Performance Evaluation of LTE and Wi-Fi Coexistence in Unlicensed Bands

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***Abstract*—The deployment of modern mobile systems has faced severe challenges due to the current spectrum scarcity. The situation has been further worsened by the development of different wireless technologies and standards that can be used in the same frequency band. Furthermore, the usage of smaller cells (e.g. pico, femto and wireless LAN), coexistence among heterogeneous networks (including amongst different wireless technologies such as LTE and Wi-Fi deployed in the same frequency band) has been a big field of research in the academy and industry. In this paper, we provide a performance evaluation of coexistence between LTE and Wi-Fi systems and show some of the challenges faced by the different technologies. We focus on a simulator-based system-level analysis in order to assess the network performance in an office scenario. Simulation results show that LTE system performance is slightly affected by coexistence whereas Wi-Fi is significantly impacted by LTE transmissions. In coexistence, the Wi-Fi channel is most often blocked by LTE interference, making the Wi-Fi nodes to stay on the *LISTEN* mode more than 96% of the time. This reflects directly on the Wi-Fi user throughput, that decreases from 70% to ≈100% depending on the scenario. Finally, some of the main issues that limit the LTE/Wi-Fi coexistence and some pointers on the mutual interference management of both the systems are provided.**

***Index Terms*—LTE, Wi-Fi, network coexistence, performance evaluation, system level simulations**

I. Introduction

In recent times, the use of smartphones, tablets and other wireless devices have caused an exponential increase in wireless capacity demands. However, lack of available spectrum has severely restricted the increase in network capacity. One of the most promising techniques for dealing with the lack of available spectrum is the concept of spectrum sharing [1] . Successful deployments using spectrum sharing are usually applied on non-heterogeneous communication systems (WLAN and WPAN ones) [2]. However, it is observed that the coexistence of heterogeneous systems in the same frequency bands causes a meaningful degradation on the system performance (e.g., Wi-Fi and Bluetooth [3], Wi-Fi and ZigBee [4], Wi-Fi and WiMAX [5]).

The lack of coordination and the inability to manage mutual interference is one of the main challenges in the coexistence of different wireless technologies. Although most systems incorporate interference management mechanisms, they are designed to work properly between the same types of networks. These built-in mechanisms become less effective in heterogeneous wireless protocols/standard e.g. which adopt asynchronous time slots, different scheduling modes (Time Division Multiple Access vs. Carrier Sense Multiple Access), disparate transmission/interference ranges, and incompatible communication mechanisms [4]. The coexistence problem is especially important for unlicensed frequency bands as well as the recently opened-up TV White Spaces band (termed TV WS) [6] since different wireless technologies can use these frequency bands.

Several works in coexistence scenarios for heterogeneous systems can be found in literature [7]–[11]. In [7]–[9], the authors address the coexistence between IEEE 802.15 standards and other wireless technologies. In the case of Long Term Evolution (LTE) and WiMAX coexistence, an approach where the multi-mode Base Station (BS) replaces transmission gap in LTE frame with subframe of 802.16m and transmits the resulting dual frame has been proposed in [10]. The multi-mode BS (or centralized BS) can simultaneously operate as LTE Uplink/Downlink (UL/DL) and 802.16m UL/DL. In [11], the LTE deployment on a license-exempt band as part of the pico-cell underlay is investigated as well as coexistence mechanism and other modifications to LTE are discussed.

As coexistence between 802.11 and 802.15.4 radios deployed in Industrial, Scientific, and Medical (ISM) 2.4GHz band has already been established [7], and the recent inclusion of features on LTE standard [12] are promoting its usage on pico and femto cells, it is possible that in the near future coexistence between LTE (-ADV) and Wi-Fi will become important. In this context, when both LTE and Wi-Fi are deployed in the same frequency band, Wi-Fi suffers from interference from LTE. In addition, if Wi-Fi devices are close to any LTE node (eNodeB or UE), then Wi-Fi has potential to interfere with LTE eNodeB and/or UE because of its transmission with maximum available power (currently no power control is available for Wi-Fi). To the best of our knowledge, there is no previous work that explicitly evaluates the network performance of LTE and Wi-Fi systems in coexistence.

This paper presents a performance evaluation of LTE and Wi-Fi coexistence in office scenarios at 900 MHz band. System level simulation results figure out some key coexistence issues. The 900 MHz frequency band was chosen in order to evaluate the coexistence behavior close to a TV WS frequency

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band. Although a specific licensed frequency band is used is this work (i.e., 900 MHz), the conclusions can be extended for any other licensed or unlicensed band.

This paper makes the following contributions: (1) System level performance evaluation for coexistence between LTE and Wi-Fi systems in office scenarios, (2) Analysis of the impact of this coexistence on several network statistics in order to figure out the main issues on this deployment scenario.

The paper is organized as follows. Section II describes the simulation methodology adopted to evaluate LTE and Wi-Fi systems on coexistence scenarios. The simulation environment, used models and key assumptions are also presented in this Section. Performance evaluation results are presented and discussed in Section III. Finally, the conclusions are summarized in Section IV.

II. LTE and Wi-Fi Simulation Models

In order to assess the network performance of LTE and Wi-Fi in coexistence, a semi-static system level simulator was used. The simulator models standard-compliant LTE and IEEE 802.11 (Wi-Fi) multi-cell and multi-user radio networks, including modeling of the network layout, nodes distribution, radio environment, physical layer (PHY), MAC layer and traffic generation.

A. Deployment Scenario

The simulator models two indoor office scenarios, one single floor and another multi-floor. The single-floor scenario has 20 rooms organized in 2 rows, whereas the multi-floor scenario has 30 rooms distributed in 3 floors, as illustrated in Figure 1. Table I lists the main parameters of the deployment scenario used in simulations.

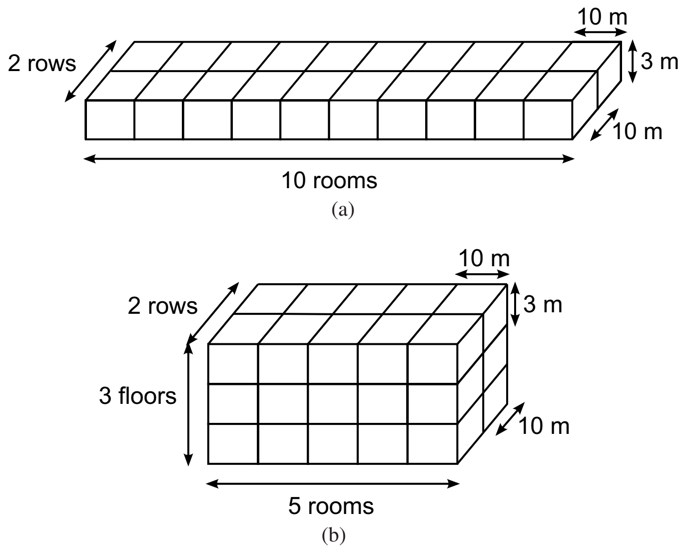


Fig. 1. (a) Single-floor scenario (10 rooms per row, 2 rows, 1 floor); (b) Multi-floor scenario (5 rooms per row, 2 rows, 3 floors).

TABLE I
DEPLOYMENT SCENARIO

Parameters	Value
Scenario	Dual stripe (single-/multi-floor)
System Bandwidth (BW)	20.0 MHz
Center frequency	900.0 MHz
Transmission Power	23.0 dBm
eNodeB/AP height	1.0 m
UE/STA height	1.5 m
Number of Tx/Rx antennas	1/1
Traffic Type	Full-buffer data only
Antenna Type	Isotropic
LTE simulation step	1 ms
Wi-Fi Simulation step	8 μs

B. Channel Models

The results presented in this paper assume an indoor single-/multi-floor environment for modeling the long-term characteristics of the wireless channel. This scenario is characterized by several rooms, single/multi floor, low antennas height and low transmit powers. TGah indoor propagation model [13] is adopted for calculating the signal path loss and shadowing. The fading characteristics of the channel are represented with a single model (Rayleigh fading) for both information-bearing and interfering signals, which ensures that the effects of the multipath propagation are captured for all relevant signals in the network. The main parameters of the channel models are described in Table II.

TABLE II
CHANNEL MODELS

Parameters	Value
Path loss model	TGah Indoor [13]
Breakpoint distance	3 m
Floor attenuation factor	12.9 dB
Lognormal shadowing	μ = 0 dB
	σ = 2 dB (before breakpoint)
	σ = 4 dB (after breakpoint)
	σ = 7 dB (multi-floor path)
Multipath fading	Rayleigh

C. LTE PHY/MAC Models

It is assumed that the LTE TDD (Time-Division Duplex) 10 ms frame is arranged in downlink (DL) and uplink (UL) subframes. The DL/UL subframes ratio is based on the eNodeBs/UEs proportion. All LTE eNodeBs are assumed to be synchronized in order to maintain common frame start times. LTE uses as basic access technique the Orthogonal Frequency-Division Multiple Access (OFDMA). The main OFDMA parameters used in the simulator are standard-compliant, however, the frequency resolution of the LTE model is captured in terms of Physical Resource Blocks (PRBs).

The LTE eNodeB scheduler allocates the two-dimensional (time-frequency) OFDMA resources among the active users. Resource allocation for each LTE subframe is made in a Proportional-Fair fashion, and the Modulation and Coding Scheme (MCS) is chosen using the available Channel Quality Indicator (CQI) from all UEs. Hybrid Automatic Repeat Request (HARQ) is implemented using the stop-and-wait protocol with multiple HARQ channels for every served UE. Chase Combining is used at the UE for successive HARQ retransmissions so that data packets received with error are stored at the receiver and softly combined with following retransmissions. The main LTE PHY/MAC parameters used in the simulator are presented in Table III.

TABLE III
LTE PHY/MAC PARAMETERS

Parameters	Value
PRB bandwidth	180 kHz
Number of subbands	100 (@ 20 MHz of BW)
Subframe duration	1 ms
Frame duration	10 ms
CQI feedback period	1 frame
Scheduling Algorithm	Proportional-Fair (PF)
HARQ Type	Chase Combining
Maximum number of HARQ Retrans.	5
Link-Adaptation Method	SINR-based
UL power control	disabled

D. Wi-Fi PHY/MAC Models

The Wi-Fi PHY uses as transmission scheme the Orthogonal Frequency Division Multiplexing (OFDM). The simulator uses a Wi-Fi frequency resolution which is two times larger than the Wi-Fi subcarrier spacing (i.e., 625 kHz). The Distributed Coordination Function (DCF) is adopted as the basic 802.11 MAC protocol in the simulator. DCF operates based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism, where each Wi-Fi node senses the channel, and if it detects that it is busy, it starts a random backoff. If after this backoff the channel is empty, it starts the packet transmission, otherwise it increases the backoff time. The collision avoidance mechanism currently uses two different thresholds. One is used for determining if the channel is busy due to another Wi-Fi transmission, while the second is used for detecting if the channel is busy due to other source of interference (LTE, in this case). ACK messages are not effectively transmitted on the air interface, but are implicitly modeled for retransmission purposes. MCS is chosen for each transmitting node based on the last available Signal to Interference plus Noise Ratio (SINR) evaluated at this node. Table IV summarizes the main Wi-Fi MAC/PHY parameters used in the simulator.

TABLE IV
WI-FI PHY/MAC PARAMETERS

Parameters	Value
Transmission scheme	OFDM
Subcarrier spacing	312.5 kHz
Frequency granularity	625.0 kHz
MAC protocol	DCF (CSMA/CA)
SIFS period	16 μs
DIFS period	32 μs
ACK period	16 μs
Initial Contention Window (CW) size	15 slot intervals
Maximum CW size	1023 slot intervals
Channel-busy detection threshold (Wi-Fi)	-82 dBm
Channel-busy detection threshold (LTE)	-62 dBm
Link-Adaptation Method	SINR-based

E. Simulation methodology and PHY abstraction

In the considered office scenarios, nodes of each technology (LTE and Wi-Fi) are randomly distributed among the rooms/floors. However, they are not allowed to be deployed in the same room. This is a reasonable assumption since it is unlikely that a LTE femtocell and a Wi-Fi hotspot using the same frequency band are deployed in the same room.

Perfect time and frequency synchronization is assumed for all LTE nodes. UEs/STAs are assigned to the best-serving eNodeB/AP according to their downlink received signal power (considering only path loss and shadow fading). Performance statistics are collected for all users served by the eNodeBs/APs in the simulation.

For physical layer (PHY) abstraction, Shannon-fitting [14] is employed to predict the PHY performance at the system-level. The PHY abstraction represents the wireless link transmission as a set of curves which describes the dependence between the Channel Quality Indicator (CQI) and the Block Error Rate (BLER). In the PHY abstraction of the simulator, the SINR is calculated for all the nodes at each data block inside a packet. Frequency resolution translation is performed to combine the interference mutually caused by LTE and Wi-Fi. A common Link-Adaptation (LA) table with 8 typical MCSs [15] is used for both systems.

III. PERFORMANCE EVALUATION RESULTS

In this section, the coexistence of LTE and Wi-Fi systems in an office environment is analyzed in two specific scenarios, i.e., single-floor and multi-floor. The wireless service is provided by LTE and Wi-Fi networks in accordance with the framework and parameters presented in Section II. The LTE only and Wi-Fi only configurations are taken as reference cases.

Discussions are carried out based on the following network statistics:

- **User Throughput:** amount of packets received correctly for each LTE/Wi-Fi node along the simulation / simulation time;
- **SINR:** mean Signal to Interference plus Noise Ratio (SINR) collected for all received packets along the simulation;
- **Wi-Fi Listen Mode:** percentage of time spent by Wi-Fi nodes for the Carrier Sensing (CS) procedure (CSMA state referred as *LISTEN_MODE*);
- **Wi-Fi Transmit/Receive Mode:** percentage of time spent by Wi-Fi nodes for data transmission/reception packets (CSMA state referred as *TX-RX_MODE*).

The first statistic is used to assess the performance of each system in terms of network transmission capacity. The following statistic is intended to quantify the quality of the wireless link and insights about the system coverage, whereas the last two statistics are used to evaluate the Wi-Fi channel access. For simplicity reasons, LTE eNodeBs and Wi-Fi APs are referenced in all simulation results as APs and LTE UEs and Wi-Fi STAs as STAs.

A. Single-Floor Scenario

Our first analysis considers the single-floor scenario shown in Figure 1a. For this environment, two deployment cases are considered: (1) Sparse deployment, where 4 APs per system (LTE/Wi-Fi) are distributed among the 20 rooms, and (2) Dense deployment, where 10 APs per system are distributed among the 20 rooms.

Figure 2 shows the aggregated (i.e., combined of DL and UL links) mean user throughput for the considered deployment cases. Two sets of number of STAs per system are evaluated, i.e., 10 and 25 STAs. From these results, we observe that LTE system in coexistence mode is slightly affected by Wi-Fi transmissions. For all cases, LTE performance in terms of user throughput is very close to the obtained when LTE stand-alone operation (labeled as LTE only) is employed. The highest LTE user throughput reduction is around 3.85% for 4 APs/10 STAs whereas the lowest one is $\approx$ 0% for 4 APs/25 STAs and 10 APs/10 STAs. On the other hand, coexistence causes a significant degradation on the Wi-Fi system performance. Wi-Fi user throughput reduction is around 70% in the best case (4 APs/25 STAs) and higher than 98% for the case with 10 APs/25 STAs. This happens because Wi-Fi nodes suffer an almost constant and meaningful amount of interference from LTE system along the time. This interference blocks the Wi-Fi channel all the time for most Wi-Fi nodes, making these nodes to stay on *LISTEN_MODE* for a considerable amount of time.

Figure 3 shows the CSMA states usage for all considered cases, where the label "Ref." refers to the percentage of time spent by Wi-Fi nodes in *LISTEN_MODE* for Wi-Fi stand-alone operation (labeled as Wi-Fi only). From this figure, we can observe clearly that Wi-Fi nodes have a meaningful increase in the percentage of time in *LISTEN_MODE* when coexistence mode is in use. For the dense deployment case (10 APs per system), this percentage is even worse, yielding Wi-Fi nodes to stay on *LISTEN_MODE* for around 99% of time, which is reflected on the low user throughputs obtained for this case (i.e., $\approx$ 0.27 Mbps and $\approx$ 0.06 Mbps).

To assess channel link quality in coexistence for the single-floor deployment cases, SINR statistics are considered. Figure 4 shows the SINR reduction due to coexistence suffered by both LTE and Wi-Fi, taking as reference the values obtained in their stand-alone operations. From results shown in Figure 4a, we verify for the all cases that LTE SINR performance is slightly decreased in coexistence mode. For sparse deployments the highest SINR reduction due to coexistence is around 4% and for dense ones is around 3%. This small performance reduction comes from the additional interference generated by Wi-Fi nodes that were able to access the channel. On the other hand, we verify from results shown in Figure 4b that Wi-Fi SINR presents a higher reduction in the coexistence mode due to LTE transmissions. For sparse deployments the range of the mean SINR reduction is between 19% and 23% whereas for dense ones this range is between 17% and 29%.

For the sake of completeness, Figures 5a and 5b show the CDF of the UL Wi-Fi SINR for sparse and dense deployments, respectively. From these results, we can confirm that in general coexistence provides a decreasing on the Wi-Fi SINR performance for both deployments. However, we can observe that in some cases (e.g., 10 APs/10 STAs) Wi-Fi SINR performance is similar or even better. This behavior refers to the fact that LTE transmissions can block several Wi-Fi nodes, removing them from channel contention and then minimizing collisions. As in coexistence only few nodes get channel access for a

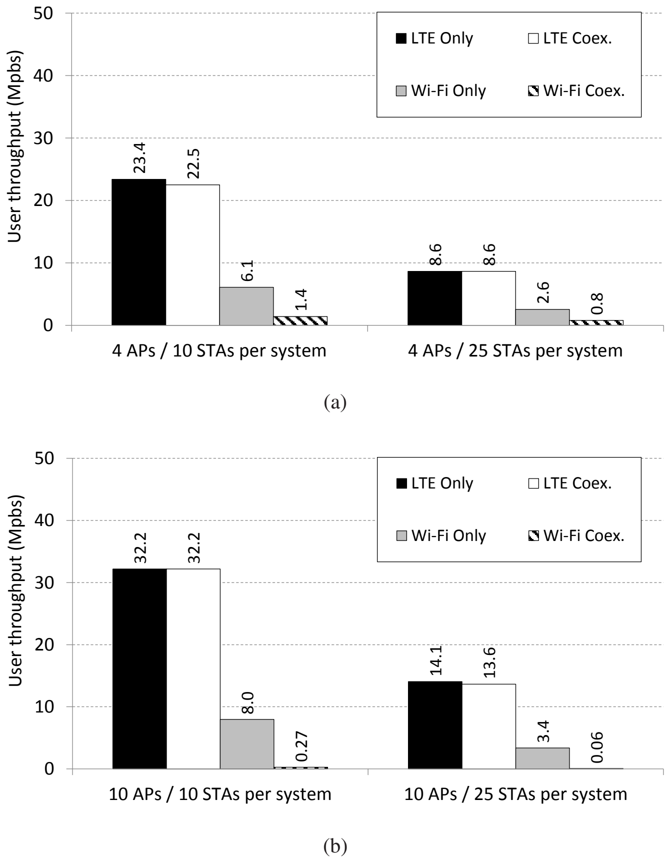


Fig. 2. User throughput performance for single-floor scenario: (a) Sparse deployment; (b) Dense deployment.

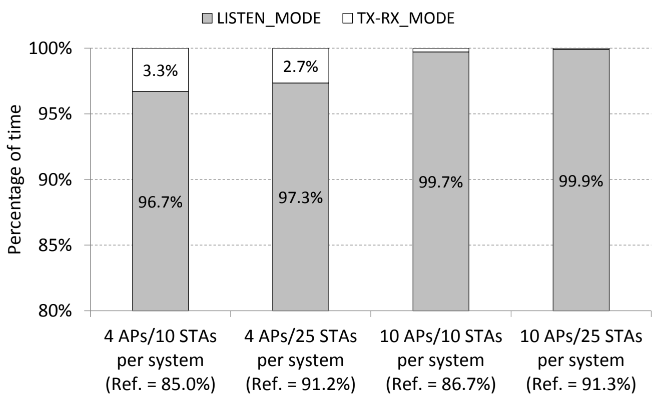
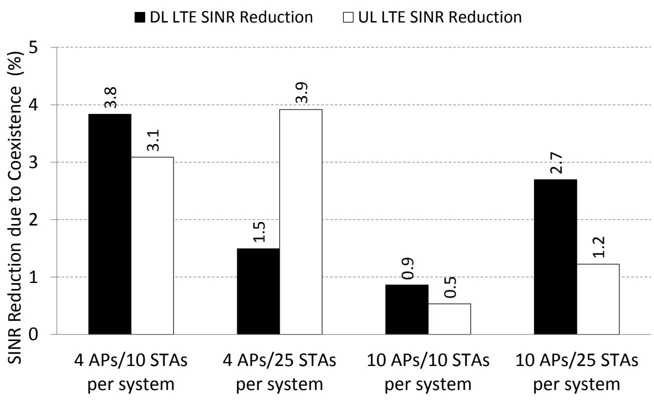
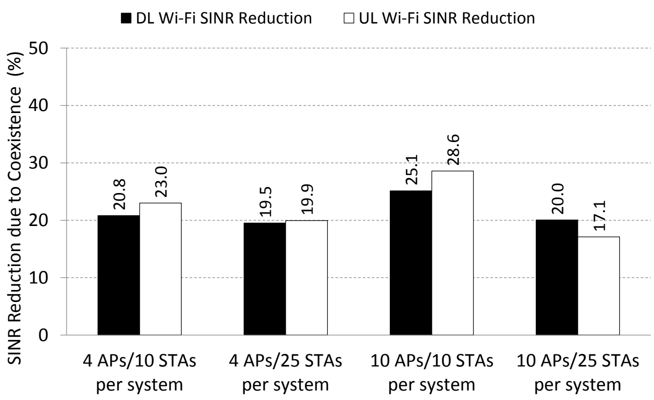


Fig. 3. CSMA states usage for single-floor scenario

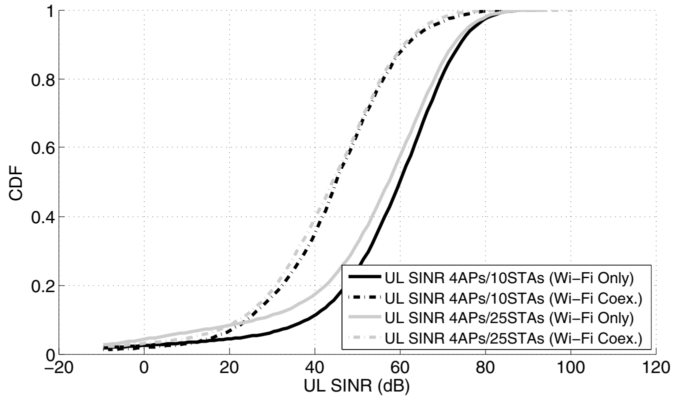


(a)

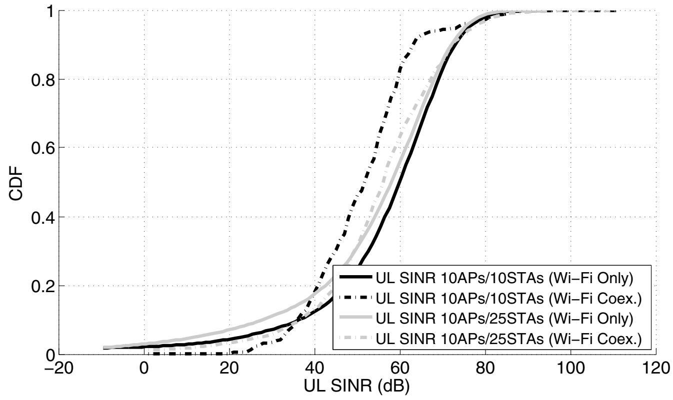


(b)

Fig. 4. Single-floor scenario: (a) LTE SINR performance; (b) Wi-Fi SINR performance.



(a)



(b)

Fig. 5. Cumulative distribution function of the UL SINR: (a) Sparse deployment; (b) Dense deployment.

short period of time, this SINR performance is not reflected on the throughput, as seen in the Figure 2b.

Although the single-floor results bring us a comprehensive understanding about the performance of coexistence between LTE and Wi-Fi systems in office environments, multi-floor results are also of interest, mainly because of the presence of a new variable to be exploited, the floor attenuation. In this context, the next Section presents simulation results for a multi-floor scenario. However, without loss of generality the analysis is carried out only in terms of throughput.

B. Multi-Floor Scenario

For the considered multi-floor scenario shown in Figure 1b, we assume 3 deployment cases: (1) Sparse deployment, where 1 AP per system (LTE/Wi-Fi) is distributed among the 10 rooms of each floor, (2) Moderate Deployment, where 2 APs per system are distributed among the 10 rooms of each floor, and (3) Dense deployment, where 5 APs per system are distributed among the 10 rooms of each floor.

Figure 6 shows the aggregated (DL+UL) mean user throughput for the considered multi-floor cases. The number of STAs for both LTE and Wi-Fi in each deployment case is assumed to be two times the number of APs, i.e., 2, 4 and 10 STAs for sparse, moderate and dense deployments, respectively.

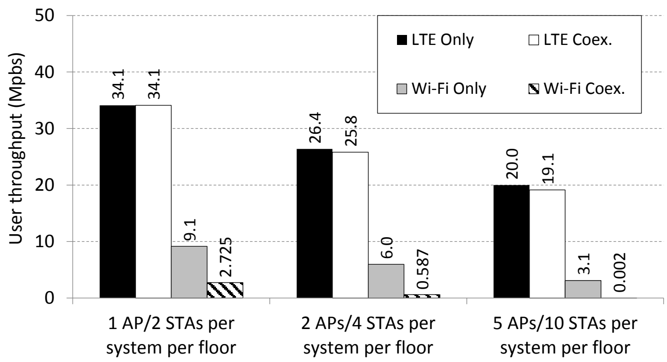


Fig. 6. Throughput performance for multi-floor study cases.

As observed in the single-floor scenario, multi-floor results also show that the Wi-Fi system performance is significantly degraded in the coexistence mode. The Wi-Fi user throughput reduction is increased from around 70% in sparse deployment case (1 AP per system per floor) to almost 100% in the dense one (5 APs per system per floor). Again, this happens because Wi-Fi nodes suffer meaningful interference from LTE that blocks the channel for Wi-Fi access. For the LTE system, the user throughput performance is again slightly impacted by the coexistence with Wi-Fi one for all cases. The LTE throughput reduction is always lower than 4.5% with the best case of $\approx 0.0\%$ obtained for sparse deployment case (1 AP per system per floor).

C. Discussion

Coordination of LTE and Wi-Fi systems may be a promising strategy of deployment in scenarios where the spectrum sharing is mandatory (e.g., TV White Space band). However, as these systems are designed under different MAC/PHY protocols/standards and no coordination to manage the mutual interference between them are defined, several issues need to be addressed to make this coexistence feasible. First of all, LTE systems usually have transmissions in every subframe with meaningful power, blocking the Wi-Fi channel most of time for Wi-Fi nodes around it. On the other hand, when Wi-Fi nodes are able to get the channel, they have potential to interfere with LTE nodes because Wi-Fi usually transmits packets with maximum available power (currently no power control is available). All these effects were observed in our simulations for both scenarios, i.e., single and multi-floor ones. These issues significantly hamper the coexistence between LTE and Wi-Fi systems. However, our results indicated a potential research hot-topic on the mutual interference management for LTE/Wi-Fi coexistence and the need of further studies. Furthermore, recent features included in Release 10 of the LTE specifications, like Enhanced Inter-Cell Interference Coordination (eICIC) techniques, can be exploited to aid this coexistence. The overall objective of the eICIC is to mute certain subframes of one layer of cells in order to reduce the interference to the other layer in heterogeneous network interference scenarios. These muted subframes are called in the LTE standard as Almost Blank Subframes (ABS). ABS together with other strategies to control the mutual interference (e.g., SINR-based power control from LTE side, adaptive channel sensing thresholds from Wi-Fi side and spatial diversity exploitation through multiple antennas techniques) can be combined with some coordination to manage the coexistence of LTE and Wi-Fi systems. This kind of approach has started to be investigated in [16], where LTE/Wi-Fi coexistence is enabled by LTE blank subframe allocation.

IV. Conclusions

In this paper, we conducted a performance evaluation of LTE and Wi-Fi coexistence under similar scenarios using a semi-static LTE/Wi-Fi system-level simulator. Two test scenarios were considered in the experiments: (1) Single-floor and (2) Multi-floor. Furthermore, we considered multiple usage models involving sparse and dense deployments of access points and stations. Our results showed that, in general, LTE outperforms Wi-Fi in similar scenarios (including standalone operation of LTE and Wi-Fi). Wi-Fi performance is further degraded when it operates concurrently with LTE while LTE performance is nearly unchanged. This behavior was caused by the LTE interference at the Wi-Fi side and due to the fundamental limitation of Wi-Fi protocol, namely carrier sensing that blocks the Wi-Fi channel and makes the Wi-Fi nodes to stay on the *LISTEN* mode for a considerable amount of time (i.e., above than 96% of the time for all simulated cases). In general, the coexistence performance depends on the system deployment in terms of spatial distribution of the nodes, number of nodes, antennas type, transmit power and the environment properties (e.g., number of floors, walls, etc.) and coexistence solutions for heterogeneous wireless deployment is becoming an increasingly important area for research.

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