Enabling LTE/WiFi coexistence by LTE blank subframe allocation

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***Abstract*—The recent development of regulatory policies that permit the use of TV bands spectrum on a secondary basis has motivated discussion about coexistence of primary (e.g. TV broadcasts) and secondary users (e.g. WiFi users in TV spectrum). However, much less attention has been given to coexistence of different secondary wireless technologies in the TV white spaces. Lack of coordination between secondary networks may create severe interference situations, resulting in less efficient usage of the spectrum. In this paper, we consider two of the most prominent wireless technologies available today, namely Long Term Evolution (LTE), and WiFi, and address some problems that arise from their coexistence in the same band. We perform exhaustive system simulations and observe that WiFi is hampered much more significantly than LTE in coexistence scenarios. A simple coexistence scheme that reuses the concept of almost blank subframes in LTE is proposed, and it is observed that it can improve the WiFi throughput per user up to 50 times in the studied scenarios.**

***Index Terms*—Radio Spectrum Management, LTE, WiFi, Cooperative Systems, 4G mobile communication**

I. Introduction

The association of increase in the demand for additional capacity in wireless communication systems with regulatory policies that assigns the limited available spectrum in a non-efficient manner has created what is called as "spectrum scarcity" problem, i.e. the existing spectrum is not enough to satisfy the demand. As a result, another model of spectrum access has been discussed in the past few years: dynamic spectrum access, which proposes that spectrum should be accessed according to the demand of each system. The development of cognitive radio concept, characterized by the adaptation of wireless transmitters to changes on the wireless medium, has further motivated the adoption of this new model of spectrum access.

The use of digital terrestrial television (DTT) unused spectrum in a given area, known as TV white spaces, TVWS, is seen as a first step towards general cognitive radio networks. Since publication of Federal Communications Commission, FCC rules [1] for the license-exempt operation in the TV broadcast bands, the operation of wireless users in a licensed band on a secondary basis is becoming a reality. In many countries, such as the United States, Canada and U.K, efforts have been made in order to change regulatory aspects to permit the operation of the so-called white space devices (WSDs). The first premise for operation of secondary users in TVWS is the avoidance of interference on primary users, which can be done by identifying primary transmissions (either by spectrum sensing or by geo-location database operation) and by restricting WSD transmissions [1], [2].

Although the problem of degrading licensed systems operating on the TVWS is expected to be minimized with the limiting regulations imposed for WSD operation, another one arises with dynamic spectrum access on this band: the coexistence of secondary users from different technologies. Although each secondary system is required to avoid interference on primary systems, nothing is required from WSDs regarding sharing resources with other secondary system. The presence of heterogeneous secondary networks on the same location and using resources on a non-cooperative basis may result in a severe interference scenario, thus impacting directly on the purpose of using the TVWS: the efficient use of the spectrum. Differences between PHY and MAC strategies may even cause one network to be completely blocked by another. The lack of interoperability, increase of transmission and interference range, and density of secondary networks are just some problems of heterogeneous coexistence pointed out in [3].

This foreseen situation may be verified by the recent publication of multiple standards that address license-exempt operation in the TVWS. The IEEE 802.22 [4], for example, is a system designed for long-range communications between fixed devices. It includes MAC and PHY specifications as well as self-coexistence mechanisms and is compliant with FCC rules for White Spaces. In 2009, ECMA-392 [5] standard was published for portable WSDs, including also self-coexistence mechanisms. Recently, an IEEE 802.16h standard amendment was published for license-exempt operation [6], and LTE is also expected to do so. Furthermore, IEEE is also working on WiFi-like operation on TVWS in IEEE 802.11af [7], and on IEEE 802.19.1 which aims to describe a general solution for heterogeneous networks coexistence.

Coexistence mechanisms may be classified according to a multiplicity of characteristics [8]: the architecture (centralized, non-centralized or autonomous), the demand of a control chan-

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nel, the coexistence cycle state (observation, adaptation), the placement in the protocol stack (medium access control, MAC, or physical layer, PHY), the synchronization mechanism, and the memory usage. Another classification, used in this work, divides the mechanisms in two groups: collaborative and non-collaborative [3]. The choice for a coexistence mechanism relies on individualities and features of each coexisting system such as the ability of exchanging messages with a different technology. It is important to note that although several works have been published in coexistence scenarios between specific systems (IEEE 802.11 and IEEE 802.15.4, for example) deployed in the Industrial, Scientific and Medical (ISM) 2.4 GHz band [9], [10], not many explored this issue on specific systems operating on TVWS, nor the coexistence of LTE (a contention-free technology) and WiFi, a contention-based technology. Since LTE and WiFi are expected to operate in a license-exempt basis on TVWS, and recent features added to LTE standards indicate its deployment on femto and pico cells (e.g. enhanced inter-cell interference coordination, eICIC), we understand that in the near future coexistence between LTE-A and WiFi will present a real issue.

In this paper, a mechanism to enable coexistence between LTE and WiFi in 900 MHz is described and analyzed through simulations in an indoor environment. This frequency band was chosen due to its proximity to the TVWS. The conclusions and preliminary insights about coexistence of these technologies can be extended for any other licensed or unlicensed band. In Section II, the general mechanism as well as the unique characteristics of LTE and WiFi that impact on coexistence are presented. In Section III, the proposed LTE adaptation for coexistence with WiFi is presented. Section IV presents the simulation tool and scenarios, and the results obtained with and without the proposed mechanism. Finally, the paper is concluded in Section V.

II. Coexistence Mechanism

In general, coexistence mechanisms can be divided in two groups, according to the exchange of messages between both systems: collaborative or non-collaborative (autonomous) [3]. Non-collaborative mechanisms may be used autonomously to facilitate coexistence with other networks and devices, while collaborative mechanisms require mutual agreement of parameters used in each network. An example of a procedure for collaborative coexistence is shown in Figure 1, in which both networks need to exchange messages to negotiate a coexistence mode.

In this procedure, it is assumed that each technology will have two operation modes. The first one, the Regular Mode, consists in normal operation of this communication system, supposing that no other technology is accessing the spectrum at that location. It is assumed that some action will trigger the coexistence detection. This coexistence detection may be done periodically or triggered by an external event: increase of the received interference or detection of a beacon of other technology, for example. Once the detection is initiated, two results are expected:

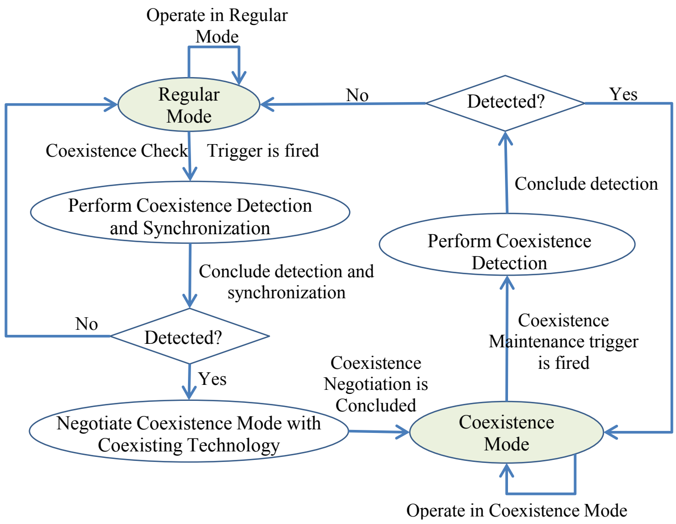


Fig. 1. Collaborative coexistence flowchart.

- Detection and identification of another secondary system.
- Synchronization with the identified system.

If another technology is detected, all systems that are sharing this spectrum band will negotiate parameters such that fair coexistence is possible. There is a trade-off between concessions made to allow the transmission of other technologies, which inevitably reduces the available resources, and the resulting throughput and system QoS. Therefore, in order to accomplish minimum transmission requirements, during the negotiation phase each system could transmit its prerequisites for coexistence. After this negotiation phase, each system is expected to change its parameters accordingly to support operation of other systems. This parameter modification is referred as Coexistence Mode.

In this mode, each system actively takes the actions agreed on the previous stage. Those actions refer to the renounce of some resources in order to enable fair coexistence. Some examples are: time sharing, frequency sharing and code division sharing. Once in Coexistence Mode, the following step consists in monitoring the shared resource in order to check whether the channel is being effectively used by other technologies or not. If the resource is still used, the system continues on Coexistence Mode; if not, the system returns to Regular Mode.

The focus of this work is the proposal of a LTE time domain coexistence mode. In the proposed solution, LTE gives up some time resources (i.e. subframes) so that coexistence with WiFi is possible. This mechanism is described in Section III. Exchange of messages to support negotiation of parameters is assumed.

III. Usage of Blank Subframes in LTE-Advanced

Differences in MAC layer strategies create major challenges for LTE and WiFi coexistence. LTE users, for example, are scheduled in consecutive frames with meaningful power (except in UL subframes when UL power control is used).

WiFi users, on the other hand, contend for channel access with Distributed Coordination Function (DCF), based on sensing the energy of the channel. When LTE and WiFi networks are deployed at the same location and frequency, some WiFi nodes may be blocked by LTE as LTE interference levels are likely to be above the threshold used by WiFi to detect channel vacancy. On the other hand, if WiFi nodes are able to get access to the channel, they have potential to interfere with LTE nodes as WiFi packets are always transmitted with maximum power.

In order to avoid that LTE network operation blocks WiFi systems, a key feature introduced in LTE Release 10 was applied on a different context: time-domain multiplex. This feature describes the use of almost-blank subframes (ABS) for enhanced inter-cell interference coordination (eICIC) purposes [11]. ABSs are subframes with reduced downlink transmission power or activity, intended to coordinate macro eNodeBs and pico eNodeBs transmissions on heterogeneous deployments, such that pico eNodeBs do not suffer severe interference during those silent periods.

One ABS requirement is backward compatibility with LTE Releases 8 and 9. Therefore, some control channels and synchronization signals are still present in ABS like the primary and secondary synchronization signals, PSS and SSS, and the physical broadcast channel, PBCH. Furthermore, Common Reference Signals (RSs) are still transmitted for demodulation and channel state information, CSI, feedback. The occurrence of ABSs is coordinated between eNodeBs by signaling over the X2 interface. The ABS pattern, represented by the number and periodicity of low power subframes, may vary according to the interference scenarios.

In this work, a modified version of ABS is proposed to allow WiFi coexistence. This modified version does not include reference signals, which yields in a silent subframe. Since this modification is meant for new frequency band, it is assumed that reference signals are not required for legacy support. During silent subframes, referred to here as blank subframes, WiFi nodes do detect channel vacancy as channel energy is below the threshold, and therefore are able to transmit. This way, LTE dominance over the available spectrum is reduced. The disadvantage for LTE networks is the loss of time resources, which inevitably decreases the throughput per user. Figure 2 shows examples of coexistence subframes patterns considering LTE TDD (Time-Division Duplex). In this figure, D denotes a downlink subframe, U an uplink subframe, S a special subframe and C a coexistence subframe. Special subframes are those that mark the switch from downlink to uplink operation.

	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 x 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 x 2 ms	D	S	C	C	U	U	S	C	C	D

Fig. 2. Example of subframe allocation considering different coexistence times.

IV. Coexistence Results

In this section, simulation scenarios used to evaluate the performance of LTE and WiFi Systems in coexistence are presented, as well as the simulation results.

A. Simulation Tool and Scenario

In order to evaluate the performance of LTE and WiFi in an indoor coexistence environment, a semi-static system level simulator was developed. A single-floor indoor environment with 20 rooms was considered in the simulation scenarios, as in Figure 3a as well as a multi-floor scenario, as in Figure 3b. Table I summarizes the scenario parameters.

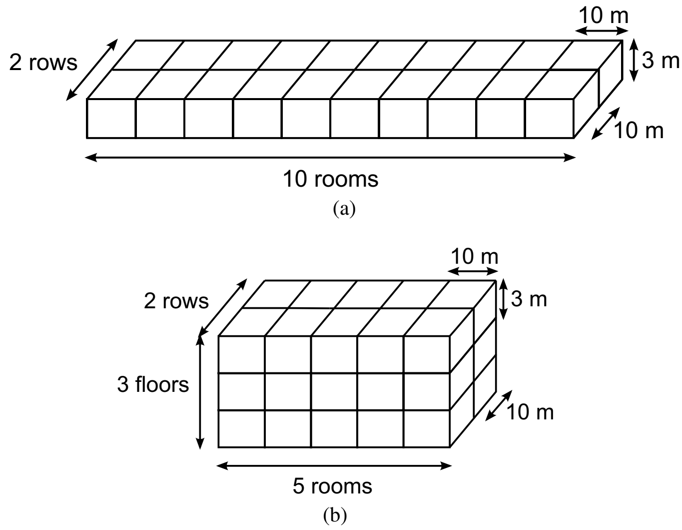


Fig. 3. Simulation Scanrios: (a) Single-floor; (b) Multi-floor.

TABLE I
Deployment Scenario

Common Parameters	Value
Scenario	Indoor single floor and indoor multi-floor
System Bandwidth	20.0 MHz
Center Frequency	900.0 MHz
Transmission Power	23.0 dBm
AP Height	1.0 m
UE/STA Height	1.5 m
Number of Tx/Rx Antennas	1/1
Traffic	Full-Buffer
LTE Parameters	**Value**
Simulation Step	1 ms
WiFi Parameters	**Value**
Simulation Step	8 μs

LTE frames are divided into downlink and uplink subframes with 1 ms duration. Synchronization of all LTE eNodeBs is considered. OFDMA resources are allocated in a proportional-fair manner, and the modulation and coding scheme (MCS) is chosen using the channel quality indicator (CQI) from UEs. Chase-combining Hybrid Automatic Repeat Request (HARQ) for LTE packets is used. The simulator frequency resolution is 180 kHz, corresponding to a Physical Resource Block in LTE.

The WiFi network considers a frequency resolution of two times the WiFi subcarrier spacing, 2×312.5 kHz. DCF, based on carrier sense multiple access collision avoidance protocol (CSMA/CA) is adopted. Two thresholds are considered for channel vacancy detection: one for WiFi transmissions, -82 dBm and another to detect LTE transmissions, -62 dBm. ACK is not explicitly modeled but is implicitly considered for retransmission purposes.

B. Results

In this work both LTE pico eNodeBs and WiFi access points (AP) are referred to as APs, and LTE user equipments (UEs) are referred as STA (stations) as in WiFi networks. Considering simulation scenario described in Section IV-A, multiple network topologies were investigated. The influence of increasing number of APs and STAs on the performance of each network was evaluated, as well as the influence of time ceded by LTE network for coexistence purposes. APs from different technologies are not allowed to be located at the same room, and STAs are associated with the AP that results in the lowest path-loss.

A first configuration considered an interference scenario with 10 APs and 10 STAs per technology in a single floor environment. Three sets of simulation were done: at first, only LTE nodes were activated. In this configuration, simulations were done considering no coexistence subframes, 2 non-contiguous blank subframes, 4 contiguous blank subframes, 4 blank subframes grouped in 2 blocks, and an extrapolation of 8 blank subframes. This set of simulations is tagged as *LTE only*. A second set of simulations only considered WiFi nodes (*WiFi Only*), in this case, due to the absence of LTE nodes it made no sense to consider different times of coexistence subframes. The last set of simulations activated all LTE and WiFi nodes and the results are presented per technology and labeled as *LTE coexistence* and *WiFi coexistence*. The mean throughput per user in each case is shown in Figure 4. The purpose of analyzing the cases with 4 contiguous blank subframes and 4 blank subframes grouped in 2 blocks, is to observe WiFi and LTE performance with disjoint opportunities in the same frame.

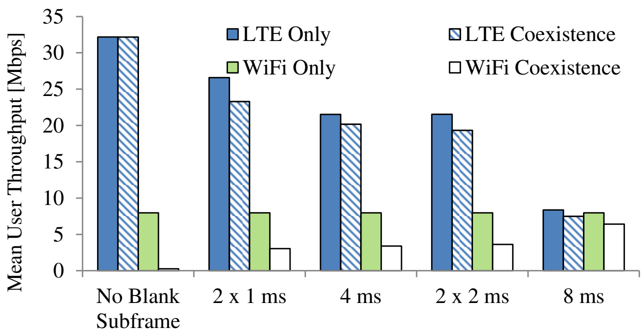


Fig. 4. Throughput results for 10 APs - 10 STAs per technology in a single-floor scenario. Configurations of blank subframes: 0 blank subframes, 2 non-contiguous blank subframes, 4 contiguous blank subframes, 2 non-contiguous groups of 2 blank subframes, 8 blank subframes.

Observing the *LTE Only* and *WiFi Only* scenarios in Figure 4, without the proposed coexistence mechanism, as expected LTE achieved a higher throughput per user than WiFi, 32.18 Mbps and 7.96 Mbps respectively. Differences between the MAC layer strategies of both technologies, non contention-based versus contention based access, explain this gap even in a non-coexistence scenario. While WiFi nodes waste simulation time sensing the channel to identify opportunities and avoid colision, LTE users are scheduled in successive frames.

In a coexistence scenario, if both networks are operating in *normal mode*, the situation labeled as *no blank subframe* in Figure 4, LTE network dominates the available spectrum reaching a mean throughput of 32.02 Mbps per user, almost blocking WiFi nodes, whose throughput per user is only 0.27 Mbps. This throughput decrease experienced by WiFi users is explained by the results shown in Figure 5, in which the time spent on Listen Mode or Transmit Mode is analyzed. When the proposed coexistence strategy is not used, WiFi nodes spend more than 99% of simulation time listening to the wireless medium and backing-off, given that the channel energy is rarely below the carrier sensing threshold. LTE throughput per user decreases less than 0.49%, whereas WiFi decreases 96.63%, comparing to the case in which both technologies are operating alone.

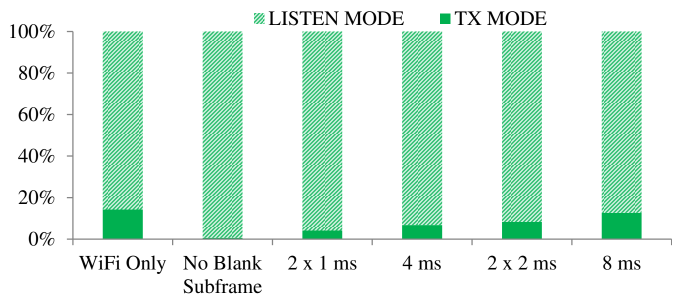
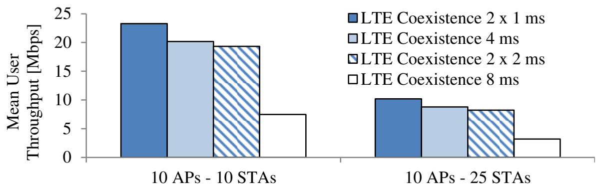


Fig. 5. WiFi uplink transmission mode and listen mode times as a function of the blank subframe pattern, in the single floor 10 APs/ 10 STAs case. In this figure, listen mode time also contains the time spent by WiFi nodes on receiving state.

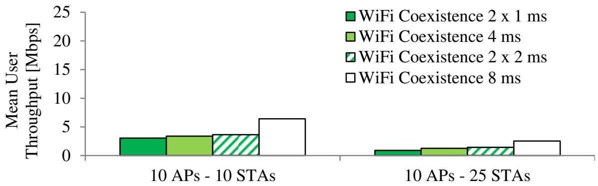
The trade-off between LTE mean throughput per user and time given up for coexistence purposes can be observed in Figure 4, in the simulations labeled as *LTE Only*. The decrease on LTE throughput, as expected, is proportional to the duration of blank subframes: 17%, 35% and 75%. In contrast to the linear decrease on LTE throughput, on *Coexistence Mode* the increase on WiFi throughput with coexistence time ceded by LTE network is not linear. For example, with 2 non-contiguous subframes, WiFi throughput increases 11 times comparing to the case in which no subframes are blanked for coexistence purposes. With 4 blank subframes this enhancement is of 12.68 times, whereas with 2 x 2 blank subframes, it goes to 13.5 times. Finally, with 8 subframes, the mean throughput per user is 24 times higher than the original one. This non-linear trend in WiFi throughput is explained by its CSMA/CA protocol, since a part of the time ceded by the LTE network is still used for listening to the channel. For the sequence of blank subframes patterns in Figure 5, the transmission time per user in uplink is: 14.28%, 0.58%, 4.12%, 6.76%, 8.24% and 12.64% (*WiFi Only*), and the respective mean throughput per user are: 0.26, 3.05, 3.39, 3.61 and 6.4 Mbps.

Another aspect worth mentioning in the results shown on Figure 4 is the performance gap between *LTE Only* and *LTE Coexistence*, caused by WiFi interference. The difference between both curves increases in two cases: 2 non-contiguous blank subframes of 1 ms, and 2 non-contiguous blocks of 2 blank subframes. Both cases create disjoint opportunities for channel access by WiFi nodes. Due to the CSMA/CA behavior, once WiFi nodes gain channel access they occupy the entire bandwidth for an amount of time. When in coexistence with LTE, they are not able to confine their transmissions within the duration of the blank subframe, causing interference on the beginning of the consecutive LTE subframe. This extra time for WiFi transmissions also increases its throughput, regarding the 4 ms blank subframe pattern, and the 2 x 2 ms pattern: the time spent on transmission mode goes from 6.76% per user to 8.24% per user, resulting in a throughput gain of 0.22 Mbps. LTE mean throughput per user, on the other hand, decays 0.87 Mbps. The chosen blank subframe pattern, represented by the coexistence time and number of disjoint opportunities within a frame, impacts the performance of both systems.

In order to evaluate the behavior of the proposed mechanism on other network deployments, the analysis done for the 10 APs/10 STAs case was repeated for other three cases: 4 APs/10 STAs, 10 APs/25 STAs and 4 APs/25 STAs distributed in a single-floor building or in a 4-floors building. The single floor results are presented in Figures 6 and 7.



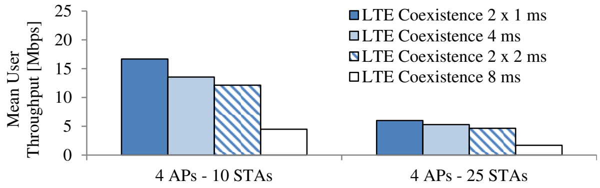
(a)



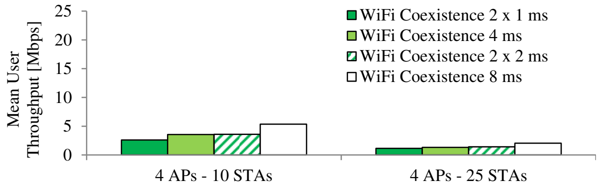
(b)

Fig. 6. Single floor results with multiple configurations of blank subframes, 10 APs: (a) LTE results, 10 or 25 STAs; (b) WiFi results, 10 or 25 STAs.

The results presented for the 10 APs/ 10 STAs case were similar to the 10 APs/ 25 STAs single floor deployments. LTE throughput decrease is inversely proportional to the time given up for coexistence purposes, Figure 6a, while WiFi throughput continues increasing with the time ceded by LTE. In Figure 6b, with 25 STAs, the maximum throughput gain obtained by WiFi users is 18 times with 2 x 1 ms subframe pattern, and 50 times with 8 ms subframe pattern, considering that the throughput achieved with no coexistence strategy equals 0.05 Mbps.



(a)



(b)

Fig. 7. Single floor results with multiple configurations of blank subframes, 4 APs: (a) LTE results, 10 or 25 STAs; (b) WiFi results, 10 or 25 STAs.

As expected, the results with 4 LTE APs, Figure 7a, follow the 10 APs case. Due to the decrease on number of APs, the mean throughput per user on LTE decays since more UEs are being served by the same AP. On the other hand, the gains obtained by the WiFi network in the 4 APs scenario, Figure 7b, are not so expressive as the ones with 10 APs. In the first case with 10 STAs, the mean throughput per user achieved with the blank subframe pattern of 8 ms was 146% higher than the value when no coexistence strategy was used (1.39 Mbps in this case). An interesting point noted is that when the number of AP is decreased and the number of STAs is maintained, the performance of WiFi network is not much affected by the LTE blank subframe allocation, indicating that the performance of WiFi in this case is limited by its own CSMA/CA protocol.

The second set of simulations considered the same number of nodes used in the single floor scenarios, but distributed in a 4-floors building. The results are shown in Figure 8 and Figure 9.

As expected, since this scenario is sparser than the single floor scenario, both LTE and WiFi are able to achieve higher data rates per user. Similar to the results presented on Figures 6 and 7, mean throughput per user in simulations with 10 APs is higher than in simulations with 4 APs for both technologies.

One interesting point on multi-floor simulation results is the blank subframe pattern required to achieve a given throughput per user, in comparison to the single floor case. For instance, by the results shown in Figures 6b and 8b for 10 STAs, in order to achieve a mean throughput per user equal 6 Mbps, 8 blank subframes are needed in the single floor scenario, while the multi-floor scenario requires only 4 blank subframes. Same results were found for the other configurations tested, indicating that the necessary number of coexistence subframes given up by LTE network also varies with the distribution of

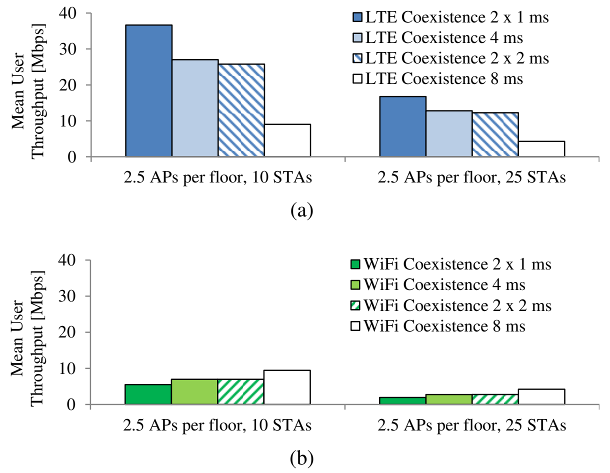


Fig. 8. Multi-floor results with different configurations of blank subframes, 10 APs.: (a) LTE results, 10 or 25 STAs; (b) WiFi results, 10 or 25 STAs.

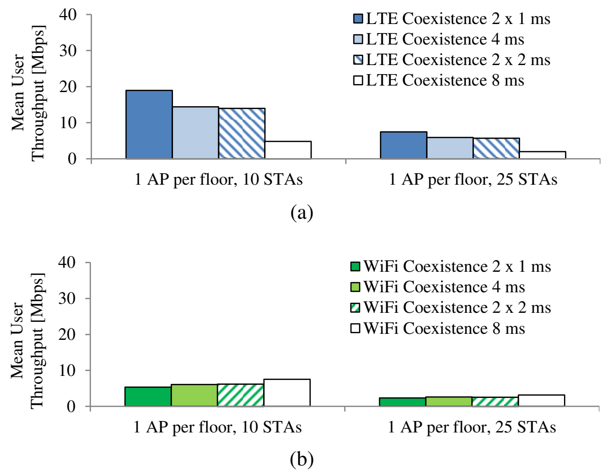


Fig. 9. Multi-floor results with different configurations of blank subframes, 4 APs.: (a) LTE results, 10 or 25 STAs; (b) WiFi results, 10 or 25 STAs.

nodes in the interference scenario.

The disparity between this last set of results for different network deployments shows the importance of the negotiation phase in the coexistence procedure. In order to adapt the number of subframes conceded by the LTE network for coexistence purposes with Wi-Fi in the parameters negotiation phase, both technologies could exchange information about their operational requirements and current network deployment.

V. Conclusions

In this paper, we show some of the challenges faced by coexistence of heterogeneous secondary users. We show that if a WiFi like technology (contention based) were to coexist with a LTE-like technology (scheduled channel access) in such unlicensed bands, the performance of the contention based technology would be severely degraded.

In order to improve the performance of WiFi, we propose a simple coexistence mechanism for LTE-WiFi systems operating on the same band, based on a LTE-Advanced feature introduced for interference coordination in heterogeneous network scenarios. This mechanism consists of blanking some LTE subframes so that WiFi transmission is possible. For assessing the impact of this coexistence mechanism in both networks performances, a semi-static LTE/WiFi system-level simulator was adopted. Two indoor scenarios with multiple configurations of APs (LTE or WiFi) and STAs (or LTE UEs), were evaluated: single floor and multi-floor.

The results show that, in general, blanking LTE subframes increases the throughput per user achieved in WiFi networks. However, one main problem arises with this mechanism: LTE throughput decreases both for losing time resources and from suffering interference of WiFi nodes, which are not able to confine their transmission within the time ceded for coexistence. Therefore, there is a compromise between the time given up by LTE and the throughput gain in WiFi network. In order to select an adequate number of blank subframes, both networks have to consider the network deployment, spatial nodes distribution and minimum operational requirements.

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