Coexistence of WiFi and LTE in Unlicensed Bands: A Proportional Fair Allocation Scheme

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***Abstract*—The use of the unlicensed spectrum by LTE networks (LTE-U or LAA-LTE) is being considered by mobile operators in order to satisfy increasing traffic demands and to make better use of the licensed spectrum. However, coexistence issues arise when LTE-U coverage overlaps with other technologies currently operating in unlicensed bands, in particular WiFi. Since LTE uses a TDMA/OFDMA scheduled approach, coexisting WiFi networks may face starvation if the channel is fully occupied by LTE-U transmissions. In this paper we derive a novel proportional fair allocation scheme that ensures fair coexistence between LTE-U and WiFi. Importantly, we find that the proportional fair allocation is qualitatively different from previously considered WiFi-only settings and that since the resulting allocation requires only quite limited knowledge of network parameters it is potentially easy to implement in practice, without the need for message-passing between heterogeneous networks.**

***Index Terms*—LTE Unlicensed, LTE-U, LAA-LTE, WiFi, coexistence, proportional fairness.**

I. INTRODUCTION

The possibility of using the unlicensed spectrum by mobile operators, known as LTE Unlicensed (LTE-U) when used for standalone operation or Licensed-Assisted Access (LAA-LTE) when used for carrier aggregation, has recently been attracting considerable attention as it may complement traditional licensed-band access in order to assist with satisfying increasing mobile traffic demands. Although a specification of LTE-U/LAA-LTE has not yet been released, the 3rd Generation Partnership Project (3GPP) is already studying its viability.

One of the major observations of the ongoing 3GPP discussion is the requirement to provide fair coexistence with other technologies working in the unlicensed spectrum [1]. Given that current technologies in the unlicensed bands, such as WiFi [2] and those based on the IEEE 802.15.4 standard [3], rely on contention-based access, starvation may occur when they co-exist with a schedule-based technology such as LTE. For instance, a WiFi station only accesses the channel when it is deemed idle for a certain amount of time (guard time plus backoff) and decreases its probability of accessing the channel after a collision occurs [2]. Mechanisms such as *Listen Before Talk*, which defines carrier sensing by the LTE-U base station [4], and duty cycle approaches based on the LTE-U network periodically releasing the channel [5], have already been outlined as possible approaches for providing smooth coexistence among LTE-U and contention-based networks. However, detailed specification and analysis is still lacking.

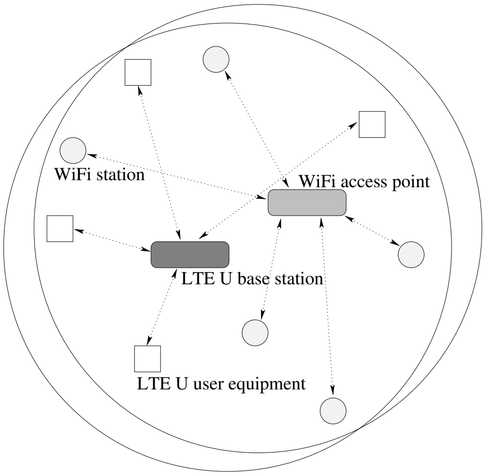


Fig. 1. Schematic illustrating co-existing WiFi and LTE-U unlicensed-band networks.

In this paper we consider the co-existence scenario illustrated schematically in Fig. 1, which consists of a WiFi network overlapping with an LTE-U deployment. In view of the almost ubiquitous deployment of WiFi, co-existence of LTE-U with WiFi is evidently of considerable interest and importance. We propose and evaluate a duty-cycle mechanism for LTE-U, which, by selecting an appropriate probability to access the channel and transmission duration, ensures proportional fairness among LTE-U and WiFi nodes. To the best of our knowledge, this is the first soundly-based derivation of a proportional fair co-existence scheme that takes account of the actual behaviour of the WiFi network (namely, taking account of collisions and idle slots). Our proposed solution dynamically adapts the probability that the LTE-U network accesses the channel and does not require communication among different network technologies, which cannot always be ensured when devices belong to different operators. The only requirement in our approach is channel monitoring by the LTE-U base station in order to infer the WiFi network status. Furthermore, our approach does not require changes to the existing WiFi network.

The remainder of this article is organised as follows. In Section II, we provide related work on LTE-U and WiFi coexistence. Then, in Section III we describe the problem setup along with our assumptions and considerations. The proposed proportional fair allocation mechanism is detailed in Section IV. We discuss practical implementation issues in Section V and show the results for some examples in Section VI. We conclude with some final remarks and future work.

II. RELATED WORK

To date there has been only very limited research on the coexistence of LTE and WiFi in unlicensed bands. There has been some work from a physical layer point of view that evaluates the interference among the two technologies, see for instance [6]. At the MAC layer, [7], [8], [9] study the impact of the coexistence of contention and scheduled-based channel accesses on the performance of LTE-U and WiFi networks and propose LTE-U duty cycling to release resources to the WiFi network. A practical way to implement duty cycling in LTE is via the almost blank subframes defined in LTE-A [8], [9], [10]. Building on this work, [11], [12], [13] define a probability for the LTE-U network to access the channel. In [11] and [13], the performance is studied from an experimental point of view, therefore no optimal channel allocation is provided. An attempt to provide fair allocation in an LTE-U and WiFi scenario is made in [12] and [14]. However, the WiFi models used lack collisions and idle periods. The problem is also analysed in [15] from a traffic-balancing point of view but the effects of collisions and idle periods in the unlicensed interface are also neglected. Our work can be seen as an extension of previous literature where the probability that the LTE-U network accesses the channel satisfies proportional fair channel allocation and considers the detailed contention behaviour of WiFi stations.

III. PROBLEM SETUP

A. Throughput Model

Consider an IEEE 802.11 WiFi network with n stations that shares a channel with an LTE-U network serving N user equipment devices (UEs). Let T denote the duration of a transmission by a WiFi station. To streamline notation we assume that both successful WiFi transmissions and collisions between multiple WiFi transmitters are of the same duration. This assumption can be relaxed using, for example, the approach in [16]. The LTE-U network transmits in bursts of duration $T^{\text{lte}} \gg T$, assigning fraction t_j of this time to UE j where $t_j \geq 0$ and $\sum_{j=1}^{N} t_j \leq 1$. The WiFi and LTE-U networks both use carrier sense to partition time into MAC slots. Each MAC slot is then either (i) an idle slot of duration σ (no station transmits), (ii) a WiFi busy slot of duration T (one or more WiFi stations transmit and all LTE-U devices are silent), (iii) an LTE-U busy slot of duration T^{lte} (the LTE-U network and possibly one or more WiFi stations transmit).

Let τ_i denote the probability WiFi station i transmits in a MAC slot and q the probability that the LTE-U network transmits, where we assume that transmissions are i.i.d. The probability of a slot being empty is then $(1-q)p_{\text{e}}$ where $p_{\text{e}} = \prod_{i=1}^{n}(1-\tau_i)$ is the probability that the WiFi network is silent. The probability that WiFi station i transmits successfully in a slot is $(1-q)p_{\text{succ},i}$ where $p_{\text{succ},i} = \tau_i \prod_{k=1,k\neq i}^{n}(1-\tau_k)$. Transmissions form a renewal process and the throughput of WiFi station i is given by

$$s_i^{\text{wifi}} = (1-q)p_{\text{succ},i}\frac{D_i}{\bar{T}}, \tag{1}$$

where $\bar{T} = (1-q)T^{\text{wifi}} + qT^{\text{lte}}$ is the mean duration in seconds of a MAC slot with $T^{\text{wifi}} = \sigma p_{\text{e}} + T(1-p_{\text{e}})$ and D_i denoting the number of payload bits delivered by station i in a successful transmission. Similarly, the throughput of LTE-U UE j is given by

$$s_j^{\text{lte}} = q\frac{t_j T^{\text{lte}} r_j}{\bar{T}}, \tag{2}$$

where r_j is the physical rate in bits/sec of transmissions to UE j (thus $t_j T^{\text{lte}} r_j$ is the number of payload bits delivered to UE j in an LTE-U transmission burst). We have neglected the impact of colliding WiFi transmissions (these may occur at the start of an LTE-U burst but will be of duration $T \ll T^{\text{lte}}$ and so have only a small impact on LTE-U throughput).

We note that the fraction of total airtime used for successful transmissions and collisions by a WiFi station i (which, following [17], we refer to as the total airtime) is $(1-q)\tau_i T/\bar{T}$, while the fraction used for successful transmissions by WiFi station i is $(1-q)p_{\text{succ},i}T/\bar{T}$. The fraction of airtime used by the WiFi network (including contention time, collisions and successful transmissions) is

$$\mathcal{T}^{\text{wifi}} = (1-q)\frac{T^{\text{wifi}}}{\bar{T}} \tag{3}$$

and the fraction of airtime used by the LTE-U network is

$$\mathcal{T}^{\text{lte}} = q\frac{T^{\text{lte}}}{\bar{T}}. \tag{4}$$

Note that since that there are no collisions between transmission within the LTE-U network, the fraction of total airtime and the successful airtime of LTE-U UE j is simply: $\mathcal{T}^{\text{lte}} t_j$.

B. Scope

1) Multiple Channels/Channel Bonding: An LTE-U network may in general transmit on multiple WiFi channels. Similarly, future WiFi networks are expected to make use of channel bonding to transmit across multiple 20MHz channels. However, provided the WiFi networks occupy disjoint channels, we can solve the LTE-U rate allocation problem separately for each set of channels using the model in Section III-A. That is, although we focus on a single channel here, the generalisation to multiple channels is immediate. The situation is more complex when multiple LTE-U networks co-exist on the same channel, and we consider this further in Section VII.

2) Lossy Channel: Extension of our model to include channel losses is straightforward. Namely, by reducing the WiFi success probability with a packet loss probability and similarly the LTE-U success probability.

3) Unsaturated Stations: Our model assumes that the WiFi and LTE-U stations are saturated, *i.e.* there is always a packet buffered for transmission. Extension to unsaturated stations can be achieved by adding offered load constraints to the utility-fair optimisation in Section IV.

4) LTE-U Overheads: Similarly to [11] and in line with current 3GPP discussions, we assume that LTE-U control messages are sent via the licensed band. Extension of our analysis to include use of the unlicensed band for the control plane messaging primarily involves suitable adjustment of the transmission overhead in our LTE-U throughput calculations.

5) Capture: Our model assumes that concurrent transmissions result in a collision and the inability of the receiver (either LTE-U or WiFi) to decode the message. The main difficulty with including capture effects in our analysis (where some receivers may successfully decode a colliding transmission) lies in specifying a suitable physical layer model and so we leave this for future work.

6) Hidden Terminals: Perhaps the most significant omission from our analysis is hidden terminals. The basic difficulty here arises from the fact that hidden terminals can start transmitting even when a transmission by another station has already been in progress for some time. The class of slotted-time models pioneered by Bianchi for 802.11 is therefore no longer valid, since these require all transmissions to occur on well-defined MAC slot boundaries, and indeed a fundamental change in modelling paradigm is required. We therefore leave consideration of WiFi/LTE-U allocation with hidden terminals to future work. It is perhaps also worth noting here that the prevalence of severe hidden terminals in real network deployments presently remains unclear. While it is relatively easy to construct hidden terminal configurations in the lab that exhibit gross unfairness, it may be that such configurations are less common in practice.

IV. PROPORTIONAL FAIR WIFI/LTE-U ALLOCATION

The proportional fair rate allocation in the mixed WiFi/LTE-U network is given by the solution to the following utility-fair optimisation problem P:

$$\max_{\substack{s_i^{\mathrm{wifi}},s_j^{\mathrm{lte}},\\ q,T^{\mathrm{lte}},t_j}} \sum_{i=1}^{n}\log s_i^{\mathrm{wifi}} + \sum_{j=1}^{N}\log s_j^{\mathrm{lte}} \tag{5}$$

$$\begin{aligned} s.t.\quad & s_i^{\mathrm{wifi}} \le (1-q)p_{\mathrm{succ},i}\frac{D_i}{\bar T},\ s_j^{\mathrm{lte}} \le q\frac{t_j T^{\mathrm{lte}} r_j}{\bar T} \\ & t_j \ge 0,\ \sum_{j=1}^{N} t_j \le 1,\ 0 \le q \le 1 \\ & T^{\mathrm{wifi}} \le T^{\mathrm{lte}} \le T^{\mathrm{wifi}} + \Delta^{\max},\ \bar T = (1-q)T^{\mathrm{wifi}} + qT^{\mathrm{lte}}. \end{aligned}$$

The first and second constraints ensure the the WiFi and LTE-U throughputs are feasible, the third and fourth that the LTE-U UE schedule is feasible, the fifth constraint that q is a probability and the sixth that T^{lte} is valid. Observe that we constrain $T^{\mathrm{lte}} \le T^{\mathrm{wifi}} + \Delta^{\max}$. Upper limit $\Delta^{\max}$ is needed as otherwise the optimum solution is to let $T^{\mathrm{lte}} \to \infty$, $q \to 0$ so as to minimise WiFi/LTE-U collisions.

Optimisation problem P is not convex. Fortunately, however, it can be reformulated via the change of variables $\tilde s_i^{\mathrm{wifi}} = \log s_i^{\mathrm{wifi}}$, $\tilde s_j^{\mathrm{lte}} = \log s_j^{\mathrm{lte}}$, $\tilde q = \log q$, $\tilde{t_j} = \log t_j$, $\tilde\Delta = \log\Delta$ and $T^{\mathrm{lte}} = T^{\mathrm{wifi}} + \Delta$ as optimisation problem $\tilde P$:

$$\min_{\substack{\tilde s_i^{\mathrm{wifi}},\tilde s_j^{\mathrm{lte}},\\ \tilde q,\tilde\Delta,\tilde{t_j}}} -\sum_{i=1}^{n}\tilde s_i^{\mathrm{wifi}} - \sum_{j=1}^{N}\tilde s_j^{\mathrm{lte}}, \tag{6}$$

$$\begin{aligned} s.t.\quad & \tilde s_i^{\mathrm{wifi}} - \log(1-e^{\tilde q}) - \log(p_{\mathrm{succ},i}D_i) + \log\bar T \le 0, \\ & \tilde s_j^{\mathrm{lte}} - \tilde q - \log r_j - \tilde{t_j} - \tilde\Delta + \log\bar T \le 0, \\ & \sum_{j=1}^{N} e^{\tilde{t_j}} - 1 \le 0,\ \tilde q \le 0 \\ & \tilde\Delta - \log\Delta^{\max} \le 0,\ \bar T = T^{\mathrm{wifi}} + e^{\tilde q + \tilde\Delta}, \end{aligned}$$

where we have also made use of the assumption that $\Delta \gg T^{\mathrm{wifi}}$. It can be verified that the function $-\log(1-e^{\tilde q})$ has second derivative $e^{\tilde q}/(1-e^{\tilde q})^2 \ge 0$ and so is convex. The transformed optimisation problem $\tilde P$ therefore has convex objective function and constraints. By solving this optimisation problem we can state our main result.

Theorem 1 (Proportional Fair WiFi/LTE-U)**.** *The solution to the optimisation problem $\tilde P$ satisfies*

$$(1-q^*)\frac{T^{\mathrm{wifi}}}{n} = q^*\frac{T^{\mathrm{lte}*}}{N} \tag{7}$$

$$T^{\mathrm{lte}*} = T^{\mathrm{wifi}} + \Delta^{\max},\ t_j^* = \frac{1}{N},\ j = 1,\cdots,N. \tag{8}$$

That is, LTE-U UEs are allocated an equal $t_j^* = 1/N$ fraction of the LTE-U network transmission burst time $T^{\mathrm{lte}*}$, the LTE-U network transmission burst time $T^{\mathrm{lte}*}$ is selected to be the largest permitted and the probability q^* of an LTE-U network transmission is selected so as to balance the WiFi and LTE-U airtimes such that

$$\frac{T^{\mathrm{wifi}}}{n} = \frac{T^{\mathrm{lte}}}{N}. \tag{9}$$

Proof: Optimisation problem $\tilde P$ is convex and has a Slater point, hence strong duality holds. The Lagrangian is

$$\begin{aligned} L(\mathbf{u},\mathbf{z}) = & -\sum_{i=1}^{n}\tilde s_i^{\mathrm{wifi}} - \sum_{j=1}^{N}\tilde s_j^{\mathrm{lte}} \\ & + \sum_{i=1}^{n}\lambda_i(\tilde s_i^{\mathrm{wifi}} - \log(1-e^{\tilde q}) - \log(p_{\mathrm{succ},i}D_i) + \log\bar T) \\ & + \sum_{j=1}^{N}\mu_j(\tilde s_j^{\mathrm{lte}} - \tilde q - \tilde\Delta - \log r_j - \tilde{t_j} + \log\bar T) \\ & + \alpha\left(\sum_{j=1}^{N} e^{\tilde{t_j}} - 1\right) + \beta\tilde q + \upsilon(\tilde\Delta - \log\Delta^{\max}), \end{aligned} \tag{10}$$

with $\mathbf{u}$ the vector of primal variables $\tilde s_i^{\mathrm{wifi}}, \tilde s_j^{\mathrm{lte}}, \tilde q, \tilde\Delta, \tilde{t_j}$, $i = 1,\cdots,n$, $j = 1,\cdots,N$ and $\mathbf{z}$ the vector of multipliers $\lambda,\mu,\alpha,\beta,\upsilon$. At an optimum the main KKT conditions solve

$$\begin{aligned} & \lambda_i^* = 1,\ i = 1,...,n \quad \mu_j^* = 1,\ e^{\tilde{t_j}^*} = \frac{1}{\alpha^*},\ j = 1,...,N \\ & N(\gamma-1) + n\left(\frac{e^{\tilde q^*}}{1-e^{\tilde q^*}} + \gamma\right) + \beta^* = 0, \\ & N(\gamma-1) + n\gamma + \upsilon^* = 0, \end{aligned}$$

where $\gamma = e^{\tilde{q}^*+\tilde{\Delta}^*}/(T^{\text{wifi}} + e^{\tilde{q}^*+\tilde{\Delta}^*})$. At an optimum we must have $\tilde{\Delta} = \log \Delta^{\max}$, else we could increase $\tilde{\Delta}$ while adjusting $\tilde{q}$ to hold $\tilde{q} + \tilde{\Delta}$ constant and improve the objective. By complementary slackness, at an optimum either $\beta^* = 0$ or $\tilde{q}^* = 0$. But when there are WiFi stations then we cannot have $\tilde{q}^* = 0$ as then $\tilde{s}^{\text{wifi}} = -\infty$ and we can improve the objective by increasing $\tilde{q}^*$. Hence, we must have $\beta^* = 0$. It then follows from the KKT conditions that

$$q^* = \frac{N T^{\text{wifi}}}{T^{\text{wifi}}(N+n) + n\Delta^{\max}}. \tag{11}$$

Rewriting Eq. 11, it can be verified that the optimal value of q satisfies:

$$(1-q^*)\frac{T^{\text{wifi}}}{n} = q^*\frac{T^{\text{wifi}} + \Delta^{\max}}{N} = q^*\frac{T^{\text{lte}}}{N}. \tag{12}$$

Furthermore, by the KKT conditions and complementary slackness we have that $\alpha^*\left(\sum_{j=1}^{N} e^{\tilde{t_j}^*} - 1\right) = \alpha^*\left(\sum_{j=1}^{N} \frac{1}{\alpha^*} - 1\right) = 0$. It follows that $\alpha^* = N$ and so $t_j^* = 1/N$, $j = 1, ..., N$. ■

It is important to note that the WiFi airtime $\mathcal{T}^{\text{wifi}}$ here differs significantly from that previously derived for proportional fairness in a WiFi-only setting, see [17]. The airtime $\mathcal{T}^{\text{wifi}}$ is the network airtime, including idle, collision and success transmission slots. This is then scaled in proportion to the number n of WiFi stations to obtain an effective per-station airtime $\frac{\mathcal{T}^{\text{wifi}}}{n}$. In contrast, in [17] the airtime that is equalised by a WiFi proportional fair rate allocation is the airtime used by each station for collisions and successful transmissions (thus double counting collisions and ignoring idle slots). Observe that by equalising the airtime $\frac{\mathcal{T}^{\text{wifi}}}{n}$ with the LTE-U station airtime $\frac{\mathcal{T}^{\text{lte}}}{N}$, the inefficiency in the WiFi network caused by random access procedures (idle slots, collisions) does not cause a penalty on the LTE-U network performance.

V. PRACTICAL IMPLEMENTATION

For the LTE-U base station to compute the optimal probability q^*, the parameters n, N, T^{wifi} and $\Delta^{\max}$ must be known. Note that no other network details are required, and this is perhaps one of the most interesting aspects of Theorem 1 since it means that the proportional fair allocation can be determined without the need for message-passing between the heterogeneous networks. The number N of LTE-U users is already available to the base station and $\Delta^{\max}$ is a configurable parameter. Additionally, the average duration of a WiFi slot (T^{wifi}) can be easily inferred by channel sensing. Thus, the main challenge is how to estimate the number n of active WiFi interfering nodes.

When cooperation among technologies is possible (for instance, when the overlapping networks are provided by a base-station with LTE-U and WiFi interfaces), determining n is trivial. However, the situation is less straightforward when the networks belong to different operators and/or are not located in the same physical device. The two main cases are: *i)* the networks have overlapping coverage ranges (the networks can be viewed as a clique) and *ii)* when not all network nodes can overhear each other (non-clique case).

a) Clique Networks: In this case, when the WiFi stations are saturated then the number of nodes can be easily inferred by the LTE-U base station by monitoring transmissions on the channel. When the WiFi stations are unsaturated, estimation of n is more challenging and as already noted this is left as future work.

b) Non-clique Networks: In situations in which not all nodes are in each others coverage range, for the LTE-U network to determine the number of interfering WiFi nodes requires that the LTE-U UEs monitor the channel and report their measurements to the LTE-U base station since the conditions observed by each UE may be different. Once collected, the LTE-U base station can use this information to infer n and so compute the optimal probability to access the channel for the network.

VI. EXAMPLES

We illustrate the proportional fair WiFi/LTE-U allocation scheme in an example network. As in [11], for simplicity we suppose that all stations (both WiFi and LTE-U) use the same physical layer and, in particular, a 64-QAM modulation and a 5/6 coding scheme which provides a 135 Mbps data rate when using a 40 MHz channel at the 5 GHz ISM band as defined in IEEE 802.11ac [18]. This allows us to easily compare the throughputs of the two networks and seems reasonable since the LTE-U PHY specifications are not yet defined.

The MAC parameters used in the WiFi network are detailed in Table I. The duration of a WiFi frame transmission is:

$$T = \text{DIFS} + T_{\text{fra}} + \text{SIFS} + T_{\text{ack}}, \tag{13}$$

where T_{fra} and T_{ack} are the transmission durations of the frame payload and the block acknowledgement [18]. The duration of a frame transmission, taking into account that up to 64 packets can be aggregated, is computed as follows [18]:

$$T_{\text{fra}} = T_{\text{plcp}} + \left\lceil \frac{L_{\text{s}} + 64(L_{\text{del}} + L_{\text{mac-h}} + D) + L_{\text{t}}}{n_{\text{sym}}} \right\rceil T_{\text{sym}}, \tag{14}$$

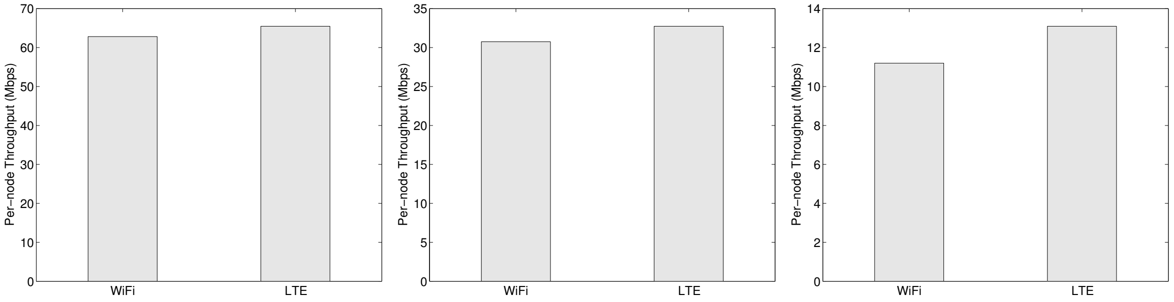
where n_{sym} is the number of bits per OFDM symbol (equal to 540 for the settings considered) and T_{sym} is the symbol duration, which is equal to 4 μs [18]. The duration of the block acknowledgement is:

$$T_{\text{ack}} = T_{\text{plcp}} + \left\lceil \frac{L_{\text{s}} + L_{\text{ack}} + L_{\text{t}}}{n_{\text{sym}}} \right\rceil T_{\text{sym}}. \tag{15}$$

For illustrative purposes we consider the transmission probability of a WiFi station to be fixed and equal to $\tau = 1/16$.

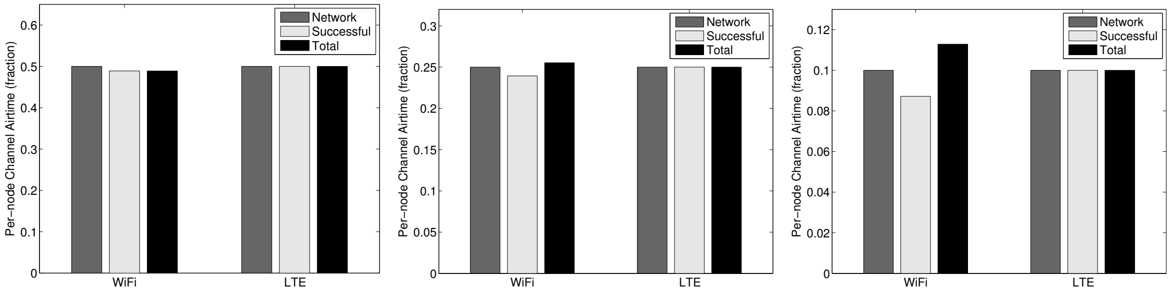
For the LTE-U network we consider a 135 Mbps data rate and apply a correction factor of 0.97 to account for protocol overheads, as recommended for LTE Frequency Division Duplexing (FDD) analysis of downlink streams in [19].

Consider the cases where $n = N = 1, 2$ and 5, respectively, and $\Delta^{\max} = 10T^{\text{wifi}}$. For these settings, the value of the optimal probability of the LTE-U accessing the channel is $q = 0.0833$. Fig. 2 shows the per-node throughput obtained



(a) $n = N = 1$ (b) $n = N = 2$ (c) $n = N = 5$

Fig. 2. Proportional fair per-node throughput for $n = N$ and $\Delta^{\max} = 10T^{\text{wifi}}$.



(a) $n = N = 1$ (b) $n = N = 2$ (c) $n = N = 5$

Fig. 3. Fraction of channel airtime per-node for $n = N$ and $\Delta^{\max} = 10T^{\text{wifi}}$. *Network* denotes the per-node fraction used by the network including contention time, collisions and successful transmissions ($\mathcal{T}^{\text{wifi}}/n$ and $\mathcal{T}^{\text{lte}}/N$), *Successful* denotes the fraction used for successful transmissions and *Total* denotes the fraction used for successful transmissions and collisions as defined in Section III-A ($(1-q)\tau_i T/\bar{T}$ for WiFi).

TABLE I
PARAMETERS IEEE 802.11AC [18]

Slot Duration (σ)	9 μs
DIFS	34 μs
SIFS	16 μs
PLCP Preamble+Headers Duration (T_{plcp})	40 μs
PLCP Service Field (L_{s})	16 bits
MPDU Delimiter Field (L_{del})	32 bits
MAC Header ($L_{\text{mac-h}}$)	288 bits
Tail Bits (L_{t})	6 bits
ACK Length (L_{ack})	256 bits
Payload (D)	12000 bits

for the different configurations. The inefficiency of the WiFi network due to overhead, idle periods (Fig. 2(a)) and collisions (Fig. 2(b) and 2(c)) compared to the schedule-based LTE-U network can be noted.

Fig. 3 shows the different channel airtimes defined in Section III-A. First, note that the network channel airtimes per-node ($\mathcal{T}^{\text{wifi}}/n$ and $\mathcal{T}^{\text{lte}}/N$) are equalised among each WiFi station and LTE-U UE as a result of the proportional fair rate allocation. Observe also that, since there are no collisions in the LTE-U network, the per UE network channel airtime is equal to the UE successful and total channel airtimes.

In Fig. 3(a) we can see how the successful and total channel airtimes at a WiFi station are smaller than the network airtime. In this particular case there are no collisions in the WiFi network (since $n = 1$). Thus, the total channel airtime ($(1-q)\tau_i T/\bar{T}$) and the airtime used for successful transmissions are equal and the difference between the total channel airtime of a WiFi station and an LTE-U UE is due to the idle slots left empty while the WiFi station is performing backoff. In Fig. 3(b) and 3(c), there are 2 and 5 WiFi nodes, respectively, contending for the channel and thus, collisions take place. The inefficiency of the WiFi network means that part of the WiFi network airtime is now spent in unsuccessful transmissions and idle periods.

Finally, note in Fig. 3(b) and 3(c), that the total airtime ($(1-q)\tau_i T/\bar{T}$) of a WiFi station is higher than the per station network airtime $\mathcal{T}^{\text{wifi}}/n$. The reason for this is the airtime spent on collisions. Since collisions involve more than one station, this collision airtime is double-counted by the per-station total airtime. Recall that for the WiFi/LTE proportional fair allocation it is the network airtime rather than the total airtime that is equalised, in contrast to the WiFi-only proportional fair allocation (see [17]).

Fig. 4 shows proportional fair WiFi/LTE-U collision probability $p = q(1-p_{\text{e}})$ vs the LTU burst duration $\Delta^{\max}$ and n while N is held equal to 10. It can be seen that p decreases with increasing $\Delta^{\max}$. This is because LTE-U transmission probability q is reduced as $\Delta^{\max}$ is increased, so as to hold the airtime used by the LTE-U network constant. Although increasing $\Delta^{\max}$ reduces the collision rate between the two technologies, the WiFi per-packet delay will also increase with $\Delta^{\max}$ as the WiFi network defers transmissions for time

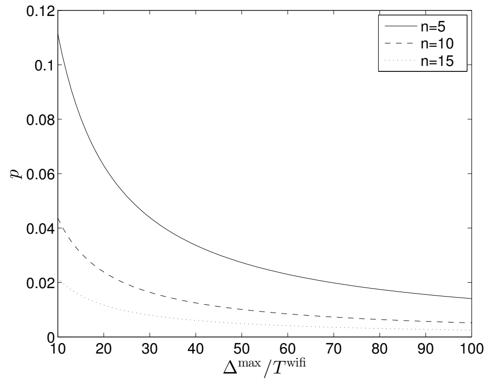


Fig. 4. Impact of $\Delta^{\max}$ on WiFi/LTE-U collision probability.

$\Delta^{\max}$. Design parameter $\Delta^{\max}$ should therefore be selected to ensure a suitable trade-off between delay and throughput.

VII. CONCLUDING REMARKS

We derive a proportional fair allocation scheme for coexistence of WiFi and LTE networks working in unlicensed bands. We show that proportional fairness is achieved by assigning equal channel times to every competing entity including idle periods, successful transmissions and collisions for the WiFi network. The airtime quantities concerned differ from those in WiFi-only proportional fair allocations. Our analysis implies that the inefficiency of WiFi due to random access does not impact the performance of the LTE-U network. We present some examples illustrating the resulting throughput and channel airtimes of WiFi stations and LTE-U UEs.

A key advantage of our proposed approach is that it can be implemented without explicit coordination among the different networks, which is an important aspect when the networks belong to different operators and/or are not located in the same physical device. For the LTE-U network to compute the optimal probability to access the channel, the parameter values that must be known can be obtained by channel monitoring and inferring the status of the WiFi network accordingly. It is also important to emphasise that in our proposal no changes are required in the WiFi network.

Future research directions include the extension to unsaturated stations and the coexistence of multiple LTE-U networks. With regard to the latter, a challenging issue is to define a collision-free slot assignment for LTE-U when multiple LTE-U networks from different operators coexist in the same unlicensed band. Learning techniques for decentralised collision-free operation [20], [21], [22] may provide a simple, practical way to make the networks converge to a suitable slot allocation without explicit message passing or coordination. However, further analysis is required to evaluate the suitability of these techniques for unlicensed LTE.

VIII. ACKNOWLEDGMENTS

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