain has transition probability $p(i_{n+1}, j_{n+1} | i_n, j_n)$,

$$\begin{cases} 1 & i_{n+1} = i_n; j_{n+1} = j_n - 1 \\ & j_n \neq 0 \\ 1 - p_{i_n} & i_{n+1} = 0, i_n \neq M; \\ & j_{n+1} \in \{0, \dots, W_0\}, j_n = 0 \\ \frac{p_{i_n}}{2^{i_{n+1}} W_0} & i_{n+1} = i_n + 1, i_n \neq M; \\ & j_{n+1} \in \{0, \dots, 2^{i_{n+1}} W_0\}, j_n = 0 \\ 1 & i_{n+1} = 0, i_n = M; \\ & j_{n+1} \in \{0, \dots, W_0\}, j_n = 0 \end{cases} \quad (1)$$

During each $(i, 0)$ state, a Wi-Fi station senses the channel, with probability P_i it detects clear channel and transmits (or re-transmits) a packet. If successful, the station stays idle or goes back to 0-th contention level for a new packet, otherwise the failed packet will be re-

transmitted until it reaches the maximum number of retry attempts. Before the i -th attempt, a random number is generated according to uniform distribution $\text{Unif}(0, W_i - 1)$ and loaded into the back-off timer. The timer decreases the registered value by one per slot time, once the back-off timer being reset, the station senses the channel for the i -th attempt.

A Wi-Fi station receiving Wi-Fi interference over -82 dbm will freeze its back-off timer, therefore a slot time can be empty (which lasts as long as the system-defined time slot), or may contain the transmission of one or more stations (in which case a freeze on backoff timer decrement happens). In order to use this Markov chain model to analyze the Wi-Fi service time, the model in [8] is further generalized by [9] and [10] after incorporating the following three assumptions:

1. The backoff transition time T_d between any two neighbor states is identically and independently distributed, and interference between any two Wi-Fi stations is always above -82 dbm threshold;
2. Based on assumption 1 and applying central limit theorem, the time interval from a back-off timer loads with an initial number j_i before i -th attempt to the timer being reset is a Gaussian random variable with mean $j_i E(D)$;
3. Collision is the only reason that induces transmission failure⁵.

Next we describe the failure probability P_i in each re-transmission trial. Let λ be the probability that there is no packet ready to transmit, and τ be the probability that a Wi-Fi station transmits (or re-transmits) a packet in a randomly chosen time slot given a packet just left the buffer and is ready to be transmitted. The number τ is a function of the number of Wi-Fi stations n and P_i . According to assumption 3, the probability P_i is simply the collision probability P_c that at least two Wi-Fi stations transmits simultaneously, which is

$$P_i = P_c = 1 - [1 - (1 - \lambda)\tau]^{N-1} \quad (2)$$

On the other hand, we have

$$\tau = \sum_{i=0}^M (1 - P_c) p(i, 0) \quad (3)$$

according to the transition probability defined in (1), where $p(i, j)$ is the stationary distribution of the Markov chain. There is no close form expression of the solution to P_i and τ , but given the system parameters and number of stations,

⁵ Since Wi-Fi to Wi-Fi interference below -82 dbm, LTE interference and noise can also cause transmission failure, the Wi-Fi access probability we obtain in this paper is an upper bound.

Fig. 4 Backoff delay components

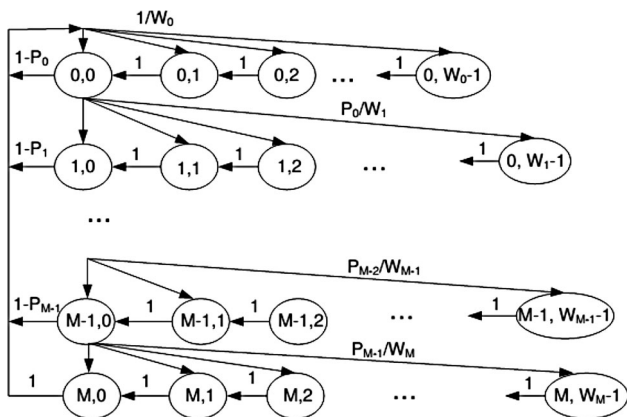
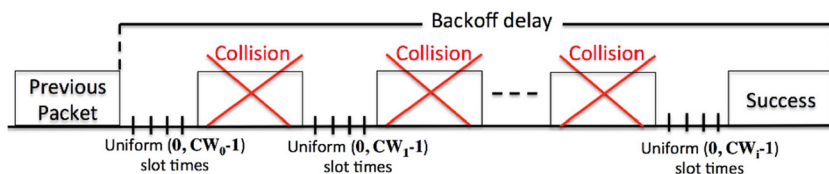


Fig. 5 Markov chain modeling of Wi-Fi DCF

they can be numerically computed. When the Wi-Fi system is saturated, i.e. the buffer in each station is never empty, i.e. $\lambda = 0$ and $P_c = 1 - (1 - \tau)^{N-1}$.

It remains to specify the distribution of backoff transition time T_d . Let T_s and T_c be the time duration, normalized to the system slot time, of one successful and failed (collided) transmission, respectively. If CTS/RTS mechanism is used, T_s and T_c can be calculated as follows

$$T_s = \text{RTS} + \text{CTS} + \text{HDR} + \text{DATA} + \text{ACK} + 3 \times \text{SIFS} + \text{DIFS} \tag{4}$$

$$T_c = \text{RTS} + \text{DIFS} \tag{5}$$

otherwise

$$T_s = \text{HDR} + \text{DATA} + \text{ACK} + \text{SIFS} + \text{DIFS} \tag{6}$$

$$T_c = \text{HDR} + \text{DATA} + \text{DIFS} \tag{7}$$

Note the packet length which reflected by the term “DATA” can be variable. Let P_s be the probability that one of the other $N - 1$ Wi-Fi station transmits successfully⁶, i.e.

$$P_s = (N - 1)\tau(1 - \tau)^{N-2} = (N - 1)[(1 - P_c)^{\frac{N-2}{N-1}} + P_c - 1] \tag{8}$$

The transition time T_d has following pmf,

$$p_{T_d}(t_d) = \begin{cases} 1 - P_c & t_d = 1 \\ P_c - P_s & t_d = T_c \\ P_s & t_d = T_s \\ 0 & \text{o.w.} \end{cases} \tag{9}$$

The amount of backoff delay depends on the number of collisions before the successful transmission of a packet. Using the total probability theorem, we have

$$\Pr\{D < L\} = \sum_{i=0}^R \Pr\{D < L | i \text{ collisions}\} p(i \text{ collisions}) \tag{10}$$

where R is the retry limit, i.e., the maximum number of collisions before the packet is discarded. Define a slot time as the time duration between two consecutive backoff decrements. Expanding (10), we have

$$\Pr\{D < L\} = \sum_{i=0}^R \sum_{j=0}^{W_i} [\Pr\{D < L | i \text{ collisions}, j \text{ slots}\} \times p(j \text{ slots} | i \text{ collisions}) p(i \text{ collisions})] \tag{11}$$

where $W_i = \sum_{k=0}^i W_k - 1$, $W_k = \min\{2^k W_0, W_{max}\}$ is the maximum contention window size after k collisions, and W_0 and W_{max} are the 0-th and maximum contention window size as defined in 802.11 standard. Note that for $W_k < W_{max}$, we have $W_k = 2W_{k-1}$, i.e., contention window size doubles after each collision. The three components in the above summation (i.e., $\Pr\{D < L | i \text{ collisions}, j \text{ slots}\}$, $p\{j \text{ slots} | i \text{ collisions}\}$ and $p\{i \text{ collisions}\}$) are obtained in [10]. Specifically, to calculate $p\{j \text{ slots} | i \text{ collisions}\}$, we note that with i collisions, the number slot times is sum of $i + 1$ uniformly distributed random variables, i.e. $\sum_{k=0}^i \text{Unif}(0, W_k - 1)$, (see Fig. 4). Consequently,

$$p(j \text{ slots} | i \text{ collisions}) = \Pr\left(\sum_{k=0}^i \text{Unif}(0, W_k - 1) = j\right) \tag{12}$$

The pmf of sum of $i + 1$ uniform random variables can be found from the convolution of individual pmfs. Using the pmf of sum, the above probability can be found in closed-form. Also, we have

$$p(i \text{ collisions}) = P_c^i (1 - P_c) \tag{13}$$

⁶ Note it is generally not true that $p_s = 1 - p_c$.

The last component, i.e., $\Pr\{D < L | i \text{ collisions}, j \text{ slots}\}$ is also found in [10]. Recall assumption 2, the distribution of backoff delay given i collisions and j slots follows a Gaussian distribution. Denoting the mean and variance of the Gaussian random variable as m_{ij} and σ_{ij} , we have

$$\Pr\{D < L | i \text{ collisions}, j \text{ slots}\} = \begin{cases} 0.5 + 0.5\text{erf}\left(\frac{L - m_{ij}}{\sqrt{2}\sigma_{ij}}\right) & \frac{L - m_{ij}}{\sqrt{2}\sigma_{ij}} \geq 0 \\ 0.5\text{erfc}\left(-\frac{L - m_{ij}}{\sqrt{2}\sigma_{ij}}\right) & \frac{L - m_{ij}}{\sqrt{2}\sigma_{ij}} < 0 \end{cases} \quad (14)$$

where

$$m_{ij} = jE[T_d] + iT_c + T_s$$

$$\sigma_{ij}^2 = j\text{Var}[T_d]$$

The mean and variance of T_d can be obtained from pmf given in (9), which practically depends on duration of interframe spacing (SIFS, DIFS and EIFS), packet size, ACK size, MAC overhead, physical layer convergence protocol (PLCP) preamble and header transmission time, and duration of an empty slot time, among other DCF parameters as formulated in (4)–(7). Particularly, for smaller the packet size, mean and variance of the Gaussian random variable will be smaller.

Substituting (12), (13) and (13) in (11), we can find the cumulative distribution function (cdf) of backoff delay (i.e., $\Pr\{D < L\}$). The statistical mean of backoff delay can be found from its cdf as follows [11]:

$$E[D] = \int_0^\infty (1 - \Pr\{D < L\})dL \quad (15)$$

Statistical mean of backoff delay can be obtained numerically from (15) after finding the cdf of D from (10). In next

section, we use the DCF parameters used in 802.11n to calculate the probability of backoff delay.

5 Performance Evaluation

In this section, we present numerical results based on the analysis performed in Sect. 4 to evaluate the coexistence challenges between LTE-U and Wi-Fi networks.

In Fig. 6, assuming a fixed Wi-Fi packet size of 1500 bytes, the probability of Wi-Fi channel access is shown versus the LTE quiet period. As we discussed in Sect. 4, the maximum quiet period that can be created by muting UL subframes in the TD-LTE mode is 3 ms. Figure 7 shows that, even when the number of Wi-Fi stations is as low as $N = 2$ (i.e., very light contention) and the LTE-U quiet period is as high as 3 ms, the probability that backoff delay is smaller than LTE-U quiet period is very small (about 0.16). This probability is even smaller when the number of Wi-Fi users increases. In other words, the probability that a Wi-Fi station can have the chance to access the medium in the presence of a LTE-U network is very small (about 16 % in the best case).

In Fig. 7, assuming four Wi-Fi users (i.e., $N = 4$), the same probabilities are found three different packet sizes of 500 bytes, 1000 and 1500 bytes. As described in Sect. 4, for smaller packet size, the conditional probabilities found in (14) will be larger and as a result, the probability of Wi-Fi channel access will also increase.

Figure 8 shows the statistical average of backoff delay versus the number of Wi-Fi stations. Mean backoff delay is obtained using equation (15) in Sect. 5. The results indicate that even when the number of Wi-Fi users is as low as two and with the Wi-Fi packet size is as small as 500 bytes, mean backoff delay (about 4 ms) is larger than the

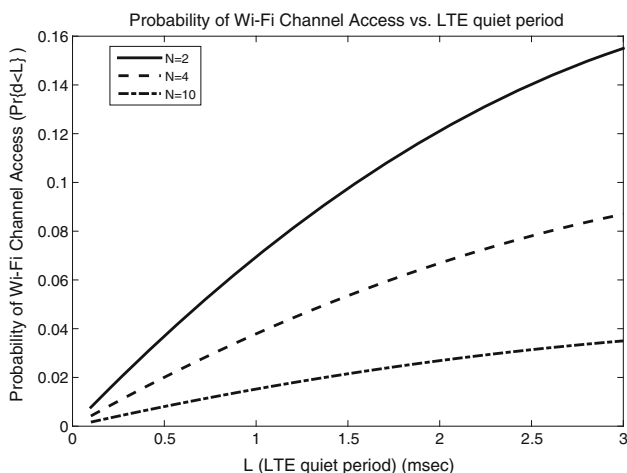


Fig. 6 Probability of Wi-Fi channel access versus LTE quiet period (packet size = 1500 Bytes)

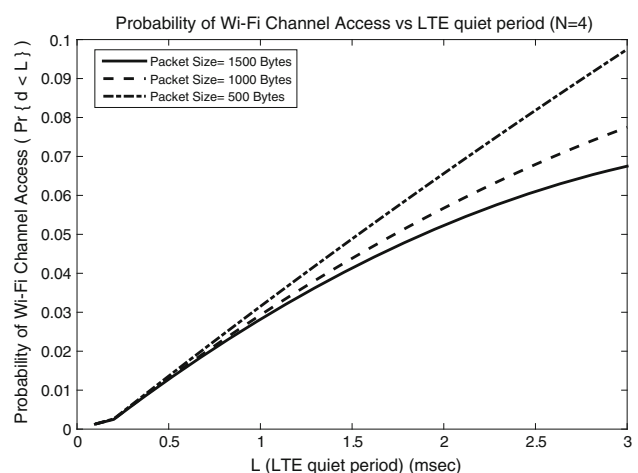


Fig. 7 Probability of Wi-Fi channel access versus LTE quiet period ($N = 4$)

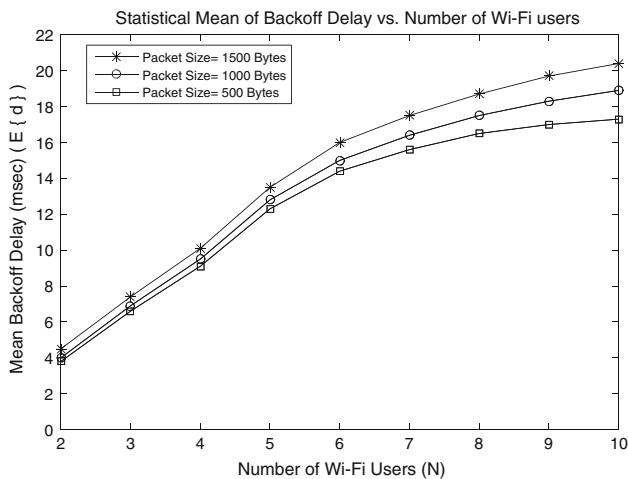


Fig. 8 Statistical Mean of Backoff Delay versus N

maximum LTE quiet period (3 ms). Increasing the packet size or number of Wi-Fi stations increases the mean backoff delay as expected.

6 Conclusions

Our probabilistic and numerical analyses show that when Wi-Fi and LTE networks operate together in the unlicensed band without modifications to existing protocols, Wi-Fi transmissions are significantly affected by the presence of LTE transmissions. Specifically, given the two potential modes of operations currently proposed for LTE-U in the unlicensed spectrum, the amount of “quiet” period presented by the LTE protocol for Wi-Fi users is too short to allow access to the channel. As a result, Wi-Fi is at risk of spending a significant amount of time in the “listening” mode when LTE transmission is present in the same channel.

Our results indicate that much work needs to be done to achieve a “fair” coexistence mechanism. LTE MAC layer will need to be redesigned if Wi-Fi is to be afforded a useful portion of the unlicensed spectrum. But how best to design coexistence into LTE-U without substantially degrading the data throughput efficiency of LTE-U remains an open question.

Ideally, coexistence requirements and solutions should provide a level playing field for each network and technology. Airtime fairness and data throughput efficiency are both important considerations, although it may be difficult to achieve both in the case of coexistence of LTE and Wi-Fi. On the one hand, one could argue that coexistence mechanisms should ideally provide each network an equal opportunity for airtime fairness. Specifically, each network needs to be able to utilize equivalent portions of spectrum

over time as traffic conditions meet or exceed the data throughput capacity of the air interface. This does not necessarily provide each device in the network the same average data rate, which is dependent upon a number of factors. Airtime fairness shares equivalent megahertz portions of spectrum equally among participants.

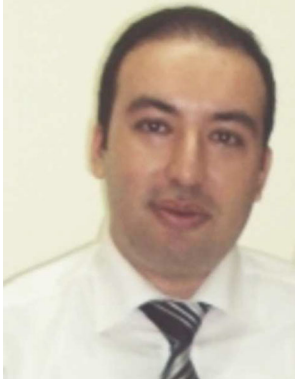
Regulatory requirements are designed to provide a certain level of airtime fairness, with arguable results towards fairness at the data throughput efficiency level. The U.S. and China do not mandate specific coexistence requirements for 5 GHz unlicensed spectrum. Europe, however, does mandate the coexistence requirements as summarized in [12].

On the other hand, coexistence mechanisms should also strive for data rate efficiency. But a range of coexistence techniques to help ensure airtime fairness may present costs to data rate efficiency. A significant portion of the LTE efficiency is due to the centralized and continuously scheduled nature of its air interface. If LTE-U were to be subject to the inefficiencies of the Wi-Fi’s “listen before talk” procedures, it would lose some of the benefit of LTE’s scheduled air interface.

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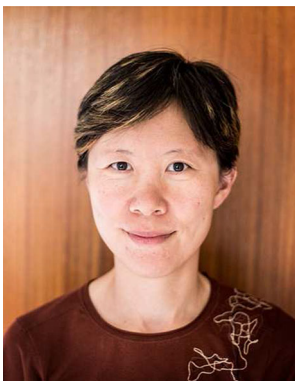
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