Enabling the Coexistence of LTE and Wi-Fi in Unlicensed Bands

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ABSTRACT

The expansion of wireless broadband access network deployments is resulting in increased scarcity of available radio spectrum. It is very likely that in the near future, cellular technologies and wireless local area networks will need to coexist in the same unlicensed bands. However, the two most prominent technologies, LTE and Wi-Fi, were designed to work in different bands and not to coexist in a shared band. In this article, we discuss the issues that arise from the concurrent operation of LTE and Wi-Fi in the same unlicensed bands from the point of view of radio resource management. We show that Wi-Fi is severely impacted by LTE transmissions; hence, the coexistence of LTE and Wi-Fi needs to be carefully investigated. We discuss some possible coexistence mechanisms and future research directions that may lead to successful joint deployment of LTE and Wi-Fi in the same unlicensed band.

INTRODUCTION

Wireless communication infrastructure is facing a great challenge with the expanding demand for wireless broadband access to Internet. A recent forecast study [1] indicates that a traffic growth beyond 500-fold is expected between 2010 and 2020, assuming the same increase in data usage is maintained. In order to improve the capacity, the Third Generation Partnership Project (3GPP) standards group has been investigating the performance gains obtained by small cell deployment in Long Term Evolution (LTE) Release 12 and beyond. On the other hand, the IEEE 802.11 Working Group (WG) just ratified a new IEEE 802.11ax Task Group (TGax) primarily focused on enhancing the system performance of Wi-Fi in dense deployment scenarios [2].

However, some practical issues impose limitations on large-scale small cell deployments. First, there are increased costs for deploying and maintaining the required infrastructure. Customers are increasingly seeing wireless Internet access as a utility, and premium taxation on faster connections becomes less of an option since the introduction of flat rate tariffs. So, as revenue is not increasing at the same pace as expenditures [1], capacity expansion requiring larger capital expenditures (CAPEX), such as acquisition and installation of cells, and operating expenditures (OPEX) (e.g., backbone maintenance) becomes an economic challenge. The second issue relates to the diminishing availability of radio spectrum, a fundamental resource that is both finite and expensive. Modern wireless technologies like orthogonal frequency-division multiplexing (OFDM), relaying, and spatial multiplexing allow high spectrum usage efficiency to be achieved, and some researchers argue that spectrum scarcity is a non-issue due to available technology [3]. Nonetheless, a bandwidth shortage of 275 MHz in the United States alone is foreseen by the end of 2014 [4].

To face these challenges, cellular operators are deploying complementary network infrastructure for data delivery, a technique known as mobile traffic offloading [5]. The two main technological advances to enable mobile traffic offloading are the introduction of small cell networks and the development of dynamic spectrum access techniques for operation in license-exempt radio bands.

The concept of small cells, as proposed for heterogeneous networks (HetNets), is two-fold. In the data plane, the goal is enabling the dense deployment of cells with smaller coverage areas, but capable of serving high traffic loads. On the other hand, in the control plane, the main goal is diminishing the dependence on an operator's backbone by implementing concepts like self-organization and self-adaptation. These requirements led 3GPP to standardize LTE small cells for operation on licensed spectrum in Release 12. 3GPP also foresees the adoption of enhanced IEEE 802.11 WLANs in unlicensed spectrum as a complementary solution. In this sense, IEEE 802.11ac networks with *Wi-Fi Passpoint* are a good starting point, while the IEEE 802.11ax standard (currently under development) is being considered for dense deployment scenarios. It is foreseen that by 2016, up to 30 percent of broadband access in cellular networks will be attained over traffic offloading networks [1].

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Dynamic spectrum access (DSA) has emerged as an alternative to overcome the increasing demand for additional capacity in wireless networks and spectrum scarcity [6]. DSA enablers like cognitive radio concepts motivated regulatory agencies to allow license-exempt operation in licensed spectrum. For instance, the United States [7] and Europe [8] recently published rules for operation of secondary users (SUs) in the so-called TV white spaces (TVWS). Another initiative is authorized shared access (ASA) [9], where incumbent spectrum holders negotiate their spectrum with SUs in underutilized locations while maintaining acceptable interference levels.

Despite small cells and DSA, spectrum demand is so intense that joint operation of LTE and Wi-Fi in the same license-exempt bands may be expected [10]. Although current spectrum allocation does not comprise any overlapped spectrum band between both technologies, there have been recent discussions in 3GPP concerning the need for feasibility studies about the deployment of LTE in unlicensed spectrum [11]. The objective of this study is to determine which enhancements would be needed from LTE to fulfill regulatory requirements to occupy those bands, for example, the 5.8 GHz industrial, scientific, and medical (ISM) band. Figure 1 shows the LTE and Wi-Fi spectrum allocation in the United States, already considering the 5.8 GHz ISM as a possibility for LTE deployment.

Coexistence of LTE and Wi-Fi in the same band poses certain technical challenges, and some performance degradation can be expected. From the early coexistence results in [12, 13], a series of questions could be made to direct future research: What issues arise from simultaneous operation of LTE and Wi-Fi in the same spectrum bands? What technology is affected the most? What can be done to improve performance of both networks while coexisting? Should enhancements be introduced for the physical (PHY) and/or media access control (MAC) layers?

This article discusses the coexistence of LTE and Wi-Fi networks in the same unlicensed spectrum bands from the radio resource management (RRM) perspective. We review the differences between LTE and Wi-Fi channel access mechanisms, and present recent results demonstrating the performance of the two technologies when they coexist in the same unlicensed band. Then we discuss coexistence mechanisms, including the adaptation of features in both LTE and Wi-Fi that may act as enablers for a coexistence scenario. Finally, we present future research trends and conclusions.

Challenges for LTE/Wi-Fi Coexistence in Unlicensed Bands

Enabling different networks to operate in the same shared spectrum requires taking some issues under consideration. One important aspect is coexistence, which involves the definition of boundaries for the occupation of radio resources (i.e. time and spectrum) by the networks, as well as intelligent modifications on the RRM algorithms to take into account coexisting dissimilar access technologies. Another important aspect is interworking, that is, intelligent management of user allocations among dissimilar access technologies, handling ongoing (e.g., handover) and incoming (e.g., access selection) connections. This work focuses on the coexistence aspects. Interworking and network selection are beyond the scope of this article.

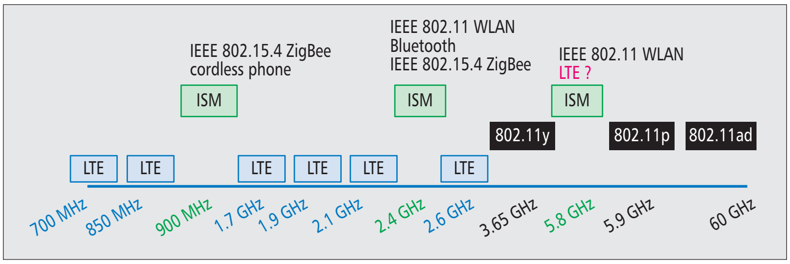

Figure 1. LTE and Wi-Fi spectrum allocation in the United States, considering future LTE deployment at the 5.8 GHz ISM band.

The lack of inter-technology coordination and mutual interference management are some of the main challenges for the efficient coexistence of different wireless technologies. Most broadband wireless access systems have interference management mechanisms, but these are designed to work properly for terminals of the same technology. These built-in mechanisms become less effective in heterogeneous wireless protocols/standards, which adopt asynchronous time slots, different channel access mechanisms, and disparate transmission/interference ranges. In fact, two of the most utilized broadband wireless access networks nowadays, LTE and Wi-Fi, are not only dissimilar but also incompatible when operating in the same band.

Wi-Fi employs OFDM for encoding digital data on multiple carrier frequencies, grouped within subcarriers where OFDM symbols are actually transmitted. In Wi-Fi infrastructure mode, an access point (AP) bridges a basic subscriber set (BSS) of wireless stations (STAs) to a wired Ethernet network. STAs and APs utilize a Wi-Fi default channel access mechanism, the distributed coordination function (DCF), to exchange data, control, and management frames. DCF uses a contention-based protocol known as carrier sense multiple access with collision avoidance (CSMA/CA), where nodes listen to the channel prior to transmission in a procedure known as clear channel assessment (CCA). A node in CCA may receive transmissions coming from other nodes, causing the channel to be seen as occupied, and hence deferring transmission to a random backoff time. CCA and backoff decrease the probability of transmission collisions in Wi-Fi at the cost of lower channel utilization.

On the other hand, LTE employs orthogonal frequency-division multiple access (OFDMA), which is a multi-user version of OFDM. Multiple access is achieved in LTE by assigning subsets of subcarriers to individual user equipments (UEs) for a specific number of symbol times (i.e., physical resource block, PRB), thus allowing simultaneous transmissions from several UEs. In

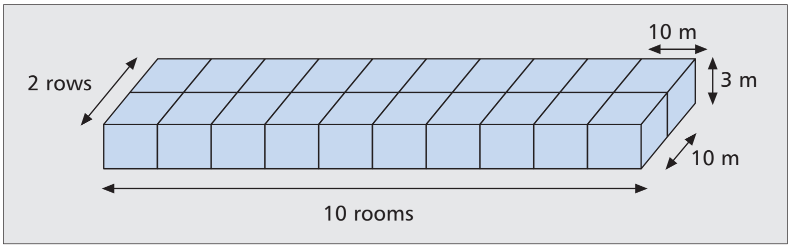

Figure 2. Single-floor/multi-room indoor scenario composed of 2 rows of 10 rooms, each measuring 10 m × 10 m × 3 m.

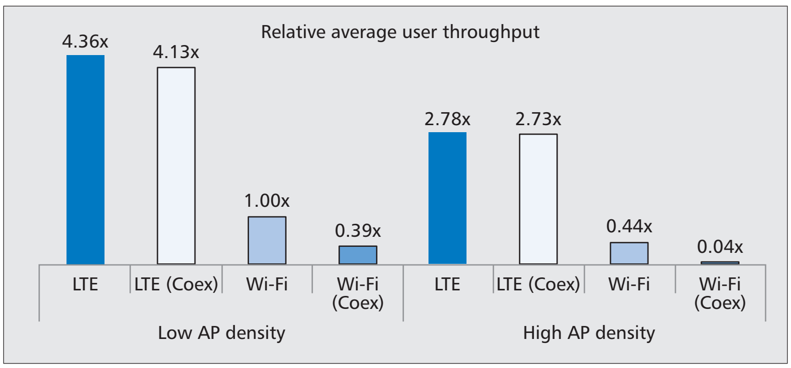

Figure 3. LTE and Wi-Fi average user throughput relative to Wi-Fi low AP density for indoor scenario. Deployments: low AP density (4 APs per technology) and high AP density (10 APs per technology) with an average STA density of 2.5 per AP for both cases. LTE and Wi-Fi evaluations: isolated (LTE, Wi-Fi) and in coexistence (LTE (Coex) and Wi-Fi (Coex)).

comparison with Wi-Fi using DCF, LTE has much more flexibility regarding resource allocation in time and frequency domains. Also, LTE does not require carrier sensing prior to transmission. Instead, the LTE base station (known as eNodeB) allocates radio communication subchannels for channel estimation and equalization, synchronization, management, control, and data transmissions. Finally, eNodeB deployment is usually planned, and inter-eNodeB communication infrastructure may be used for spectrum usage coordination.

Another challenge is the LTE deployment model for unlicensed spectrum bands. The first limiting factor is that regulatory agencies restrict the effective isotropic radiated power (EIRP) in unlicensed spectrum bands to much lower levels than typically used in LTE macrocells. Additionally, LTE should be able to determine whether Wi-Fi is jointly operating in the same spectrum as well as establishing a coexistence mechanism with it. From this, LTE small cells appear as a natural deployment model for LTE operation in unlicensed spectrum.

A potential traffic offloading scenario with coexisting LTE and Wi-Fi deployments is the single floor/multi-room indoor environment with LTE small cells and Wi-Fi, illustrated in Fig. 2. This scenario, composed of 2 rows of 10 rooms, each measuring 10 m × 10 m × 3 m, is adopted by both 3GPP and IEEE as a realistic scenario to represent residential and small office uncoordinated deployments.

In standalone single-floor/multi-room indoor deployments, it can be expected that LTE outperforms Wi-Fi in terms of average user throughput due to its more efficient usage of radio resources. A recent performance study [12] not only confirmed that, but also showed that when nodes of the two technologies coexist in the same frequency band, LTE interference severely affects Wi-Fi operation (Fig. 3).[1] The main reason is that LTE, in contrast to Wi-Fi, does not sense for channel vacancy prior to transmissions; thus, Wi-Fi nodes have a tendency to be blocked by LTE transmissions. Hence, while LTE is seldom affected by Wi-Fi interference, Wi-Fi is almost silenced when coexisting with LTE. This can be clearly seen on the average user throughput performance of both technologies presented in Fig. 3, especially for the high node density case.

The next section explores enabling features for efficient coexistence between LTE and Wi-Fi.

LTE/Wi-Fi Coexistence Enablers

Coexistence mechanisms can be broadly classified into collaborative and non-collaborative (autonomous), according to the exchange of messages between coexisting systems. Non-collaborative mechanisms may be used autonomously to facilitate coexistence with other networks and devices, while collaborative mechanisms require mutual agreement on the parameters used in each network.

A classic example of a non-collaborative coexistence mechanism is CSMA/CA with CCA in Wi-Fi, which enables coexistence with other wireless network technologies in unlicensed bands such as IEEE 802.15.4 (Bluetooth). On the other hand, a representative example of a standardized collaborative coexistence mechanism is IEEE 802.19.1, which defines a series of network elements, functions, and interfaces for the coexistence and coordination of different networks in TVWS bands. Utilization of collaborative coexistence mechanisms has greater potential to provide better performance for all coexisting networks than non-collaborative mechanisms. We describe a generalized procedure for collaborative coexistence through the flowchart in Fig. 4.

The generalized collaborative procedure assumes two operation modes: regular mode (RM) and coexistence mode (CM). RM represents standard operation, where no other technology is assumed to be using the spectrum at the same location and time. Here, the search for coexisting systems is done periodically, or triggered by external events such as the increase of the received interference or the detection of a beacon of another technology.

If a coexisting system is detected, the following actions are expected: identification of coexisting systems and synchronization with the identified systems. Synchronization can be done by reusing synchronization signals of the coexisting technology, such as the primary and secondary synchronization signals (PSS and SSS) of LTE and the preamble of Wi-Fi. Additional synchronization information can also be obtained by exploring the cyclic prefix repetitions of the coexisting technology.

Next, a negotiation phase is started. At this stage, the systems sharing the spectrum agree on

[1] Network performance assessed by system-level simulations modeling multi-cell and multi-user standard-compliant time-division duplexing LTE (TDD-LTE) and IEEE 802.11 (Wi-Fi). As detailed in [12, 14], these simulations include modeling of network layout, nodes distribution, radio environment, mutual interference, PHY and MAC layer, and traffic generation.

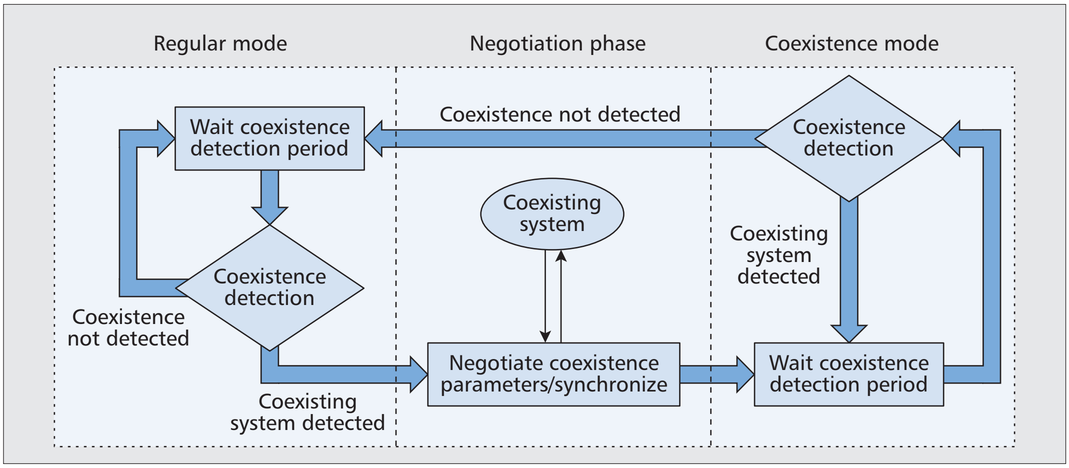

Figure 4. Generalized collaborative coexistence algorithm.

Non-collaborative mechanisms may be used autonomously to facilitate coexistence with other networks and devices, while collaborative mechanisms require mutual agreement on the parameters used in each network.

system parameters for a fair coexistence. Each system is expected to renounce some resources (e.g., time or frequency) it would use if operating in RM. However, minimum operational requirements of individual systems must be satisfied. If there are no mechanisms for communication between the coexisting technologies, each system should trigger coexistence techniques that avoid channel access domination by any of the coexisting radio access technologies.

Finally, each system reconfigures to agreed parameters, thus switching to CM. Once in CM, the systems monitor the shared resources in order to check whether there is effective operation of the coexisting systems. The system should also check for new secondary users, and return to the negotiation phase when necessary. When no coexisting system activity is detected, the operation is switched back to RM.

A number of *enabling features* can help with implementing collaborative coexistence mechanisms for LTE and Wi-Fi. For once, new spectrum utilization opportunities for both LTE and Wi-Fi can be created by allowing spectrum incumbents to grant access to subutilized licensed spectrum portions for secondary users, known as flexible spectrum access (FSA). In addition, given a specific spectrum portion, the selected *spectrum sharing technique* may operate on distinct dimensions (time, frequency, and space). Some LTE mechanisms for *interference management* can be adapted to enable coexistence with Wi-Fi STAs. On the other hand, since LTE interference has the potential to block Wi-Fi STAs using DCF, some features can improve Wi-Fi performance in coexistence with LTE, such as *channel selection* and *contention-free operation*. Table 1 presents a brief taxonomy of these enabling mechanisms for LTE/Wi-Fi coexistence according to the radio access technology.

Mechanisms listed in Table 1 can be used in CM operation within the general collaborative coexistence procedure illustrated in Fig. 4. Such coexistence enablers are described below.

Enabling mechanism	Technology
Flexible spectrum access	LTE/Wi-Fi
Channel selection	Wi-Fi
Blank subframes	LTE
Transmit power control	LTE

Table 1. Taxonomy for LTE/Wi-Fi coexistence enablers.

Flexible Spectrum Access

Two opposite spectrum licensing models regulate the operation of wireless broadband access systems. In the licensed model, a spectrum incumbent acquires exclusive utilization rights from governmental regulatory agencies via, for example, auctions. On the unlicensed model, spectrum portions are specifically allocated for non-exclusive utilization, and specific rules are set to ensure coexistence. DSA techniques have been considered as alternatives for improving utilization of spectrum portions. However, DSA efficiency in ensuring primary user rights, as well as the economic viability of systems operating under unpredictable portions of the spectrum, are aspects still under evaluation.

An alternative spectrum allocation model, FSA, has been recently proposed in the literature. One major example of FSA is authorized shared access (ASA) [9], where the spectrum incumbent economically explores its underutilized spectrum assets by granting exclusive access rights to third-party small cell systems, which also brings a number of complementary benefits. FSA grants can be constrained in frequency, time, and space, which ensures protection of incumbents and increases predictability for long-term investments in both the spectrum incumbent and the leasing third-party system. In addition, since small cells have a diminished coverage radius, they can be located nearer to the spectrum incumbent than conventional macrocells. The ASA approach takes advantage of existing products and standards such as LTE systems. As such, ASA has potential for being cost effective by reusing the available LTE infrastructure for complementary wireless service. Also, due to the opportunity for wider spectrum

The uncoordinated nature of Wi-Fi deployments and the limitation of non-overlapping channels in the ISM bands have motivated several studies about channel selection for Wi-Fi networks, which could also be exploited in coexistence with LTE.

	Subframe number									
Coexistence time	0	1	2	3	4	5	6	7	8	9
0 ms	D	S	U	U	D	D	S	U	U	D
2 × 1 ms	D	S	C	U	D	D	S	U	U	C
4 ms	D	C	C	C	C	D	S	U	U	D
2 × 2 ms	D	S	C	C	U	U	S	C	C	D

Table 2. Examples of null-subframe allocation considering LTE TDD. The coexistence time denotes the amount of time given for coexistence with Wi-Fi. D and U denote regular DL and UL subframes, respectively. S denotes a special subframe for signaling. C denotes coexistence subframes (with no LTE transmissions).

aggregation, it enables further performance improvements.

Channel Selection

Two major differences between Wi-Fi and LTE technologies are channel allocation and network deployment. While Wi-Fi was developed to be used in unlicensed bands with uncoordinated deployments, LTE was meant to be used in licensed spectrum bands and planned deployments. When both of them share the same frequency band, Wi-Fi performance is severely degraded by LTE transmissions, as discussed previously. Therefore, channel selection seems to be an important enabler for LTE/Wi-Fi coexistence.

The uncoordinated nature of Wi-Fi deployments and the limitation of non-overlapping channels in the ISM bands have motivated several studies about channel selection for Wi-Fi networks, which could also be exploited in coexistence with LTE. Some Wi-Fi access points (APs), for example, already implement simple channel selection techniques, such as least congested channel search (LCCS), in which the AP monitors its own channel, also searching for incoming packets from other APs, and selects the least congested one.

As a refinement, the subcarrier allocation flexibility provided by OFDM and OFDMA techniques can also be exploited in coexistence scenarios. Instead of fixed bandwidth channels, adaptive bandwidth channels could be defined and selected in coexistence scenarios.

Since Wi-Fi can be blocked by LTE when coexisting, it is in Wi-Fi's best interest to select the least congested channel for operation. In this case, some coordination between Wi-Fi APs and LTE eNodeBs for channel selection could ease the task of channel selection. This is an issue since exchange of information between nodes experiencing interference relies on a common intertechnology communication framework, which is currently unavailable for LTE and Wi-Fi.

Blank Subframes

An intuitive way to share the spectrum is avoiding technologies to access the channel at the same time. According to the discussion above, the probability of Wi-Fi being blocked when coexisting with LTE is high, and since regulatory rules usually mandate that technologies should share channel access in unlicensed spectrum, a time-sharing coexistence technique would require LTE silent periods. For this, a key LTE feature introduced in Release 10, the almost blank subframe (ABS), can be exploited. ABSs are LTE subframes with reduced downlink transmission power or activity, intended to coordinate transmission of macro and pico eNodeBs in heterogeneous deployments. During an ABS, LTE macro eNodeBs cause less interference to pico eNodeBs.

A modified version of ABS, where uplink (UL) and/or downlink (DL) subframes can be silenced, and no LTE common reference signals are included, is proposed in [14] as null-subframes to support coexistence with Wi-Fi. It is shown that Wi-Fi is able to reuse the blank subframes ceded by LTE, and that throughput increases with the number of null-subframes. Table 2 shows an example of null-subframe allocation inside an LTE frame. However, since LTE throughput decreases almost proportionally to the number of ceded blank subframes, a trade-off is established. Additional LTE performance degradation may be observed if blank subframes are nonadjacent, since Wi-Fi transmissions are not completely confined within LTE silent periods. This is illustrated in Fig. 5a, which summarizes the main results in [14]. However, if the duration and occurrence of LTE blank subframes is reported to Wi-Fi during the negotiation phase (Fig. 4), Wi-Fi nodes might be able to conveniently confine their transmissions within blank subframes and thus avoid interfering with LTE.

Transmit Power Control

LTE UL transmit power control is an alternative to the LTE blank subframes time-sharing approach for LTE/Wi-Fi coexistence. Here, a controlled decrease of LTE UEs' transmit powers diminishes the interference caused to neighboring Wi-Fi nodes, thus creating Wi-Fi transmission opportunities as Wi-Fi nodes detect the channel as vacant. Conventional LTE UL power control compensates only a fraction of the path loss. This effectively reduces LTE intercell interference, as UEs experiencing high path loss, usually in the cell edge, have their UL transmit power diminished. However, LTE power control

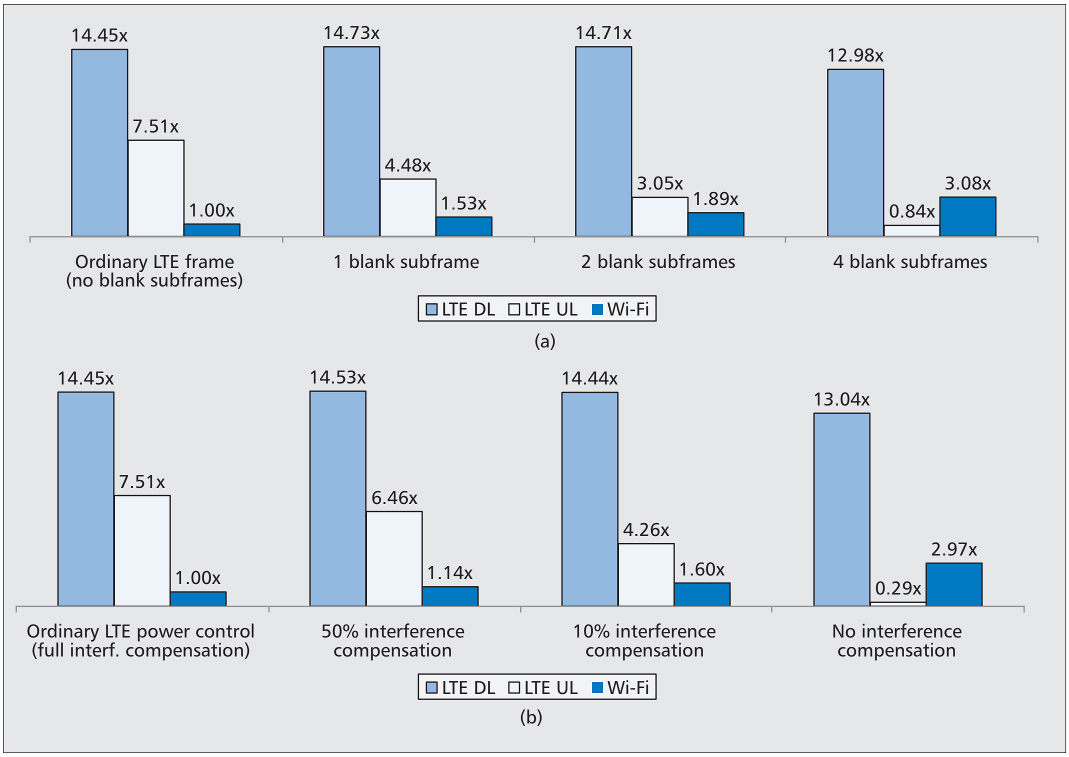

Figure 5. LTE and Wi-Fi average user throughput performance in coexistence with a deployment of 10 APs/25 STAs per technology in a 20-room single-floor indoor scenario, relative to Wi-Fi with no blank subframe. a) blank subframes allocation; b) LTE UL power control with an interference-aware operating point.

Studies undertaken so far clearly reveal that some challenges need to be addressed for the coexistence of LTE and Wi-Fi in the same unlicensed band. Standardization bodies (i.e., 3GPP and IEEE) are addressing some of these challenges.

based on path loss is not effective for Wi-Fi coexistence, which requires transmit power reduction of UEs causing high interference to Wi-Fi nodes.

An LTE UL power control with an interference-aware power operating point is proposed in [15] for enabling coexistence with Wi-Fi. Interference measurements performed at LTE eNodeBs and/or UEs allow estimating the presence and proximity of Wi-Fi nodes. UEs measuring high interference are more likely to cause high interference, so UL transmit power is reduced according to a fractional compensation of the measured interference. LTE UL power control defines UE transmit powers so that path loss and interference are compensated and a given signal quality (i.e., a target signal-to-interference-plus-noise ratio, SINR), is achieved at the LTE eNodeB receiver. This fractional compensation of the measured interference corresponds to decreasing the target SINR when high interference is observed. As such, LTE UE throughput is decreased accordingly. As seen in Fig. 5b, the reduction of key LTE UEs' transmit powers indeed allows neighboring Wi-Fi transmissions at the cost of decreasing LTE throughput.

Simulated throughput results in Fig. 5 actually demonstrate that LTE blank subframes and UL transmit power control define different trade-off configurations for LTE and Wi-Fi in coexistence. While Fig. 5a shows the simultaneous Wi-Fi throughput increase and LTE throughput decrease with the number of blank subframes allocated, in Fig. 5b the decrease in the fraction of interference compensated by LTE UL transmit power control also decreases LTE throughput in favor of Wi-Fi throughput increase.

LTE/Wi-Fi Standardization for Coexistence in Unlicensed Bands

Studies undertaken so far clearly reveal that some challenges need to be addressed for the coexistence of LTE and Wi-Fi in the same unlicensed band. Standardization bodies (i.e., 3GPP and IEEE) are addressing some of these challenges.

From the perspective of LTE, 3GPP has recently started discussion on operation in unlicensed bands. A Study Item was created for defining modifications necessary to LTE radio for deployment in unlicensed spectrum [11]. On the other hand, with Wi-Fi conventionally operating in unlicensed bands, IEEE has worked on standardized mechanisms for allowing efficient coexistence among heterogeneous wireless broadband access technologies within TVWS bands. One major example of IEEE initiatives for operation in TVWS is the IEEE 802.19 Working Group (WG) [16], where a task group named 802.19 TG1 addresses coexistence for IEEE 802 networks and devices. These studies can also be useful for non-IEEE 802 networks and TV band devices (TVBDs). Another initiative is the IEEE 802.11af standard, published in February 2014, which covers Wi-Fi operation in the VHF and UHF bands between 54 and 790 MHz.

With the increasing relevance of Wi-Fi for traffic offloading in cellular networks, improving Wi-Fi efficiency in terms of end-user performance in the presence of dense deployment of APs and STAs has become more important.

With the increasing relevance of Wi-Fi for traffic offloading in cellular networks, improving Wi-Fi efficiency in terms of end-user performance in the presence of dense deployment of APs and STAs has become more important. Recognizing this, IEEE 802 WG created the IEEE 802.11 High Efficiency WLAN (HEW) Study Group (SG) [2] in May 2013, aiming to enhance the quality of experience (QoE) of wireless users in everyday high-density scenarios. As a result of the discussions in HEW SG, the IEEE 802.11ax Task Group (TGax) was recently established to substantially increase user throughput in dense networks with a large number of users and devices, dense heterogeneous networks, and outdoor deployments. TGax includes improvements to cellular offloading as one of its major requirements, and is also investigating mechanisms to increase spatial capacity with PHY-MAC enhancements to the existing IEEE 802.11 standard in the 2.4 GHz and 5 GHz radio frequency bands. A first draft of TGax amendments to IEEE 802.11 is expected to be concluded by 2016.

Conclusions

The wireless communications community has been searching for solutions to handle the increasing demand for wireless broadband access. In this context of spectrum scarcity, there has been recent discussion about allowing wireless network technologies like LTE and Wi-Fi to coexist in the same unlicensed bands. In this article, we show that Wi-Fi is severely affected by concurrent operation of LTE in the same band. This indicates a serious need for coexistence mechanisms to improve the performance of both systems. The applicability of some coexistence enabling features for both LTE and Wi-Fi are discussed, and research directions for further development of inter-technology coexistence are presented. We also propose coexistence mechanisms by reusing the blank subframe approach and the UL transmit power used in LTE, and show that it can significantly improve Wi-Fi performance when coexisting with LTE in the same unlicensed bands.

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