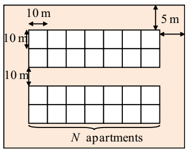
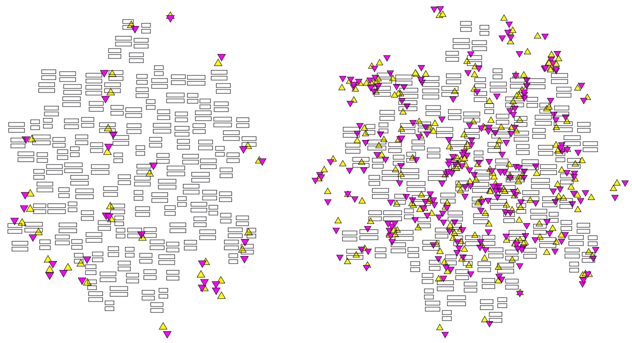


Fig. 2. Bird's-eye view of the urban building block model (each building of N apartments per row has L floors) [10]. N is randomly varied between 5 and 10, and L between 3 and 5, with a 3 m height per floor.



(a) (b)

Fig. 3. Example of random spatial positioning of urban building blocks (yellow) for real outdoor picocell locations [11] in (a) Cologne and (b) London. The outdoor LTE-U picocells are shown in yellow and their associated users in magenta, whereas Wi-Fi APs (not shown here) are deployed indoors.

However, despite the significant initial contributions in [3]–[8] and recent LTE-U coexistence guidelines by 3GPP, a systematic and large-scale network-wide study of LTE-U and Wi-Fi performance in a range of realistic deployment scenarios and network densities, in the unlicensed 5 GHz band, is still missing from the literature. In particular, studies of possibly dense urban deployments, quantifying interference effects and evaluating the success of various coexistence mechanisms, are still required. The key questions that remain unanswered are: (i) is it actually worthwhile for LTE operators to deploy LTE-U from the perspective of the expected throughput, given potential interference with Wi-Fi and other LTE-U networks, (ii) how much would legacy indoor Wi-Fi networks be affected assuming realistic indoor shielding and projected deployment densities, and (iii) which are the most effective strategies to mitigate interference in such scenarios?

In this paper we present the results of our detailed system-level study on the coexistence of LTE-U with indoor residential IEEE 802.11n Wi-Fi operating in the 5 GHz band, thereby obtaining an estimate of the expected performance of LTE-U for a range of possible network densities and deployment scenarios (i.e. indoor LTE-U femtocells and outdoor LTE-U picocells). We consider the effect of LBT and interference-aware channel selection and we evaluate the downlink throughput of LTE-U and Wi-Fi users. We show that both networks benefit from the large number of available channels and inherent indoor shielding at 5 GHz. Additionally, interference-aware channel selection is more efficient than LBT in mitigating the interference between LTE-U and Wi-Fi, but LBT can further mitigate interference among LTE-U base stations (BSs).

The remainder of this paper is organized as follows. Section II presents related work in the literature, Section III describes our system model, and Section IV presents our interference and throughput model. Section V presents the results of our study and Section VI concludes the paper.

II. Related Work

Since Qualcomm first proposed LTE-U [2], several fundamental studies have evaluated the impact of LTE operating in the unlicensed bands and the possible interference effects to existing unlicensed technologies. The authors in [3] analyze the performance degradation of Wi-Fi in the presence of LTE-U, by obtaining numerically the probability of Wi-Fi accessing the channel. The authors conclude that Wi-Fi is significantly affected by conventional LTE operation, due to LTE's almost continuous transmission, which subsequently blocks Wi-Fi. Consistent results are presented in [4], where a single-building indoor scenario in the 900 MHz band is analyzed based on simulations, but no mechanism to enable coexistence is considered. In [5] the authors analyze possible benefits of LTE blank subframe allocation in coexistence scenarios where indoor co-channel Wi-Fi and LTE-U nodes transmit in the 900 MHz band. By contrast, we consider networks operating in the unlicensed 5 GHz band (as recommended by 3GPP), we explicitly model interference in large deployments, and investigate several distributed coexistence mechanisms, namely channel selection schemes and LBT.

The authors in [6] evaluate LTE-U blank subframe allocation and power control, whereas [7] proposes a mechanism similar to blank subframe allocation, which mutes the LTE-U nodes and thus shares the band in time with co-channel Wi-Fi access points (APs) in an indoor scenario with one building and a fixed node density. By contrast, we consider LBT which shares the band in time in a distributed manner, not a scheduled one, and defers transmissions only when interferers are detected.

Similarly to our work, [8] presents the analysis of outdoor and indoor large deployment scenarios for Wi-Fi and LTE-U coexistence. However, the authors assume only a fixed network density and that 80% of the LTE-U users are indoors when the LTE-U BSs are deployed outdoors according to a Poisson point process distribution. Furthermore, channel selection schemes are exclusively applied for the outdoor LTE-U BSs and only the LTE-U user throughput is analyzed in this case. By contrast, we vary the network density over a wide range, we use real outdoor BS locations, and we consider channel selection schemes for both indoor and outdoor scenarios.

III. System Model

In this section we present our system model comprising multiple LTE-U use-case scenarios, different coexistence mechanisms, a detailed network model, and a range of representative network densities. All networks operate in the 5 GHz unlicensed band, with 19 indoor and 11 outdoor 20 MHz channels in Europe [12], [13]. In the remainder of this paper AP denotes both Wi-Fi APs and LTE-U BSs.

A. LTE-U Use-Case Scenarios

We consider two major urban use-case scenarios for LTE-U: (i) indoor LTE-U femtocells, or (ii) outdoor LTE-U picocells. In either scenario we assume coexistence with legacy indoor Wi-Fi APs. All users associated with outdoor LTE-U picocells are located outdoors and all users associated with indoor LTE-U or Wi-Fi APs are placed indoors.

TABLE I. LTE-U COEXISTENCE MECHANISMS CONSIDERED

LTE-U channel selection \ LTE-U channel sharing	w/o LBT	LBT w.r.t. Wi-Fi APs	LBT w.r.t. Wi-Fi and LTE-U APs
random	*rand, on*	*rand, LBTWiFi*	*rand, LBTWiFiLTE*
interference-aware	*sense, on*	*sense, LBTWiFi*	*sense, LBTWiFiLTE*

B. Coexistence Mechanisms and Channel Allocation Schemes

We assume that Wi-Fi operates in its conventional mode and avoids interference by implementing CSMA/CA and random channel selection. We assume that each IEEE 802.11n AP selects randomly one of the 19 indoor 20 MHz channels in the 5 GHz band. For reference, we consider a Wi-Fi *"baseline"* case whereby the Wi-Fi network is not interfered by LTE-U.

For LTE-U, we assume each AP operates on a 20 MHz channel[1], as Wi-Fi does. In indoor scenarios, the total number of 20 MHz channels available is 19, whereas in outdoor scenarios, the total number of available 20 MHz channels is 11.

We consider two main coexistence mechanisms: (i) LBT which shares the channel in time similarly to CSMA/CA, and (ii) interference-aware channel selection which randomly selects one channel unoccupied by legacy Wi-Fi APs[2] (i.e. channels where the received Wi-Fi signal level is below the LTE reference sensitivity power level of -93.5 dBm [15]).

For LBT we further consider two sub-cases: (i) LTE-U APs implement LBT with respect to both LTE-U and Wi-Fi APs, or (ii) LTE-U APs implement LBT only with respect to Wi-Fi APs. We note that for Wi-Fi APs these two sub-cases are transparent, as LTE-U defers to Wi-Fi in both sub-cases. For a thorough evaluation, we also consider the cases when LTE-U (i) implements random channel selection, (ii) does not implement LBT, or (iii) implements combinations of LBT and channel selection mechanisms. Table I shows all considered LTE-U coexistence mechanisms and the related terminology.

In order to gauge the performance degradation for LTE-U from Wi-Fi interference, we also consider as a benchmark the *"baseline"* case of an LTE-U only scenario without interference from Wi-Fi. For the LTE-U *baseline* case each LTE-U AP randomly selects a channel out of all available channels.

C. Network Model

We consider a detailed and realistic network model suitable for both considered use-case scenarios. We model all indoor Wi-Fi and LTE-U AP distributions based on the 3GPP recommendations [10]. We consider a total area of 1.5155 km^2 (i.e. total recommended network coverage area of 7 macro BSs with 500 m inter-site distance [10]), over which building blocks are randomly placed. The APs are randomly located within building blocks defined in 3GPP's dual stripe model, as shown in Fig. 2. All indoor APs work in closed group mode, as this is representative for privately owned and managed devices.

For the outdoor LTE-U picocell locations we use a set of real BS locations from two major European cities, i.e. central London and Cologne, as examples of high and low outdoor cell network densities that are likely to be considered for

[1] We note that LTE systems implement guard bands that reduce the actual used bandwidth of a channel to 18 MHz (100 resource blocks of 180 kHz). We will further take this into account in our throughput model.

[2] If all channels are occupied, LTE-U selects the channel with the lowest Wi-Fi occupancy.

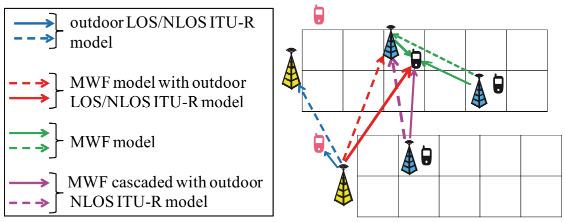


Fig. 4. A subset of the considered network area, showing the propagation models for scenarios with outdoor LTE-U picocells (yellow) and indoor Wi-Fi APs (blue). The solid-line arrows show links between APs and users, and the dashed-line arrows show links between APs. In the alternative use-case of indoor LTE-U APs, the same propagation models as for Wi-Fi APs apply.

future LTE-U picocell deployments. In order to obtain the outdoor locations, we use the data set of BS location estimates based on measurements by user devices, provided by the Mozilla Location Service [11]. Although the selected locations from [11] refer to different generation BSs (i.e. 2G, 3G, and 4G) operating in the licensed spectrum, we assume instead that these are LTE-U picocells, in order to obtain results for a realistic example deployment. As the initial locations in [11] refer to BSs with various coverage ranges (macro, micro, pico), whereas we only study outdoor picocells, we select those BS locations corresponding to a coverage range of up to 300 m. Additionally, we consider only BS locations with minimum 20 measurement observations, in order to obtain more accurate locations. Finally, we overlay the BS locations[3] on the building layout described above, wherein the legacy indoor Wi-Fi APs operate. We consider random picocell heights between 9 and 11 m, such that they are lower than the mean building height. By way of example, in Fig. 3 we show a network realization for the two considered outdoor LTE-U picocell location sets. The outdoor users are randomly located within the coverage area of the picocell they are associated with, at a maximum distance of 50 m from the picocell, at a height of 1.5 m [16]. We note that we do not consider LTE-U users outside the picocell coverage area, as they would typically be served by other (micro/macro) BSs, likely operating in the licensed spectrum.

The LTE-U and Wi-Fi APs were deployed with various densities, so as to capture realistic current and future scenarios. For the indoor Wi-Fi APs we have considered two densities: 500 or 5000 APs/km^2. We note that these network densities are consistent with the Wi-Fi measurements in [14], where it was found that in central Cologne there are currently about 500 and 5000 APs/km^2 operating in the 5 GHz and 2.4 GHz band, respectively. We consider the higher network density for the 2.4 GHz band to be a plausible future density for the 5 GHz band. For the indoor LTE-U femtocells we consider the following comparable network densities to be representative: 100, 500, and 5000 APs/km^2. For the outdoor LTE-U picocells we vary the network density based on the number of operators that deploy the cells throughout the considered areas. For the central Cologne locations, where the measurements in [14] were conducted, there are 4 operators that own 13, 11, 4, and 3 cells, respectively. For the central London locations there are 7 operators that own 82, 44, 31, 21, 17, 16, 12 cells, respectively.

We assume different propagation models according to different link types in our scenarios, as shown in Fig. 4. For out-

[3] When doing so, we ensure that all picocells are outdoors, by moving them outside the closest external wall of the building, in case they overlap with any.

door links we consider either the ITU-R model for line-of-sight (LOS) propagation within street canyons, or the ITU-R non-line-of-sight (NLOS) model for over roof-top propagation [16]. For indoor links we use the multi-wall-and-floor (MWF) model with the respective parameters in [17], and we select a building entry loss of 19.1 dB for the external walls [16]. For outdoor to indoor links or indoor to outdoor links we consider cascaded models of indoor and outdoor propagation models. We assume log-normal shadowing with a standard deviation of 4 dB for indoor links and 7 dB for all other links [18].

IV. Throughput and Interference Model

To realistically estimate LTE-U and Wi-Fi performance, we carefully consider multiple interference sources and we base our analysis on the downlink user throughput. For simplicity, we assume only one user per AP and thus we obtain the estimated throughput per AP, which in real scenarios can be further shared among multiple associated users. We assume full-buffered downlink traffic, thus considering a worst-case interference scenario for the users.

A. Wi-Fi

As the considered Wi-Fi and LTE-U networks operate over the same channels, Wi-Fi users are interfered in the downlink by both Wi-Fi APs and LTE-U APs. We calculate the signal-to-interference-and-noise-ratio (SINR) and throughput for Wi-Fi users based on the method in [19], which considers the CSMA/CA MAC protocol for interfering co-channel APs. The contention domain is the area around an AP x in which CSMA/CA prevents all other co-channel APs from transmitting simultaneously. Two co-channel Wi-Fi APs are in the same contention domain if the signal they receive from each other is stronger than the carrier sense threshold, specified for IEEE 802.11n as -82 dBm [12]. Equivalently, a Wi-Fi AP defers to other co-channel technologies when the received signal strength exceeds the threshold of -62 dBm; if so, we consider LTE-U APs to be in the Wi-Fi AP's contention domain.

In order to account for other APs in its contention domain, we assume that the fraction of time an AP x is granted the channel is roughly equal to the inverse of the sum of the number of Wi-Fi and LTE-U APs in its contention domain [19], [20], $|\mathbf{C}_x^j|$ and $|\mathbf{D}_x^j|$, respectively. Additionally, Wi-Fi or LTE-U APs located outside the contention domain of AP x interfere with AP x by decreasing its SINR. Thus the throughput of user u associated with AP x is approximated as

$$R_u^{WF} = \frac{1}{|\mathbf{C}_x^j| + |\mathbf{D}_x^j|} \rho_{WF}(SINR_u^{WF}), \tag{1}$$

where ρ_{WF} is the auto-rate function specified in the IEEE 802.11n standard [12], mapping the SINR to the throughput. We denote $\mathbf{C}_y^j = \mathbf{C}^j \setminus \mathbf{C}_x^j$, where $\mathbf{C}^j$ the set of all Wi-Fi APs transmitting on channel j and $\mathbf{C}_x^j$ the set of all Wi-Fi APs in the contention domain of AP x. Similarly, $\mathbf{D}_y^j = \mathbf{D}^j \setminus \mathbf{D}_x^j$, where $\mathbf{D}^j$ is the set of all LTE-U APs transmitting on channel j and $\mathbf{D}_x^j$ is the set of all LTE-U APs in the contention domain of AP x. The SINR of user u associated to AP x is given by

$$SINR_u^{WF} = \frac{P^{WF}(L_{u,x})^{-1}}{N_0 + \sum\limits_{y \in \mathbf{C}_y^j} P^{WF}(L_{u,y})^{-1} + \sum\limits_{y \in \mathbf{D}_y^j} P^{LT}(L_{u,y})^{-1}}, \tag{2}$$

where N_0 is the noise power (with a thermal noise density of -174 dBm/Hz), P^{WF} is the Wi-Fi AP transmit power, P^{LT} is the LTE-U AP transmit power, $L_{u,x}$ is the path loss from user u to its associated AP x, and $L_{u,y}$ from user u to AP y.

Additionally, if the LTE-U APs inside the contention domain of a co-channel Wi-Fi AP are *not* implementing the LBT mechanism, we assume that the LTE-U APs are continuously transmitting and the respective Wi-Fi AP is thus continuously blocked and stops transmitting; in this case, $R_u^{WF} = 0$.

B. LTE-U pico- and femtocells

The LTE-U users are interfered in the downlink by other LTE-U and Wi-Fi APs. As detailed in Section III-B, when considering channel time sharing, for LTE-U there are two cases: (i) *on* and (ii) *LBT*. In the *LBT* case, the LTE-U APs defer transmitting in case the received signal from another co-channel AP is higher than -62 dBm. Thus, the *LBT* case for LTE-U has essentially the same behavior as the CSMA/CA MAC protocol for Wi-Fi. Thus, similarly to Wi-Fi, we define a contention domain and for the *LBT* case we calculate the SINR at user u associated with AP x as

$$SINR_u^{LT} = \frac{P^{LT}(L_{u,x})^{-1}}{N_0 + \sum\limits_{y \in \mathbf{A}_y^j} P^{LT}(L_{u,y})^{-1} + \sum\limits_{y \in \mathbf{B}_y^j} P^{WF}(L_{u,y})^{-1}}, \tag{3}$$

where $\mathbf{A}_y^j = \mathbf{A}^j \setminus \mathbf{A}_x^j$, where $\mathbf{A}^j$ is the set of all LTE-U APs transmitting on channel j and $\mathbf{A}_x^j$ the set of all LTE-U APs in the contention domain of AP x, $\mathbf{B}_y^j = \mathbf{B}^j \setminus \mathbf{B}_x^j$, where $\mathbf{B}^j$ is the set of all Wi-Fi APs transmitting on channel j and $\mathbf{B}_x^j$ the set of all Wi-Fi APs in the contention domain of AP x.

For the *on* or *LBTWiFi* cases in Table I, LTE-U users incur SINR-reducing interference from all other co-channel LTE-U APs, not just from those outside the contention domain. However, for both *LBTWiFi* and *on* cases, LTE-U incurs interference only from Wi-Fi APs outside the contention domain, as the Wi-Fi APs in the same contention domain as LTE-U APs always defer to LTE-U.

For LTE-U we map the SINR to the throughput of LTE-U user u with the auto-rate function ρ_{LT} and we obtain the throughput per user by dividing by the sum of the number of LTE-U and Wi-Fi APs in the same contention domain, $|\mathbf{A}_x^j|$ and $|\mathbf{B}_x^j|$, respectively,

$$R_u^{LT} = \frac{1}{|\mathbf{A}_x^j| + |\mathbf{B}_x^j|} \rho_{LT}(SINR_u^{LT}). \tag{4}$$

If LTE-U operates in the *on* case, then $\mathbf{A}_x^j = \mathbf{B}_x^j = \varnothing$ for all x and all j. If LTE-U implements *LBTWiFi*, then $\mathbf{A}_x^j = \varnothing$ for all x and all j. For the LTE-U system we adopt as the auto-rate function the mapping between SINR and spectral efficiency in [21].

V. Results and Analysis

In this section we present our simulation results from extensive Monte Carlo system-level simulations in MATLAB of LTE-U and Wi-Fi network-wide performance, based on the scenarios and models outlined in Sections III and IV. For each scenario and network density we present the results from 40 random network realizations. We assume that all APs transmit with a power of 23 dBm, unless specified otherwise.

A. *Indoor LTE-U Femtocell Use-Case Scenario*

Fig. 5 shows the throughput distribution (as the cumulative distribution function, CDF) per user for the indoor LTE-U scenario, for a range of LTE-U and Wi-Fi network densities, for all considered cases in Table I. For lower network densities in Fig. 5(a) and Fig. 5(b) almost all users achieve the maximum throughput regardless of the coexistence technique applied[4]. This is due to the large number of channels that the APs can randomly select from and the shielding provided by the indoor walls of the buildings, effectively isolating APs and preventing mutual interference. This suggests that for these network densities, high performance for LTE-U and legacy Wi-Fi networks is achieved even without coexistence mechanisms.

By contrast, for considerably higher network densities (i.e. 5000 APs/km^2) in Fig 5(c), implementing *LBT* or *sense* for LTE-U has a noticeable impact on the user throughput. From the Wi-Fi perspective, the same user throughput is achieved for the Wi-Fi *baseline* case when no LTE-U network is deployed as for the case when LTE-U selects the least interfered channel. This suggests that if the interference-aware *sense* coexistence mechanism is implemented, LTE-U does not affect the legacy Wi-Fi network at all. However, worse performance results are obtained for Wi-Fi if LTE-U implements only LBT on randomly chosen channels (as proposed in [8], [9]): 26% of the Wi-Fi users have a lower throughput than the maximum, compared to 17% in the previous case. LTE-U with LBT on randomly chosen channels is efficient only for about 10% of the Wi-Fi users, i.e. users with a throughput below 30 Mbps. From the LTE-U user throughput perspective, implementing *sense* also achieves comparable performance to LTE-U *baseline* and further applying LBT on the least interfered channel does not improve the results, since the number of channels that LTE-U detects as unoccupied by legacy Wi-Fi is already high enough (i.e. at least 7). This suggests that *sense* is the most efficient coexistence mechanism for the indoor scenario. The results for the number of unoccupied channels sensed by LTE-U are summarized for all scenarios in Table II.

We note that high LTE-U network densities can also be interpreted as the coexistence of several LTE-U femtocell networks deployed by multiple operators. Additionally, techniques involving LTE-U interference-aware channel selection can be beneficial in scenarios where LTE-U coexists in the 5 GHz band with legacy technologies other than Wi-Fi, that do not implement LBT-like mechanisms to share the channel in time.

As in reality the building structure shielding may vary, in Fig. 6 we also show the results for a worst-case bound indoor scenario without internal walls. Fig. 6(a) shows that implementing *sense* achieves a high Wi-Fi throughput, comparable to the Wi-Fi *baseline* case, but *sense* is unfair to the LTE-U users (about 60% of them experience 0 Mbps). Further, results in Fig. 6(b) suggest that two different approaches, with possible regulatory implications, can be taken in terms of coexistence mechanisms, depending on the intended LTE-U coexistence design: (i) if the primary aim is to protect legacy Wi-Fi from LTE-U interference, then *sense* is able to isolate Wi-Fi from LTE-U and LBT can be further implemented to share the channel in time among co-channel LTE-U APs, such

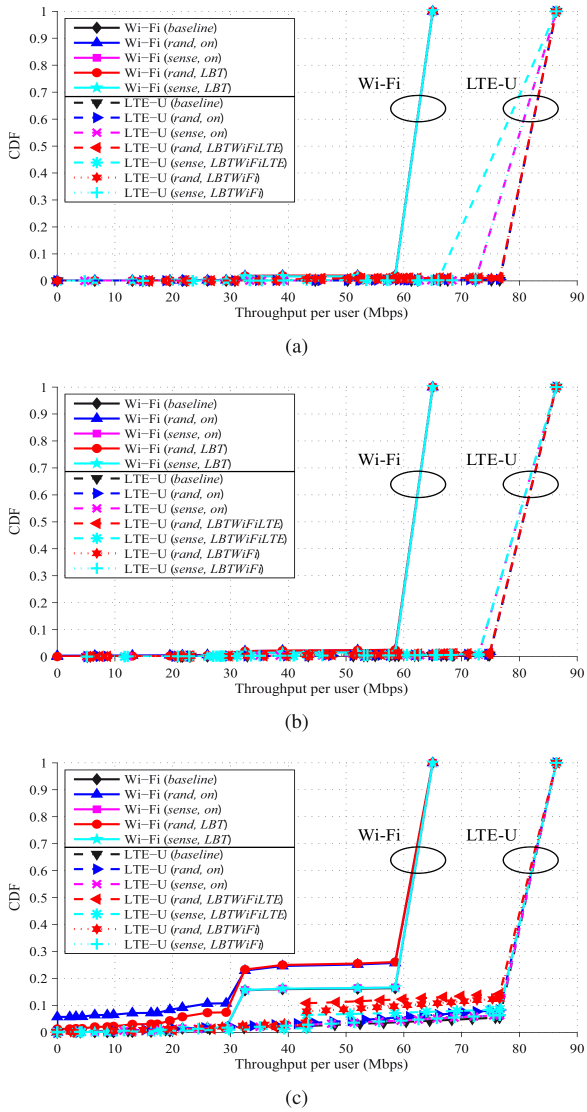


Fig. 5. Throughput distribution per user for Wi-Fi and LTE-U with all coexistence techniques in Table I, in the indoor scenario, for network densities of (a) 500 Wi-Fi and 100 LTE-U APs/km^2, (b) 500 Wi-Fi and 500 LTE-U APs/km^2, and (c) 5000 Wi-Fi and 5000 LTE-U APs/km^2.

that they achieve a reasonable throughput performance; (ii) if on the other hand LTE-U assumes that Wi-Fi will suffer from additional LTE-U interference such that both technologies get a fair share of the channels in time, then LTE-U can also implement the conventional Wi-Fi behavior, i.e. *rand* and LBT. However, for the same behavior, LTE-U achieves a higher throughput than Wi-Fi due to its better PHY spectral efficiency.

B. *Outdoor LTE-U Picocell Use-Case Scenario*

Fig. 7 shows the user throughput distribution for all considered cases in Table I, for the outdoor central London LTE-U scenario, for a range of Wi-Fi network densities. Owing to the high building penetration loss at 5 GHz, the performance of the indoor Wi-Fi network is not influenced by the outdoor picocells regardless of the network densities, the coexistence mechanisms that are applied to LTE-U, or the LTE-U transmit power; thus we show a single throughput curve for Wi-Fi users.

[4]We note that in Fig. 5(a) some of the curves for LTE-U apparently perform worse than the others, but this is just the effect of having very sparse APs, so a narrower and sparser range of throughput values is achieved. This effect is less pronounced in Fig. 5(b) where the LTE-U network density is higher.

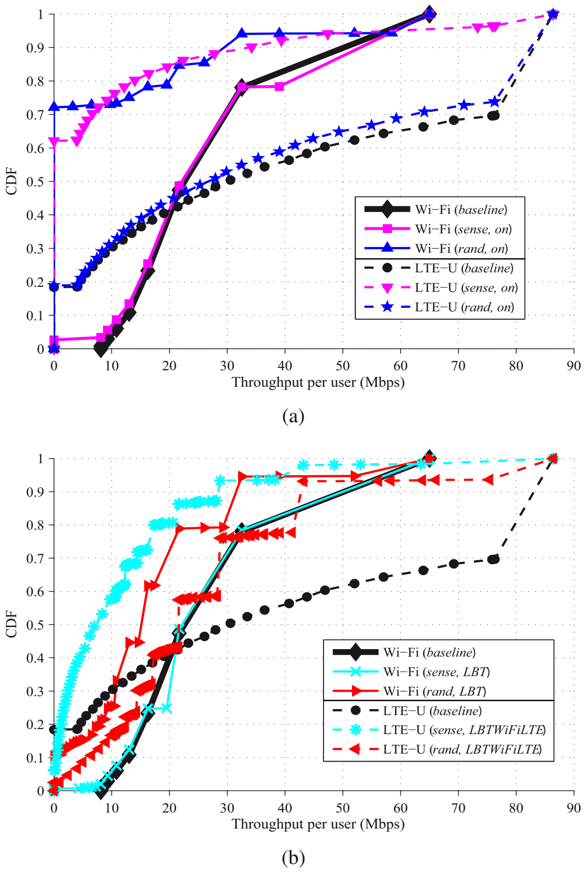


Fig. 6. Throughput distribution per user for Wi-Fi and LTE-U in the indoor scenario without internal walls, for a network density of 5000 Wi-Fi APs/km^2 and 5000 LTE-U APs/km^2, with (a) LTE-U *on*, and (b) LTE-U *LBT*.

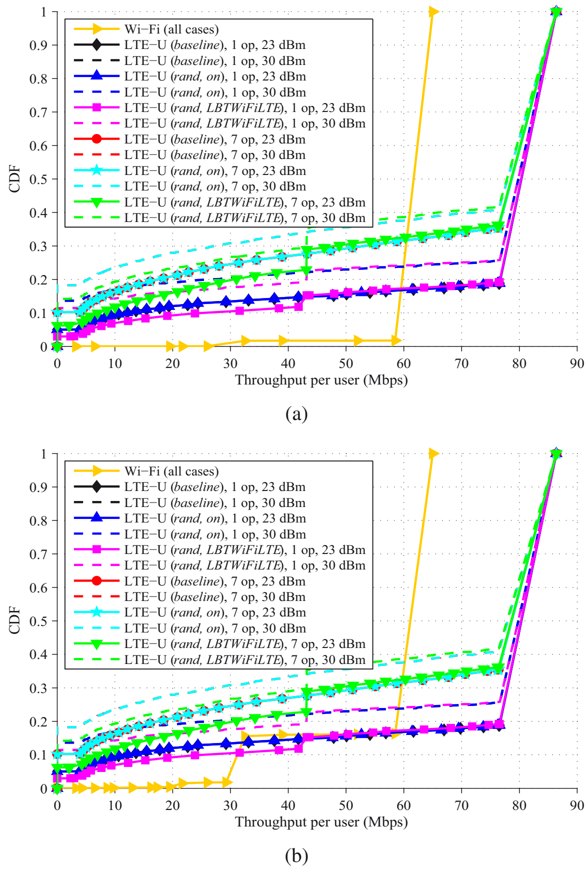


Fig. 7. Throughput distribution per user for Wi-Fi and LTE-U with all coexistence techniques as defined in Table I, in the London outdoor scenario, for 1 or 7 LTE-U operators, for LTE-U transmit powers of 23 dBm or 30 dBm, and Wi-Fi densities of (a) 500 Wi-Fi APs/km^2, and (b) 5000 Wi-Fi APs/km^2.

TABLE II. NUMBER OF CHANNELS UNOCCUPIED BY WI-FI, AS DETECTED BY LTE-U

Scenario / Wi-Fi density [APs/km^2]	indoor with walls	indoor w/o walls	outdoor
500	14-19	12-19	9-11
5000	7-19	0-10	9-11

Comparing Fig. 7(a) and Fig. 7(b), we note that the outdoor LTE-U network is also not influenced by the density of the indoor Wi-Fi network, therefore choosing the least interfered channel does not bring improvements, so *sense* is not shown here. Consequently, the outdoor LTE-U performance analysis can be conducted separately from indoor Wi-Fi.

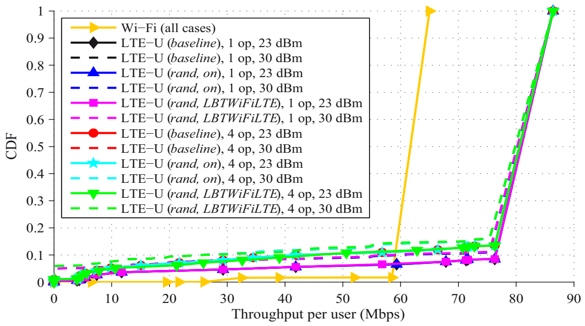
Thus we are interested in evaluating the performance of LTE-U outdoor picocells in Fig. 7 when multiple LTE-U operators have nearby networks. In case only one operator deploys LTE-U APs, applying LBT with respect to the other LTE-U picocells only slightly increases the throughput for users with throughput below 43 Mbps. However, when multiple (7) operators deploy LTE-U networks, the interference among LTE-U APs is subsequently increased. For such higher network densities, implementing LBT is justified, as LBT's contribution to increasing the user throughput is more pronounced.

Since a higher outdoor transmit power than 23 dBm is allowed and this may result in increased user throughput, we also consider $P^{LT} = 30$ dBm for the outdoor LTE-U picocells. However, our results show a worse network performance for the higher transmit power, since at 23 dBm the LTE-U user received power is already high enough to achieve a high throughput, so increasing the transmit power only increases the outdoor LTE-U to LTE-U interference.

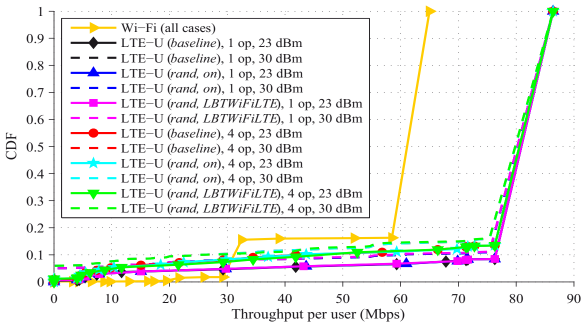
Fig. 8 shows the user throughput distribution for the central Cologne scenario with outdoor LTE-U picocells and users. The trends are similar to those for the central London scenario. However, we note that only randomly selecting one of the 11 outdoor channels is enough to achieve high throughput for LTE-U users, due to the overall low picocell network density, though LBT does not harm LTE-U performance.

C. Discussion

As LTE-U is intended to operate in the unlicensed spectrum, other unlicensed frequency bands than 5 GHz could also be considered for LTE-U. One example is the 2.4 GHz ISM band, which comprises 3 non-overlapping channels of 20 MHz and which is also used by Wi-Fi. However, our results show that the good throughput performance achieved by Wi-Fi and LTE-U when coexisting in the 5 GHz band is largely due to (i) the large number of non-overlapping channels in the 5 GHz band and (ii) the higher propagation losses at 5 GHz due to the intrinsic properties of transmissions at higher frequencies. Consequently, our results suggest that selecting the unlicensed



(a)



(b)

Fig. 8. Throughput distribution per user for Wi-Fi and LTE-U with all coexistence techniques as defined in Table I, in the Cologne outdoor scenario, for 1 or 4 LTE-U operators, for LTE-U transmit powers of 23 dBm or 30 dBm, and Wi-Fi densities of (a) 500 Wi-Fi APs/km^2, and (b) 5000 Wi-Fi APs/km^2.

5 GHz band for LTE-U operation is a favorable option.

VI. Conclusions

In this paper we presented a system-level throughput performance evaluation of LTE-U and IEEE 802.11n Wi-Fi legacy indoor networks operating in the 5 GHz band in two major realistic coexistence scenarios: indoor LTE-U femtocell and outdoor LTE-U picocell deployments. We analyzed the effectiveness of listen-before-talk and interference-aware channel selection in LTE-U networks for coexisting with legacy indoor Wi-Fi and other LTE-U networks deployed by multiple operators. We considered a range of realistic network densities, real outdoor picocell locations from two European cities, realistic propagation effects, multiple available channels, and several transmit power levels for the outdoor LTE-U picocells. Our results show that in all considered coexistence scenarios both Wi-Fi and LTE-U networks benefit from the large number of available channels in the 5 GHz band, as the co-channel interference is limited due to low per-channel occupation. Our results thus suggest that deploying LTE-U with a random channel selection scheme is feasible for lower network densities. Additionally, for typical indoor deployments of high density, implementing LTE-U interference-aware channel selection with respect to Wi-Fi is superior to LBT in terms of achieved throughput for both technologies. In the less likely cases when the indoor building shielding is low, the adopted coexistence mechanisms depend on the intended behavior of LTE-U: if LTE-U is to protect Wi-Fi, interference-aware channel selection isolates Wi-Fi, and LBT among LTE-U femtocells ensures a reasonable LTE-U throughput; otherwise, if Wi-Fi is to suffer from additional interference for fair channel sharing in time with LTE-U, then LBT *only* is preferable. In outdoor LTE-U picocell scenarios, LTE-U and Wi-Fi are isolated from each other due to the large signal attenuation from external building walls and LBT can be further used to increase the LTE-U throughput by sharing the outdoor channels in time between LTE-U picocells deployed by multiple operators. In our future work we will investigate fine-tuning channel selection and LBT carrier sense threshold for improving LTE-U and Wi-Fi user throughput in coexistence scenarios.

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