Using LTE in Unlicensed Bands: Potential Benefits and Coexistence Issues

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Using LTE in unlicensed bands will allow operators to access additional spectrum to meet the increasing demand for mobile services. The authors provide an overview of the different approaches currently being considered for LTE operation in unlicensed bands and their interaction with WiFi networks.

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ABSTRACT

Using LTE in unlicensed bands will allow operators to access additional spectrum to meet the increasing demand for mobile services. In this article, we provide an overview of the different approaches currently being considered for LTE operation in unlicensed bands and their interaction with WiFi networks. In summary, LTE-Unlicensed with carrier sense adaptive transmission is likely to be available in the short term, but cannot be used in all regions due to regulatory restrictions. License assisted access is intended for use more widely, so it will include listen-before-talk and other features required to conform with, for example, European and Japanese regulations. However, this will require changes to the LTE standards, so license assisted access is likely to take longer to deploy. In addition to describing the trade-offs between these approaches, we also discuss the issue of fair coexistence with existing unlicensed band users, especially WiFi devices.

INTRODUCTION

The use of unlicensed spectrum by mobile network operators, particularly in the 5 GHz band, has recently been attracting considerable attention, and vendors and operators are already actively studying its viability for Long Term Evolution (LTE)/fourth generation (4G) cellular networks. The use of the unlicensed spectrum for cellular operation represents a significant change in cellular network deployment and management, and there are, at this stage, still many open questions in terms of both business case and technology as a whole.

Two main approaches to unlicensed LTE are currently being investigated, referred to as LTE-Unlicensed (LTE-U) [1] and licensed assisted access (LAA) [2]. Both augment an existing LTE licensed band interface with unlicensed band transmissions, but LTE-U is a simplified scheme that targets early deployments. LTE-U aims to operate in accordance with the existing Release 10/11/12 LTE physical (PHY)/medium access control (MAC) standards, and thus does not use listen-before-talk (LBT). However, the absence of LBT restricts its use to regions, such as the United States, where this is not required by unlicensed band regulations. LAA is intended for use more widely, and hence will include LBT and other features (e.g., minimum bandwidth occupancy, transmit power spectral density) required to conform with, for instance, European and Japanese regulations. Although still under discussion, it seems likely that both of these unlicensed LTE approaches will be used only for transmissions by the base station (downlink transmissions) in first releases, and that most control signaling will be sent via the licensed interface. Extension of LAA to standalone operation (including uplink transmissions), without pairing to a licensed band, is also under consideration.

LTE-U and LAA are particularly attractive to operators that do not own WiFi infrastructure, and are likely to be deployed in very targeted areas using small cells. Initially, it will be an indoor solution in large enterprises and crowded commercial areas like shopping malls, sports arenas, and convention centers, where these operators urgently need more capacity. Once the technology matures, it is likely to expand to outdoor hotspots.

A major aspect of ongoing discussions is the requirement to provide fair coexistence with other technologies working in the unlicensed spectrum. Given that current technologies in unlicensed bands, such as WiFi, rely on contention-based access, there is a concern that starvation and other forms of unfairness may occur when they coexist with a schedule-based technology such as LTE. Currently, two main approaches are under consideration for allowing coexistence when WiFi and LTE nodes share the same channel [3, 4]: carrier sense adaptive transmission (CSAT), which is compatible with existing LTE equipment and thus suitable for use with LTE-U; and listen-before-talk (LBT), which requires modification of the current LTE standard and thus more suitable for use with LAA. In this article, we describe and evaluate both LTE-U/CSAT and LAA/LBT.

LTE SCHEDULING

We begin by giving an overview of the LTE fundamentals that impact its deployment in the unlicensed band as well as coexistence with WiFi and with other LTE operators.

LTE FRAMING

In an LTE wireless cell, time is partitioned into slots of 10 ms duration, referred to as frames (Fig. 1a). Each frame is, in turn, subdivided into 10 subframes of 1 ms duration. Each subframe consists of a set of time-frequency resources and all LTE transmissions within a cell, by both

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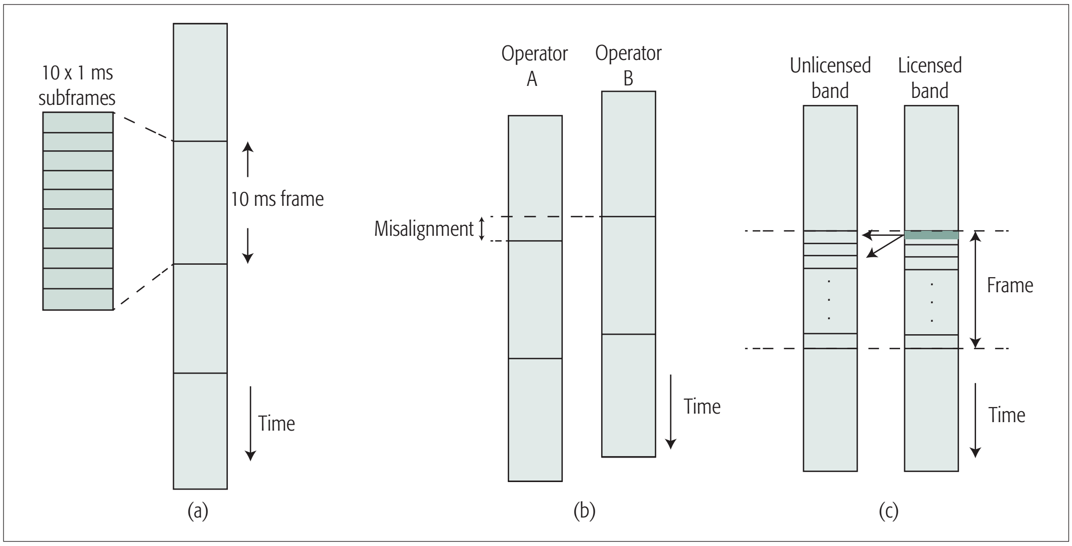

Figure 1. Illustrating use of frames and subframes for scheduling and carrier aggregation in LTE: a) frames and subframes; b) frame misalignment; c) carrier aggregation.

WiFi takes a decentralized approach to scheduling transmissions, unlike the centralized approach used by LTE. When a WiFi device wants to send a transmission, it senses the radio channel and performs a clear channel assessment check.

the base station and user equipments (UEs), are assigned to these resources by the LTE base station scheduler. Scheduling is therefore carried out in a centralized manner within the cell, and all UEs within it must be tightly synchronized in both time and frequency. To assist with managing interference, neighboring cells and their UEs are also required to maintain tight time synchronization (typically ±1 μs) so that, for example, a subframe left empty by one cell can be safely reused by another without interfering with adjacent subframes [5].

Since LTE was originally designed for operation in licensed bands, the implicit assumption is that the scheduler at the base station can allocate time-frequency resources without other restrictions. Further, since in the licensed setting different operators use different spectrum bands, there is no requirement for their frame boundaries to be aligned across networks. That is, transmissions by two different network operators may be misaligned, as illustrated in Fig. 1b.

Carrier Aggregation: Use of Unlicensed Spectrum in LTE

A base station is not confined to scheduling time-frequency resources within a single spectrum band but rather can simultaneously schedule resources in multiple bands, which may be disjoint, by means of carrier aggregation [5]. In particular, this can be used to opportunistically augment licensed band transmissions with bandwidth from unlicensed spectrum in the 5 GHz band (and, in due course, also from other unlicensed bands). Using the unlicensed bands for carrier aggregation requires that the licensed interface is always available and active in the base station.

Such carrier aggregation is illustrated in Fig. 1c. Using cross-scheduling, the control plane information specifying the assignment of transmissions to time-frequency resources and the choice of modulation and coding scheme in each subframe can be transmitted in the licensed band, while the user plane information can be simultaneously transmitted in the unlicensed band; for example, the shaded area in Fig. 1c indicates the control plane information in the licensed band, and the arrows indicate a scheduling grant in the unlicensed band. Although the control plane information could also be transmitted in the unlicensed band, the great advantage of using the licensed band for transmitting this information is that it avoids the potential corruption by interference on the unlicensed band (e.g., by WiFi transmissions). However, relying on the licensed band for transmission of control plane information requires two active receiving chains at the UE side and the alignment between the frames in the licensed and unlicensed bands, as shown in Fig. 1c.

As already noted, initial deployments of unlicensed LTE are likely to focus on carrier aggregation in the downlink. This implies that acknowledgments (ACKs) and other transmissions from UEs (uplink transmissions) are also sent using the licensed band.

WiFi Scheduling

WiFi takes a decentralized approach to scheduling transmissions, unlike the centralized approach used by LTE. When a WiFi device wants to make a transmission it senses the radio channel and performs a clear channel assessment (CCA) check. If no transmissions are detected for a period of time,referred to as a distributed inter-frame space (DIFS), the transmission proceeds. Otherwise, the WiFi device draws a number, uniformly at random between 0 and 15 (or between 0 and 31 for 802.11b/g), and starts to count down while pausing the countdown during periods when the channel is detected to be busy. When the counter reaches zero, a transmission is sent. If another device also transmits at the same time, a collision occurs. When a transmission fails (which is detected by the absence of an ACK from the receiver [6]), a new random number is drawn, and the process repeats. Usually, the interval from which the random number is drawn is doubled on each collision (i.e., increasing as 16, 32, 64, etc.). This random access process is referred to as carrier sense multiple access with collision avoidance (CSMA/CA).

One basic question is what advantages and disadvantages unlicensed LTE offers over WiFi. The jury is still out on this, but one important advantage that does seem clear for operators is that network management can be unified by the use of LTE in both licensed and unlicensed bands.

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 ($L_{mac\text{-}h}$)	288 bits
Tail bits (L_t)	6 bits
ACK length (L_{ack})	256 bits
Payload (D)	768,000 bits (64× 1500B)

Table 1. IEEE 802.11ac MAC parameters [6].

IEEE 802.11ac	236.9 Mb/s
LTE (CFI = 0)	373.3 Mb/s
LTE (CFI = 1)	300.8 Mb/s
LTE (CFI = 2)	283.2 Mb/s
LTE (CFI = 3)	256.6 Mb/s

Table 2. Comparison of the peak throughput of LTE and WiFi (5 GHz band, 20 MHz channel, 64-QAM, 5/6 [IEEE 802.11ac] and 948/1024 [LTE] coding rate, 4 × 4 MIMO).

Comparing with LTE, observe that WiFi transmissions are not confined to periodic frame times, and so will generally not be synchronized with LTE transmissions. Further, WiFi defers transmissions when it detects the channel to be busy. It is these two features which make it necessary to take extra measures to ensure that LTE coexists reasonably fairly with WiFi[1] when using unlicensed bands. In particular, their use of channel sensing means that WiFi devices might[2] not start a transmission while LTE is transmitting, and unless LTE leaves idle periods where WiFi devices can access the channel, WiFi devices may be starved of access. Conversely, since WiFi transmissions occur at random times, these transmissions may overlap with LTE frame boundaries and cause significant interference or cause LTE to refrain from transmission. We discuss LTE/WiFi coexistence in more detail.

LTE and WiFi Comparison

One basic question is what advantages and disadvantages unlicensed LTE offer over WiFi. The jury is still out on this, but one important advantage that does seem clear for operators is that network management can be unified by the use of LTE in both licensed and unlicensed bands. For LTE operators without an existing WiFi network, there is also the advantage of access to additional spectrum and bandwidth.

A key issue when discussing these advantages and disadvantages is the throughput and delay performance of LTE and WiFi. With the introduction of new WiFi standards such as IEEE 802.11ac, it is currently difficult to compare these, and more work on this is urgently needed. The difficulty is in part because the impact of the requirement for LTE to coexist with WiFi on performance is not yet clear, but also because the complexity/flexibility of both LTE and WiFi can make simplistic comparisons misleading.

For instance, consider throughput performance. LTE and WiFi use essentially the same physical layer technology, that is, orthogonal frequency-division multiplexing (OFDM), quadrature amplitude modulation (QAM), and multiple-input multiple-output (MIMO). They do differ in transmit power and channel bandwidth, as well as in the available choices of modulation and error correction coding (in 802.11 the minimum rate modulation and coding scheme is binary phase shift keying [BPSK] 1/2, while for LTE it is quadrature phase shift keying [QPSK] 78/1024, which affect the coverage range), and the retransmission mechanism on packet loss (WiFi uses automatic repeat request [ARQ], whereas LTE uses hybrid ARQ). Importantly, however, the scheduling, MIMO operation, and link adaptation as well as MAC overheads of LTE and WiFi also differ.

In terms of scheduling, LTE uses centralized scheduling, whereas WiFi uses random access. Although both approaches can achieve the same throughput capacity {as shown in [7, 8]), the particular random access approach used by 802.11 results in persistent collisions when more than one device are transmitting. As the number of active devices increases, the number of collisions tends to increase, so network throughput falls. However, in LTE the network throughput also tends to fall as the number of UEs increases since the control plane overhead associated with scheduling transmissions increases. That is, with higher number of UEs, the number of downlink control information (DCI) messages increases, thus increasing the control format indicator (CFI) value [9, 10]. This might be mitigated by appropriate scheduling, but such scheduler details are vendor-specific.

Nevertheless, and with these caveats in mind, it is possible to quantify the maximum downlink throughput achievable by both technologies in the 5 GHz unlicensed band. We consider the same bandwidth, MIMO configuration, and modulation for a channel with high signal-to-noise ratio (SNR) so that the highest allowed coding rate can be used, and ignore coexistence requirements (e.g., requirements for LTE channel idle time). We focus on the downlink as LTE unlicensed transmissions are currently confined to this, with uplink transmissions (including ACKs) sent via the licensed band.

As an illustration, consider 64-QAM, a 20 MHz channel, and 4 × 4 MIMO. For WiFi, the 5/6 coding rate is used, and the other MAC parameters are detailed in Table 1. For LTE, the coding rate of 948/1024 is used, and a range of values for the minimum CFI are considered. The goal is to assess whether for the same conditions the use of LTE provides substantially higher throughput performance. However, note that WiFi currently allows for a larger number of aggregated channel widths, which provides a higher peak throughput performance.

The peak throughput is shown in Table 2 for both LTE and WiFi. Observe that LTE offers a 27 percent increase in throughput compared to

[1] It is still unclear which notion of fairness is appropriate in this context. Discussions in the Third Generation Partnership Project (3GPP) are focused on LTE not impacting WiFi performance more than another WiFi network. However, other notions of fairness, such as equal LTE/WiFi throughput or proportional fairness, may well also be of interest.

[2] This depends on the details of the channel sensing used by WiFi and of the signal transmitted by the LTE base station (especially the received signal strength at WiFi devices), so it is by no means certain that WiFi devices will always defer to LTE transmissions.

WiFi IEEE 802.11ac when the CFI equals 1, falling to 7 percent when the CFI equals 3. When the licensed band is used for the LTE downlink control plane, the associated CFI overhead in the unlicensed band falls to zero, and the LTE unlicensed band throughput rises correspondingly to 373.3 Mb/s, which is 57.6 percent higher than WiFi. Once again, it should be borne in mind that even this idealized comparison is still not really "fair" since it neglects the LTE control plane overheads in the licensed band. However, the results obtained do not seem to provide substantially higher throughput so as to justify the use of unlicensed LTE compared to WiFi. Nevertheless, as we stated before, the unification of network management can instead be a strong motivating factor for unlicensed LTE rollout.

LTE/WiFi and LTE/LTE Coexistence

An important constraint on LTE unlicensed band operation is the requirement for efficient coexistence with other unlicensed band users, in particular with WiFi users and different LTE operators. Coexistence of multiple LTE operators within the same unlicensed band is a major concern, although it has received only limited attention to date. Instead, the main focus until now has been on LTE/WiFi coexistence, due to the large volume of already deployed WiFi nodes.[3]

In this section, a survey of current LTE/WiFi coexistence mechanisms is presented.

Channel Selection

Perhaps the simplest approach to coexistence is to ensure that WiFi and LTE devices use different channels that do not interfere with one another. As shown, for example, in [11], efficient selection of non-interfering channels is feasible, and can be realized using decentralized algorithms that do not require explicit communication among nodes. The 5 GHz band has a relatively large number of non-overlapping 20 MHz channels, which simplifies such channel selection. However, in certain locations such as the United States, with four 20 MHz channels in the U-NII-1 band and five 20 MHz channels in the U-NII-3 band, it may be challenging to find clear channels.

Power Control

Adjustment of the transmission power of the cell might also be used to assist coexistence by reducing interference. However, simply reducing transmit power adversely affects cell coverage and data rate, so more sophisticated schemes, which adapt power per carrier and sub-carrier (each 20 MHz channel is divided into a number of narrow-band sub-carriers) to achieve a targeted coverage/performance, are also of interest.

Discontinuous Transmission

In the event that channel selection and power control are not sufficient to avoid interference, LTE can use discontinuous transmission. That is, rather than using every available time-frequency resource to make a transmission, some slots are left blank for the sake of interference coordination. While in principle each time-frequency resource might be considered independently, in practice attention has mainly focused on leaving subframes or entire frames blank.

Recall that one basic difference between the two technologies, LTE and WiFi, is that LTE unlicensed band transmissions must be aligned with fixed frame/subframe boundaries (Fig. 1c), whereas WiFi transmissions are not subject to this constraint. Another is that WiFi defers transmissions when it detects the channel to be busy. With these in mind, the main approaches currently under consideration for ensuring coexistence when LTE and WiFi nodes share the same channel are discussed in the following.

LTE-U/Carrier Sense Adaptive Transmission (LTE-U/CSAT): One approach is LTE-U/CSAT [3, 4], which is mainly targeted at early deployments and for the U.S. market, where LBT is not required. In this approach, an LTE base station schedules transmissions periodically, leaving idle times between transmissions to allow WiFi devices to transmit. For example, the base station may transmit on every other frame boundary so that it transmits one 10 ms frame and then leaves the channel idle during the next 10 ms frame, yielding a 50 percent on-off duty cycle (Fig. 1). In order to enhance performance, subframe granularity is desired.

To implement LTE-U/CSAT, the existing almost blank sub-frames (ABS) framework of LTE was initially considered in [12]. However, since synchronization signals and control information are still present in ABS, there may still be an impact on WiFi transmissions and carrier sensing. Instead, the MAC channel element activation and deactivation feature of carrier aggregation has been adopted by the LTE-U Forum [13], which is compatible with Release 10/11/12 LTE PHY/MAC standards. In this way, the LTE base station can activate and deactivate the unlicensed carrier in the UE. The LTE base station may sense the channel during the idle times in order to adapt the on-off duty cycle so as to leave more or less time for WiFi transmissions.

Note that a WiFi transmission may start toward the end of an LTE-U/CSAT idle period and hence overlap with the start of an LTE transmission due to the absence of channel sensing, as illustrated in Fig. 2a (where it is marked "collision"). Such collisions at the start of an LTE transmission essentially reduce both LTE and WiFi throughput (even if colliding transmissions can be decoded, which may be far from straightforward, the information rate is necessarily reduced). For a given on-off duty cycle, this reduction in throughput can be minimized by making the LTE transmission as long as possible, thus reducing the collision probability, but of course this comes at the cost of increased delay for all devices. Therefore, there is a throughtput-delay trade-off.

To illustrate these effects, we show in Fig. 3 the WiFi and LTE throughput obtained from simulations when we vary the number of subframes transmitted at each LTE busy period. We have implemented the specific modules for LTE and WiFi channel access in an event-based simulator framework that provides a time reference, modules, and interconnection capabilities. The same parameters shown in Table 1 are used for the WiFi network, and the physical parameters used for the throughput comparison in Table 2 (with CFI = 0) are used for the LTE network. We provide simulation results for different scenarios

Co-existence of multiple LTE operators within the same unlicensed band is a major concern, although one that has received only limited attention to date. Instead, the main focus until now has been on LTE/WiFi co-existence, due to the large volume of already deployed WiFi nodes.

[3] In the United States a number of WiFi operators have already expressed their concerns and approached regulatory government bodies indicating that LTE-U and LAA operations may have a detrimental impact on existing and future use of unlicensed or shared spectrum.

A long on and off period duration, such as 20 ms, significantly increases the delay variability for both WiFi and LTE, and it is not yet clear how sporadic long delays may affect TCP and higher layer dynamics, or whether issues may arise such as causing a WiFi station to de-associate from its access point.

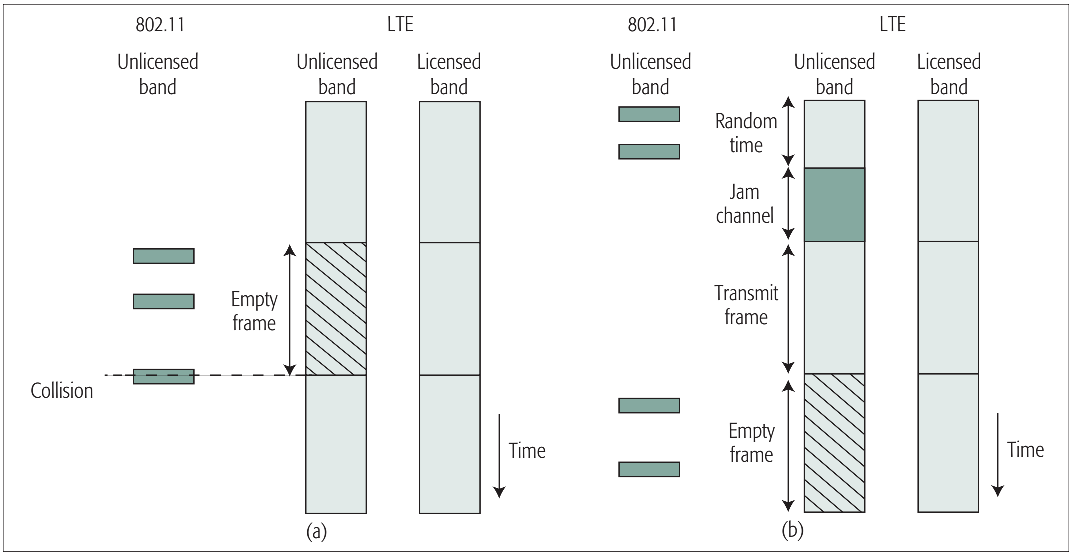

Figure 2. Illustrating main LTE coexistence approaches: a) LTE-U/CSAT; b) LAA/LBE.

where n denotes the number of WiFi users. In more detail, we consider two scenarios with a WiFi access point providing service to a single WiFi user (n = 1) or five WiFi users (n = 5), while sharing the channel with an LTE base station providing service to one UE. As a baseline, we also show the throughput obtained when the LTE base station is replaced by a WiFi access point (labeled as *WiFi only* n = 2 and n = 6, respectively — the LTE UE becomes a WiFi user).[4] The on-off duty cycle of the LTE base station is configured at 50 percent; we consider saturated conditions and ideal WiFi carrier sensing (WiFi stations always defer upon detection of LTE transmissions). The LTE base station, WiFi access point, and users are all within coverage range; thus, no hidden terminal problems arise. Collisions, both between WiFi stations and among WiFi and LTE, are considered. We also assume that only LTE subframes that do not overlap with WiFi transmissions contribute to the LTE throughput, which represents a lower bound. The main goal of the simulation setup is to provide a controlled scenario that allows insight into the effect of the LTE transmission duration.

Figure 3 shows that when the LTE idle period duration is smaller than a WiFi transmission, which lasts approximately 3 ms, WiFi does not have any opportunity to access the channel, and thus the resulting WiFi throughput is zero. When the LTE idle period duration increases, it can be seen that the throughput for both technologies tends to increase as WiFi has room to access the channel, and the collision probability becomes smaller. Also note the zig-zag effect, which depends on the value of the number of subframes transmitted per LTE channel access. This is a quantization effect associated with the number of WiFi transmissions that can completely fit within an LTE idle period. Importantly, Fig. 3 shows that to optimize throughput the duration of this idle period should be carefully selected, and we should consider that longer on and off period durations tend to reduce collision probability between both technologies. However, a long on and off period duration, such as 20 ms, significantly increases the delay variability for both WiFi and LTE, and it is not yet clear how sporadic long delays may affect TCP and higher layer dynamics, or whether issues may arise such as causing a WiFi station to de-associate from its access point.

It is also important to note in Fig. 3 that when the LTE base station and WiFi access point are serving the same number of users and traffic (this is the case for n = 1), and the LTE busy period duration is similar to the WiFi transmission duration (immediately longer than three subframes per channel access), the throughput obtained per user for both LTE and WiFi is comparable. However, when n = 5, we can observe that no configuration provides similar user throughput for LTE and WiFi since there are 5 times less LTE users than WiFi ones. Therefore, a reduced duty cycle with a larger LTE idle period duration needs to be used to leave more transmission opportunities for WiFi if the goal is to achieve equal throughput between WiFi/LTE users.

With regard to coexistence as defined in [2], we can also derive from Fig. 3 the value of the on and off period durations that should be used for LTE to impact WiFi throughput in a similar manner as another WiFi. For n = 1, where the LTE base station and WiFi access point are serving the same number of users and traffic, and the same channel time is given to both technologies (the on-off duty cycle of the LTE base station is configured at 50 percent), this coexistence is achieved at different configurations, the one with shorter LTE on and off durations being 7 LTE subframes. However, in order to further improve throughput, we can achieve this coexistence metric at longer LTE on and off durations, at the expense of WiFi delay increased variability. For durations equal to or larger than 20 subframes, we can say that LTE-U/CSAT always achieves this coexistence target, and the throughput of both technologies is maximized since the collision probability is reduced. However, as for the equal throughput case, for n = 5, we observe that a larger idle period duration is needed to achieve this coexistence target since there are 5 times less LTE users than WiFi ones. Thus, both the duty cycle and the duration of the LTE on and off period durations are key parameters for providing a certain metric of fairness.

[4] Note that in the WiFi only case, performance is no longer dependent on the number of LTE subframes per channel access since there is no LTE transmission.

LAA/LBT: An alternative to LTE-U/CSAT is LAA/LBT, in which the LTE base station senses the channel using energy detection within a designated time before starting transmissions in the unlicensed band. Such sensing is mandatory in regions such as Europe and Japan.

LAA/LBT approaches can be classified according to various categories, but the most relevant is LBT-Load Based Equipment (LBE) Category 4: LBT with random backoff and variable size of contention window [2, Sec. 8.2]. This is similar to the random access procedure used by WiFi devices and is recommended by the 3GPP as the baseline approach for LAA downlink transmissions.

A significant advantage of using a similar random access procedure to 802.11 devices to win transmission opportunities is that fair coexistence with 802.11 devices can be guaranteed more easily. Importantly, coexistence of multiple LTE networks within the unlicensed band can also be ensured in a more straightforward manner.

When using LAA/LBT-LBE, data transmission can start right after the carrier sensing procedure. However, when a transmission opportunity is obtained, it will, of course, not usually be aligned with an LTE frame boundary, and LTE devices cannot start transmissions until the next frame boundary is reached. To hold onto the channel and prevent WiFi devices from starting transmissions, the LTE base station may transmit a reservation signal, causing WiFi devices to detect the channel as being busy and so defer their transmissions. This is illustrated in Fig. 2b. A disadvantage is that the use of this reservation signal carries an overhead since no device can transmit data during this period,[5] and this overhead can significantly impact network throughput. This signal, however, may carry control information to assist automatic gain control/synchronization, broadcast control information, or enhanced packet data control channel (PDCCH), thus minimizing the waste of resources. Note that transmitting no reservation signal may result in a large number of unsuccessful transmission attempts, since a WiFi node may start transmission before the subframe boundary is reached.

Figure 4a shows the throughput for LTE and WiFi using LAA/LBT-LBE with the same parameters and configurations used in the last subsection. It can be observed here that the number of LTE subframes per channel access that LTE should transmit to provide equal LTE/WiFi throughput as well as to impact WiFi as another WiFi network are similar. Note that, in this case, the value of the LTE active time to achieve both objectives is around 3 ms, which is approximately the duration of a WiFi transmission in the considered scenario. Basically, since LTE is using the same access method (i.e., LAA/LBT with random backoff and variable size of contention window) and channel access parameters as WiFi, coexistence as defined above is achieved when LTE and WiFi grab the channel for the same amount of time, in this case, 3 ms.

Figure 4b also shows the percentage of channel resources used for transmitting the reservation signal. Note the trade-off between efficiency and the impact on WiFi performance. While increasing the transmission duration of LTE decreases the inefficiency caused by the transmission of the reservation signal, the WiFi throughput degrades considerably since both LTE and WiFi have the same channel access opportunities, but WiFi only accesses the channel for 3 ms (the transmission duration of WiFi is upper bounded by the maximum number of packets that can be aggregated in a single transmission and by the maximum allowed duration of a packet/burst transmission [6]).

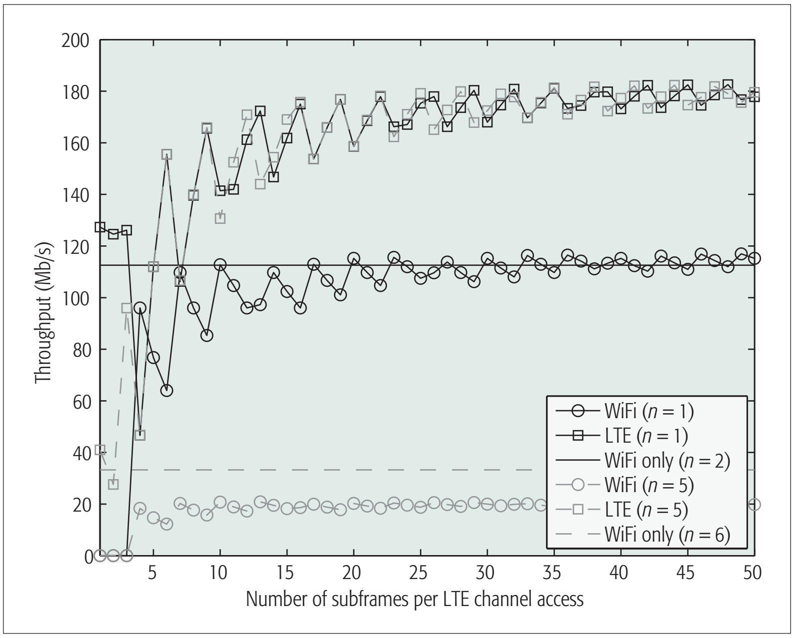

Figure 3. Per-station/UE throughput for WiFi and LTE using LTE-U/CSAT with $n = 1$ and $n = 5$ WiFi users. LTE throughput is the aggregate over all UEs.

Scope and Future Directions

In our evaluation we have made a number of considerations. In this section we examine these assumptions in detail and discuss associated future research directions.

Unsaturated Stations: In our evaluation, we have assumed that the WiFi and unlicensed LTE stations are saturated, that is, there is always a packet buffered for transmission. Note that coexistence between unlicensed LTE and WiFi is more problematic when the networks have to cope with high traffic demands. From the point of view of LTE, this seems a valid assumption, as otherwise the licensed band will suffice. It also seems probable that the activity of the LTE network will result in saturation of the coexisting WiFi stations. However, further work considering a broad range of offered loads and traffic distributions, for both LTE and WiFi, might be in place in order to understand the complex dynamics of these interactions and their impact on coexistence.

Perfect WiFi Carrier Sensing of LTE: We assume in this work that WiFi defers its channel access attempts when the medium is busy due to LTE transmissions. At this point, it is still not clear under which conditions WiFi carrier sense fails to detect LTE transmissions, and extensive experimental works on this should be carried out. It is important to point out that mechanisms such as clear to send (CTS)-to-self [14] can be used in LTE to ensure WiFi reliably detects LTE transmissions.

Hidden Terminals: The basic difficulties here arise from the fact that the effects of hidden termi-

[5] In order to deal with this inefficient use of channel resources, the 3GPP is looking at the definition of a more flexible transmission time interval (TTI) where transmissions do not need to start at the subframe boundary or be confined to one subframe.

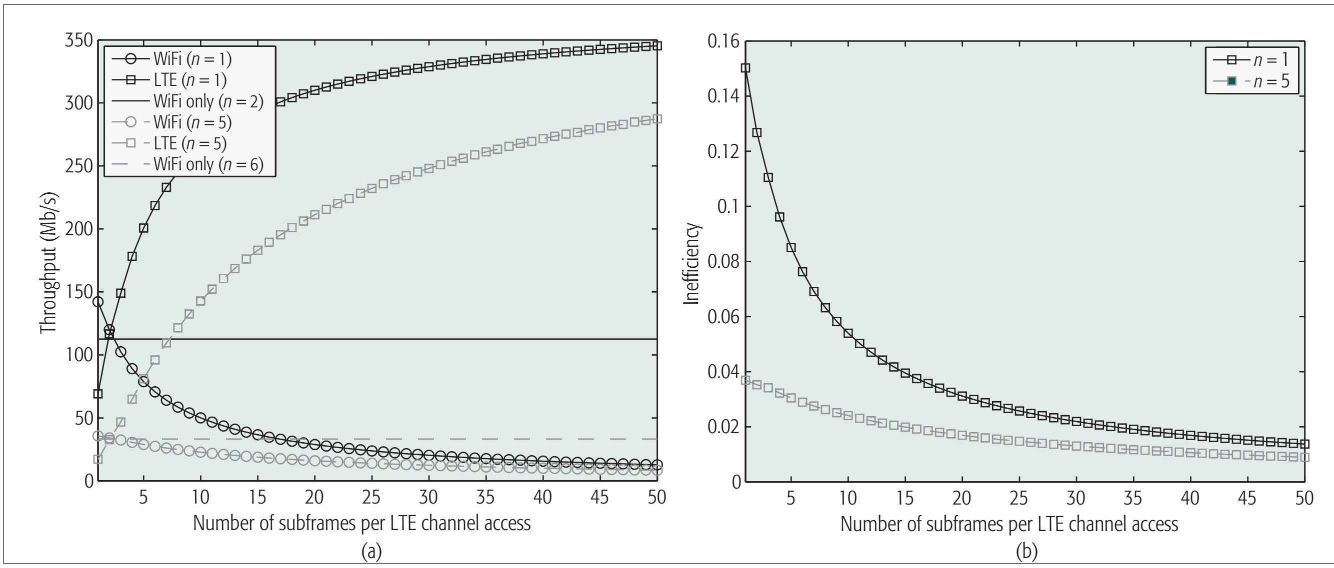

Figure 4. Performance for WiFi and LTE using LAA/LBT-LBE with n = 1 and n = 5 WiFi users. LTE throughput is the aggregate over all UEs: a) per-station/UE throughput; b) inefficency.

nals are highly dependent on the scenario of evaluation, and an extensive evaluation is required in order to obtain meaningful conclusions. It is perhaps also worth noting here that the prevalence of severe hidden terminals in real network deployments presently remains unclear, especially in small cell scenarios.

Multiple LTE Networks: We have considered in our evaluation that only one LTE network is active in a given channel. The consideration of multiple LTE networks sharing the unlicensed spectrum has challenges associated related to the misalignment of the subframes' boundaries among networks belonging to different operators.

Note that given this, results are extremely dependent on the magnitude of that *de-synchronization*, and an extensive evaluation should be carried out to shed some light on this. However, although this consideration is interesting from a scientific point of view, it is not clear whether in practice multiple LTE networks will be configured to select a channel already in use by another unlicensed LTE operator.

Final Remarks

The use of unlicensed band spectrum to opportunistically augment licensed band transmissions potentially offers great benefits for cellular operators. In addition to access to additional spectrum and bandwidth, and thus capacity, network management can be unified by use of LTE in both licensed and unlicensed bands, streamlining authentication, handover, and resource allocation. However, these benefits for cellular operators should not be realized at the expense of other technologies operating in the unlicensed band. Simulation results presented in this article shed some light on this, and show that LTE-U/CSAT and LAA/LBT can impact WiFi throughput in a similar manner as another WiFi if they are properly designed and configured. For LTE-U/CSAT, the duty cycle and the duration of the on and off periods are key parameters for achieving coexistence, which should be tuned according to the number of neighboring WiFi devices to achieve the desired metric of fairness and minimize collisions with ongoing WiFi transmissions. For LAA, the adoption of LAA/LBT with random backoff and variable size of the contention window as well as a maximum channel occupancy time similar to WiFi is key for easily reaching coexistence between technologies.

The first commercial LTE-U small cell products have become available on the market in the second half of 2016, although efforts to enhance the performance of LTE-U/CSAT as a coexistence method are also expected to continue. In parallel, the 3GPP TSG-RAN group finalized the first LAA specification in March 2016 as part of LTE Release 13, and LAA commercial products are expected to follow in 2017. The standardization work on LAA continues in LTE Release 14, where the major efforts are on enhancements to support aggregation for uplink transmissions. The standardization teams are also working on coexistence issues. The 3GPP, the IEEE, and the Wi-Fi Alliance are working together to finalize the LAA design features, and are discussing technical aspects, mostly related to LAA/LBT, which may impact coexistence.

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Holger Claussen [SM] is head of the Small Cells Research Department at Bell Labs, Nokia with a team in Ireland and the United States. In this role, he and his team are innovating in all areas related to future evolution, deployment, and operation of small cell networks to enable exponential growth in mobile data traffic. His research in this domain has been commercialized in Nokia's (formerly Alcatel-Lucent's) Small Cell product portfolio and continues to have significant impact. He received the 2014 World Technology Award in the individual category Communications Technologies for innovative work of "the greatest likely long-term significance." Prior to this, he was the head of the Autonomous Networks and Systems Research Department at Bell Labs Ireland, where he directed research in the area of self-managing networks to enable the first large-scale femtocell deployments from 2009 onward. He joined Bell Labs in 2004, where he began his research in the areas of network optimization, cellular architectures, and improving energy efficiency of networks. He received his Ph.D. degree in signal processing for digital communications from the University of Edinburgh, United Kingdom, in 2004. He is an author of more than 90 publications and 110 filed patent applications. He is a Fellow of the World Technology Network and a member of the IET.

Douglas J. Leith graduated from the University of Glasgow in 1986 and was awarded his Ph.D., also from the University of Glasgow, in 1989. In 2001, he moved to the National University of Ireland, Maynooth, and then in December 2014 to Trinity College Dublin to take up the Chair of Computer Systems in the School of Computer Science and Statistics. His current research interests include wireless networks, network congestion control, distributed optimization, and data privacy.