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LTE in Unlicensed Bands Is Neither Friend nor Foe to Wi-Fi

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ABSTRACT Proponents of deploying LTE in the 5 GHz band for providing additional cellular network capacity have claimed that LTE would be a better neighbour to Wi-Fi in the unlicensed band, than Wi-Fi is to itself. On the other side of the debate, the Wi-Fi community has objected that LTE would be highly detrimental to Wi-Fi network performance. However, there is a lack of transparent and systematic engineering evidence supporting the contradicting claims of the two camps, which is essential for ascertaining whether regulatory intervention is in fact required to protect the Wi-Fi incumbent from the new LTE entrant. To this end, we present a comprehensive coexistence study of Wi-Fi and LTE-in-unlicensed, surveying a large parameter space of coexistence mechanisms and a range of representative network densities and deployment scenarios. Our results show that, typically, harmonious coexistence between Wi-Fi and LTE is ensured by the large number of 5 GHz channels. For the worst-case scenario of forced co-channel operation, LTE is sometimes a better neighbour to Wi-Fi—when effective node density is low—but sometimes worse—when density is high. We find that distributed interference coordination is only necessary to prevent a "tragedy of the commons" in regimes where interference is very likely. We also show that in practice it does not make a difference to the incumbent what kind of coexistence mechanism is added to LTE-in-unlicensed, as long as one is in place. We therefore conclude that LTE is neither friend nor foe to Wi-Fi in the unlicensed bands *in general*. We submit that the systematic engineering analysis exemplified by our case study is a best-practice approach for supporting evidence-based rulemaking by the regulator.

INDEX TERMS LTE, Wi-Fi, IEEE 802.11, unlicensed, coexistence, spectrum regulation.

I. INTRODUCTION

Deploying LTE in the unlicensed 5 GHz band has recently emerged as a way to address growing data traffic volumes in cellular networks. Proponents have gone so far as to assert that LTE in the unlicensed bands would not only deliver better performance to its own users than relying on Wi-Fi offloading, but that it would also improve the performance of existing Wi-Fi networks [1], [2]. Namely, LTE-in-unlicensed is claimed to be a better unlicensed neighbour to Wi-Fi than Wi-Fi is to itself. On the other side of what has become a heated debate, the Wi-Fi community has objected that LTE will be detrimental to Wi-Fi networks [3], i.e. that LTE will not be a friend, but rather a foe to Wi-Fi. (The potential for LTE-in-unlicensed to be used in anti-competitive ways is beyond the scope of this paper.) Unfortunately, there has been a lack of transparent, reproducible, systematic engineering analysis submitted as evidence of such claims, by either lobbying camp.

Various mechanisms have been proposed to ensure harmonious coexistence of LTE with Wi-Fi, the key variants being the LBT (listen-before-talk) based LAA (license assisted access) [4] and the duty-cycle based LTE-U [1]. However, the limited industry reports (e.g. [1]) evaluating the impact of LTE-in-unlicensed variants on Wi-Fi are very vague on the exact assumptions and scenarios underlying their results, whereas existing academic research (see e.g. literature review in [5]) typically focuses on optimizing specific aspects of coexistence mechanisms. Consequently, the Federal Communications Commission (FCC) in the US has taken the unusual step—given its traditionally strong technology-neutral stance—of issuing a Public Notice [6] requesting comments on how LTE-in-unlicensed will coexist with other technologies, including Wi-Fi.

The burning public policy question is whether *regulatory action* is required to protect Wi-Fi, as the soft incumbent[1] of the unlicensed band, from the new entrant LTE technology. Specifically, key engineering questions that the spectrum regulator needs answered to make a reasoned policy decision are: (i) under what circumstances is LTE-in-unlicensed a friend or a foe to Wi-Fi; (ii) does the LTE-in-unlicensed coexistence mechanism, e.g. LTE-U vs. LAA, matter; (iii) how sensitive are the conclusions to the network scenarios considered; and (iv) what is the typical vs. worst-case coexistence performance?

In this paper, we study coexistence of Wi-Fi with a variety of candidate LTE-in-unlicensed entrants for different network densities and deployment scenarios, in order to identify whether or where issues warranting regulatory intervention may arise. Our results show that, for realistic network densities, near-perfect coexistence between Wi-Fi and LTE-in-unlicensed is ensured simply by virtue of the large number of 5 GHz channels, so that co-channel operation is easily avoided. For the worst-case scenario of forced co-channel operation—or equivalently, locally higher-than-typical network density—LTE is sometimes a better neighbour to Wi-Fi than a Wi-Fi entrant, but sometimes worse. Beyond this LTE/Wi-Fi case study, we argue that such a systematic engineering analysis, exploring a large design parameter space [7] for entrant technologies and scenarios, is a best-practice approach *in general* for supporting evidence-based rulemaking by the regulator.

II. METHODOLOGY & SCENARIOS

In our case study an entrant LTE-like system coexists with incumbent Wi-Fi operation in the 5 GHz unlicensed band. We assume the incumbent access points[2] (APs) and their associated users are always ***Wi-Fi*** devices, implementing the PHY layer of IEEE 802.11n and LBT[3] with random binary exponential backoff at the MAC layer [8]. In order to broadly yet systematically evaluate the potential impact on incumbent APs coexisting with likely entrant AP variants in different deployment scenarios, we explore a large design parameter space for entrant technologies, and we evaluate the network performance for several distinct deployment scenarios, for different incumbent and entrant AP densities, as summarized in Table 1. We perform a coexistence analysis for each considered case by estimating the *downlink throughput per AP*[4] based on Monte Carlo simulations in MATLAB. For simplicity, we assume each AP (incumbent or entrant) has one associated user and that traffic is downlink and full-buffered. Thus, we report the per-AP throughput by measuring the throughput of its associated user.[5]

We argue that the systematic engineering analysis exemplified by our case study is best-practice for facilitating evidence-based discussion among different stake-holders and supporting rulemaking by the regulator. The key aspect of the methodology we advocate is to describe the proposed technologies, scenarios, performance metrics, and evaluation methods such that the results are readily reproducible by third parties. Moreover, the analysis ought to be conducted using the best publicly available knowledge and consider a broad parameter space at an abstraction level that provides sufficiently accurate yet generalizable conclusions.

We note that for evaluating the regulatory implications of potential coexistence issues during the pre-standardization stage of new entrant technologies like LTE-in-unlicensed, it is also crucial to select a *scalable* analysis model which can produce generalizable results that characterize the proposed technology at the network level. At such a stage any existing entrant devices implement pre-standard or proprietary algorithms and are typically not available for commercial use or testing. Therefore, no decision of general interest and relevance can be made based solely on illustrative proof-of-concept measurements, e.g. [2], using such devices. It follows that a measurement-based methodology *alone* cannot answer the public policy question of whether regulatory intervention is required to ensure harmonious coexistence between LTE and Wi-Fi in the unlicensed bands, given the network-wide effects that should be taken into account for various candidate LTE-in-unlicensed variants, representative scenarios, and network densities. We thus argue that to support evidence-based rulemaking, it is imperative to use scalable models that survey a large parameter space and enable a comparative and transparent engineering analysis.

A. ENTRANT TECHNOLOGIES & COEXISTENCE MECHANISMS

We model all entrant technologies by varying the relevant key parameters at the PHY and MAC layers, as specified in Table 1. We consider six variants for the entrant APs and users. The first three entrant variants represent the key flavours of LTE-in-unlicensed that have emerged in various industry and research discussions on LAA [4] and LTE-U [1]: **(i)** ***LAA*** with an LTE PHY layer and LBT at the MAC layer; **(ii)** ***LTE-U fixed 50% duty cycle*** with an LTE PHY layer and a fixed 50% duty cycle MAC; and **(iii)** ***LTE-U adaptive duty cycle*** with an LTE PHY layer and an adaptive duty

[1] We adopt the term *incumbent* to reflect the status of Wi-Fi as the dominant current technology in the unlicensed band, and the resulting expectation of Wi-Fi stakeholders that its operation should not be degraded by an entrant technology beyond what further Wi-Fi densification would do. However, both LTE entrants and Wi-Fi incumbents have *equal* rights in the unlicensed band.

[2] We use the term "access point" to refer to both Wi-Fi APs and LTE-in-unlicensed base stations, since both belong to small-cell infrastructure networks with similar functionalities.

[3] Since the CSMA/CA MAC mechanism implemented by IEEE 802.11 Wi-Fi is a version of the more general LBT mechanism, we also refer to it as LBT.

[4] We note that throughput, aside from being the fundamental network performance evaluation metric *in general*, is also considered as the primary performance metric in major LTE/Wi-Fi coexistence studies, e.g. [1], [3].

[5] In the case of multiple users per AP, this per-AP downlink throughput would be split among the users.

TABLE 1. Explored parameter space—entrant variants and scenarios.

<table>
<tr><th colspan="2">SCENARIO / PARAMETER</th><th>Indoor/indoor
(indoor incumbent, indoor entrant)</th><th>Indoor/outdoor
(indoor incumbent, outdoor entrant)</th><th>Outdoor/outdoor
(outdoor incumbent, outdoor entrant)</th></tr>
<tr><td colspan="2">Network size</td><td>incumbent: 1 or 10 APs
entrant: 1–10 APs</td><td>incumbent: 500 or 5000 APs/km^2
entrant: 1–20 APs</td><td>incumbent: 1 or 10 APs
entrant: 1–10 APs</td></tr>
<tr><td colspan="2">AP transmit power</td><td>23 dBm</td><td>incumbent: 23 dBm
entrant: 23 or 30 dBm</td><td>23 or 30 dBm</td></tr>
<tr><td colspan="2">Maximum number of available channels (Europe)</td><td>19</td><td>incumbent: 19
entrant: 11</td><td>11</td></tr>
<tr><td rowspan="2">Coexistence mechanism</td><td>Channel selection</td><td colspan="3">incumbent: random or forced co-channel
entrant: random or sense (select channel with fewest incumbent APs) or forced co-channel</td></tr>
<tr><td>MAC</td><td colspan="3">incumbent: Wi-Fi: LBT, CS threshold of (-62)-82 dBm for (non-)Wi-Fi devices
entrant:
LAA: LBT, CS threshold of -62 dBm
LTE-U fixed 50% duty cycle: ON/OFF with 50% duty cycle
LTE-U adaptive duty cycle: ON/OFF with adaptive duty cycle based on number of entrant & incumbent APs within CS range (CS threshold = -62 dBm)
LTE-U ideal: ideal TDMA
LTE: always ON (continuous transmission)
Wi-Fi: LBT, CS threshold of (-62)-82 dBm for (non-)Wi-Fi devices</td></tr>
<tr><td colspan="2">PHY</td><td colspan="3">incumbent: Wi-Fi: IEEE 802.11n spectral efficiency ρ_{WiFi}, noise figure NF=15 dB
entrant:
LAA: LTE spectral efficiency ρ_{LTE}, NF=9 dB
LTE-U fixed 50% duty cycle: LTE spectral efficiency ρ_{LTE}, NF=9 dB
LTE-U adaptive duty cycle: LTE spectral efficiency ρ_{LTE}, NF=9 dB
LTE-U ideal: LTE spectral efficiency ρ_{LTE}, NF=9 dB
LTE: LTE spectral efficiency ρ_{LTE}, NF=9 dB
Wi-Fi: IEEE 802.11n spectral efficiency ρ_{WiFi}, NF=15 dB</td></tr>
<tr><td colspan="2">LBT parameters & assumptions</td><td colspan="3">binary exponential random backoff with CW_{min}=15, CW_{max}=1023,
time slot duration σ=9 μs, SIFS=16 μs, DIFS=SIFS+2σ=34 μs (cf. IEEE 802.11)</td></tr>
<tr><td colspan="2">LBT frame duration T_f</td><td colspan="3">Wi-Fi: $T_f = fn(rate,\ MSDU,\ PHY_{header},\ MAC_{header})$,
$MSDU$=1500 Bytes, PHY_{header}=40 μs, MAC_{header}=320 bits (cf. IEEE 802.11)
LAA: T_f=1 ms (i.e. duration of LTE subframe)</td></tr>
<tr><td colspan="2">Duty cycle ON-time</td><td colspan="3">LTE-U variants: 100 ms (i.e. maximum ON-time specified in [2])</td></tr>
<tr><td colspan="2">User distribution</td><td colspan="3">1 user per AP</td></tr>
<tr><td colspan="2">Traffic model</td><td colspan="3">downlink full-buffered</td></tr>
<tr><td colspan="2">Channel bandwidth</td><td colspan="3">20 MHz</td></tr>
<tr><td colspan="2">Frequency band</td><td colspan="3">5 GHz (5150–5350 and 5470–5725 MHz)</td></tr>
</table>

cycle MAC, based on the number of other entrant and incumbent APs detected within the carrier sense (CS) range.

Additionally, we consider the entrant variant **(iv)** ***LTE-U ideal*** to represent the upper bound of coordination achievable among LTE-in-unlicensed entrants, equivalent to a perfect TDMA schedule among APs within CS range of each other.[6] We also consider **(v)** ***LTE*** as the most basic LTE entrant variant, which transmits continuously and implements no mechanism to facilitate coexistence with the Wi-Fi incumbent. Finally, to help us answer the question of whether these LTE-like entrant variants are better neighbours to Wi-Fi than Wi-Fi is to itself, as has been suggested by proponents of LTE-U [2], we consider the incumbent **(vi)** ***Wi-Fi*** as the reference baseline entrant.

We focus on the combination of *channel allocation* and *MAC* protocol that chiefly[7] constitutes a *coexistence mechanism* in the case of multiple wireless systems (whether implementing the same technology or not) sharing a common radio spectrum band. To this end, we also consider different basic channel selection mechanisms that the incumbent and entrant APs use to select one of the available 20 MHz operating channels in the 5 GHz band. We assume that the incumbent *Wi-Fi* APs randomly select an operating channel, whereas the entrant APs use either ***random*** channel selection, or ***sense*** channel selection where the entrant AP selects (randomly) a channel unoccupied by an incumbent AP.

The total number of available 20 MHz channels in the 5 GHz band in Europe is nineteen for indoor or eleven for outdoor operation [8]. Given this large number of available channels, our considered scenarios and typical network densities (see Table 1) result in only one or two APs per channel on average. We thus expect that *sense* channel selection will not have a large impact on incumbent-entrant coexistence compared to *random* selection. Therefore, we also consider ***forced co-channel*** channel allocation, where all incumbent and entrant APs in the scenario occupy a single 20 MHz operating channel. The *forced co-channel* case represents a worst-case interference scenario, modelling important scenarios with a higher than usual risk of inter-system interference, such as: locally higher-than-typical network density; restricted availability of channels (e.g. only

[6] *LTE-U ideal* is thus a variant of *LTE-U adaptive duty cycle* where transmissions from entrant APs within each other's CS range never occur simultaneously (*cf.* possibility of entrant-entrant interference given uncoordinated transmissions in *LTE-U fixed* and *LTE-U adaptive* variants).

[7] Any other parameters, e.g. transmit power, that influence the extent of mutual interference could arguably also be considered part of a "coexistence mechanism", but their primary function is not to facilitate coexistence.

four non-DFS channels in Europe); or implementing channel aggregation to operate over fewer higher-bandwidth channels, as in IEEE 802.11ac. We argue that although such worst-case scenarios may occur infrequently, they are crucial since they best reflect the situations when coexistence problems, and possible calls for regulatory intervention, would arise.

B. DEPLOYMENT SCENARIOS

We study entrant and incumbent network coexistence in three major deployment scenarios, as illustrated in Fig. 1 and summarized in Table 1. In the ***indoor/indoor*** scenario, both the incumbent and entrant networks are indoors; in the ***indoor/outdoor*** scenario, the incumbent APs and users are indoors, whereas the entrants are outdoors; in the ***outdoor/outdoor*** scenario, both the incumbent and entrant networks are outdoors.

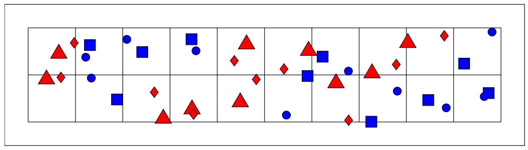
For all outdoor deployments, we generate the network topology by randomly allocating each outdoor AP to one of 20 real cellular pico base station locations from central London [9]. The associated outdoor users are randomly located within the AP's coverage area and at a maximum distance of 50 m. For indoor network deployments, we assume the 3GPP dual stripe model [10].

In the *indoor/indoor* scenario, we assume all incumbent and entrant APs coexist in one single-floor building with twenty apartments, as shown in Fig. 1(a). We consider one AP or fewer per apartment, so that the corresponding indoor network densities of 600–6000 APs/km^2 are consistent with the recent Wi-Fi measurements in [11]. In the *indoor/outdoor* scenario, as per the 3GPP dual stripe model, multi-floor buildings are randomly overlayed[8] on the study area containing the outdoor AP locations, as shown in Fig. 1(b). The incumbent APs and users are randomly located inside the apartments with a density of 500–5000 APs/km^2, whereas we consider one to 20 outdoor entrant APs (corresponding to an outdoor network density of 7–150 APs/km^2). In the *outdoor/outdoor* scenario, we consider up to 20 outdoor entrant and incumbent APs in total (corresponding to an outdoor network density of 14–150 APs/km^2), as shown in Fig. 1(c).

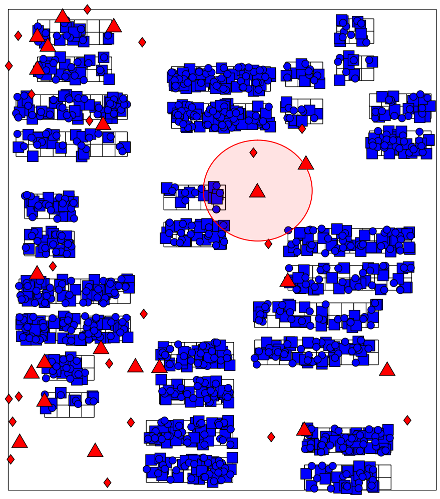
III. SIMULATION & THROUGHPUT MODEL

We estimate the performance of the coexisting incumbent and entrant technologies using Monte Carlo simulations in MATLAB, for 3,000 network realizations for the *indoor/indoor* scenario, and 1,500 network realizations for the *indoor/outdoor* and *outdoor/outdoor* scenarios. We assume propagation models corresponding to indoor and outdoor deployments in our scenarios. For outdoor links we assume the ITU-R model for line-of-sight (LOS)

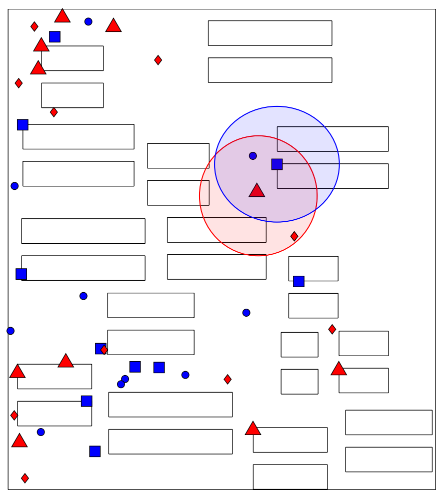
[8] We note that although our modelling of the urban layout is thus a simplification of a real (typically more regular) city layout, this is not expected to significantly affect our results given the ITU-R LOS/NLOS outdoor propagation model (*cf.* Section III).



(a) *Indoor/indoor* scenario: the incumbent and entrant networks are located inside a single-floor building with 20 apartments (each of 10 m × 10 m × 3 m). Each AP and its associated user are randomly placed in a single apartment.



(b) *Indoor/outdoor* scenario: the incumbent APs and users are located indoors and the entrant APs and users are located outdoors. The outdoor entrant users are located in the coverage area of and at a maximum distance of 50 m from the AP that they are associated with. The length of the buildings is randomly selected between 3–10 apartments and the height is randomly selected between 3–5 floors. The size of the total study area is 346 m × 389 m, corresponding to the area in London where the real locations of the outdoor entrant APs were observed.



(c) *Outdoor/outdoor* scenario: the incumbent and entrant APs are randomly allocated one real outdoor location. The outdoor users are located in the coverage area of and at a maximum distance of 50 m from the AP that they are associated with.

FIGURE 1. Network layout based on the 3GPP dual stripe model for indoor deployments and real outdoor picocell locations for outdoor deployments, for the (a) *indoor/indoor*, (b) *indoor/outdoor*, and (c) *outdoor/outdoor* scenarios, showing example locations of incumbent APs (■), incumbent users (●), entrant APs (▲), and entrant users (♦).

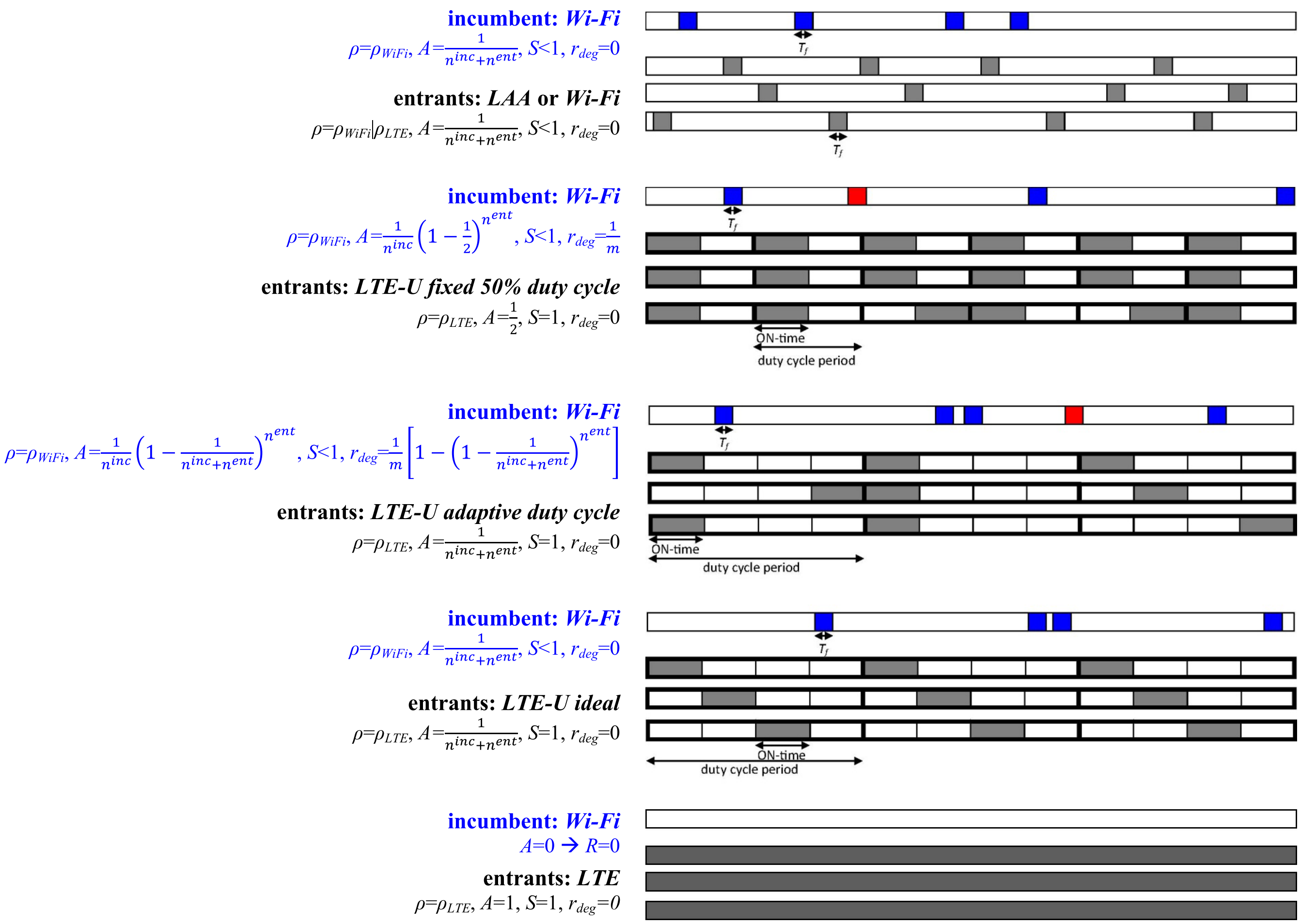


FIGURE 2. Illustration of our throughput model [5] for different LTE-in-unlicensed entrant technologies coexisting with the *Wi-Fi* incumbent, showing the example case of 1 incumbent and 3 entrant APs (all 4 APs are co-channel and within CS range of each other). AP transmissions are represented as coloured time periods: *grey* represents entrant AP transmissions, *blue* represents the incumbent AP transmissions that do not suffer a collision, and *red* represents incumbent frames lost due to collisions with the entrant. During *white* time periods the AP is not transmitting, in accordance with its MAC coexistence mechanism.

propagation within street canyons and the ITU-R non-line-of-sight (NLOS) model for over roof-top propagation [12]. For indoor links we assume a multi-wall-and-floor (MWF) model [13] with a building entry loss of 19.1 dB for external walls. For outdoor/indoor 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 [14].

In order to help explain our throughput model, which we present in detail in [5], Fig. 2 gives example transmission sequence diagrams when the *Wi-Fi* incumbent coexists with each of our six considered entrant technologies. For technologies that implement LBT at the MAC layer—i.e. *Wi-Fi* and *LAA*—we estimate the downlink throughput per AP by taking into account other incumbent and entrant APs within CS range. We assume LBT prevents all co-channel APs within each other's CS range from transmitting simultaneously and that an AP implementing LBT is granted the channel only for a fraction of time, while the rest of the time is used by other APs within CS range. Co-channel incumbent or entrant APs located outside the CS range of the considered AP interfere with this AP by decreasing the SINR (signal to interference and noise ratio) of its associated user.

For technologies that implement duty cycling at the MAC layer—i.e. *LTE-U* variants—we estimate the downlink throughput per AP by assuming a slotted time model where all entrant APs use the same duty cycle ON-time slot duration of 100 ms [2] and each entrant AP randomly selects a slot to transmit on (i.e. transmissions from different co-channel entrant APs may overlap in the same slot). Consequently, for *LTE-U fixed 50% duty cycle*, the total duration of a duty cycle period is always equal to two ON-time slots, whereas for *LTE-U adaptive duty cycle*, an entrant AP calculates a variable duty cycle period as the number of ON-time slots equal to the number of incumbent and entrant APs within its CS range. Consequently, the throughput of each *LTE-U* entrant is proportional to its duty cycle period and the SINR of its associated user is decreased by taking into account the interference from all other co-channel *LTE-U* entrants (and out-of-CS-range co-channel incumbents).

In general, we estimate the downlink throughput[9] of an incumbent or entrant AP as

$$R = \rho\{SINR\} \times A \times S \times (1 - r_{deg}), \quad (1)$$

where ρ is the PHY spectral efficiency depending on the SINR of the AP's associated user, A is the fraction of airtime the AP transmits for [15] and [16], S is the LBT MAC efficiency accounting for sensing time and collisions among LBT frames, and r_{deg} is the degradation of throughput due to collisions between frames from incumbents and any entrants implementing *LTE-U* duty cycle. The relevant parameters in (1) are specified per entrant variant in Fig. 2, alongside the illustrative examples of coexistence with the incumbent. We adopt the following notation: n^{inc} and n^{ent} are the number of co-channel incumbent and entrant APs within CS range, respectively, m is the number of frames transmitted by all incumbents within CS range in one duty cycle ON-time slot, ρ_{WiFi} is the IEEE 802.11n spectral efficiency [8] mapping the SINR at the associated user to the throughput, and ρ_{LTE} is the LTE spectral efficiency [17]. We estimate S based on Bianchi's model [18] which we modify in order to take into account parameter values specific to IEEE 802.11n in the 5 GHz band, and a combination of APs with variable frame duration depending on the adaptive rate (assumed for *Wi-Fi*) and fixed frame duration (assumed for *LAA*) [5]. We note that in order to estimate n^{inc} and n^{ent} we apply the CS threshold values in Table 1. We also note that r_{deg} is relevant only for incumbent APs; i.e. for the entrants we do not consider additional throughput degradation for duty cycle due to collisions with incumbent frames, since the *LTE-U* entrants have better spectral efficiency and longer transmission time than the *Wi-Fi* incumbents.

The SINR at the incumbent or entrant AP's associated user is given by

$$SINR = fn\{P_{tx}, I^{inc}, I^{ent}, N\}, \quad (2)$$

where P_{tx} is the transmit power of the AP (given in Table 1 for incumbents and entrants), I^{inc} is the sum of the co-channel interference from other incumbent APs outside CS range, I^{ent} is the sum of the co-channel interference from entrant APs, and N is the noise power (where thermal noise is 174 dBm/Hz and NF is given in Table 1). For *LAA*, *Wi-Fi*, and *LTE-U ideal*, I^{ent} is calculated only based on the co-channel entrant APs outside the CS range, whereas for *LTE*, *LTE-U fixed 50% duty cycle*, and *LTE-U adaptive duty cycle*, I^{ent} is calculated based on all co-channel entrant APs and on the long-term average probability that their transmissions overlap with the considered entrant AP. Finally, we note that if an *LTE* entrant exists within CS range of an incumbent, the incumbent is always prevented from transmitting since *LTE* is always on, and its throughput is zero.

[9]Our model focuses on the long-term average throughput to characterize the general coexistence performance, and captures the PHY/MAC behaviour of the incumbent and entrant technologies sharing the unlicensed band at a correspondingly appropriate level of complexity and detail; we thus expect other (e.g. packet-level) simulators that capture a finer time granularity to nonetheless provide comparable long-term throughput estimates.

IV. RESULTS

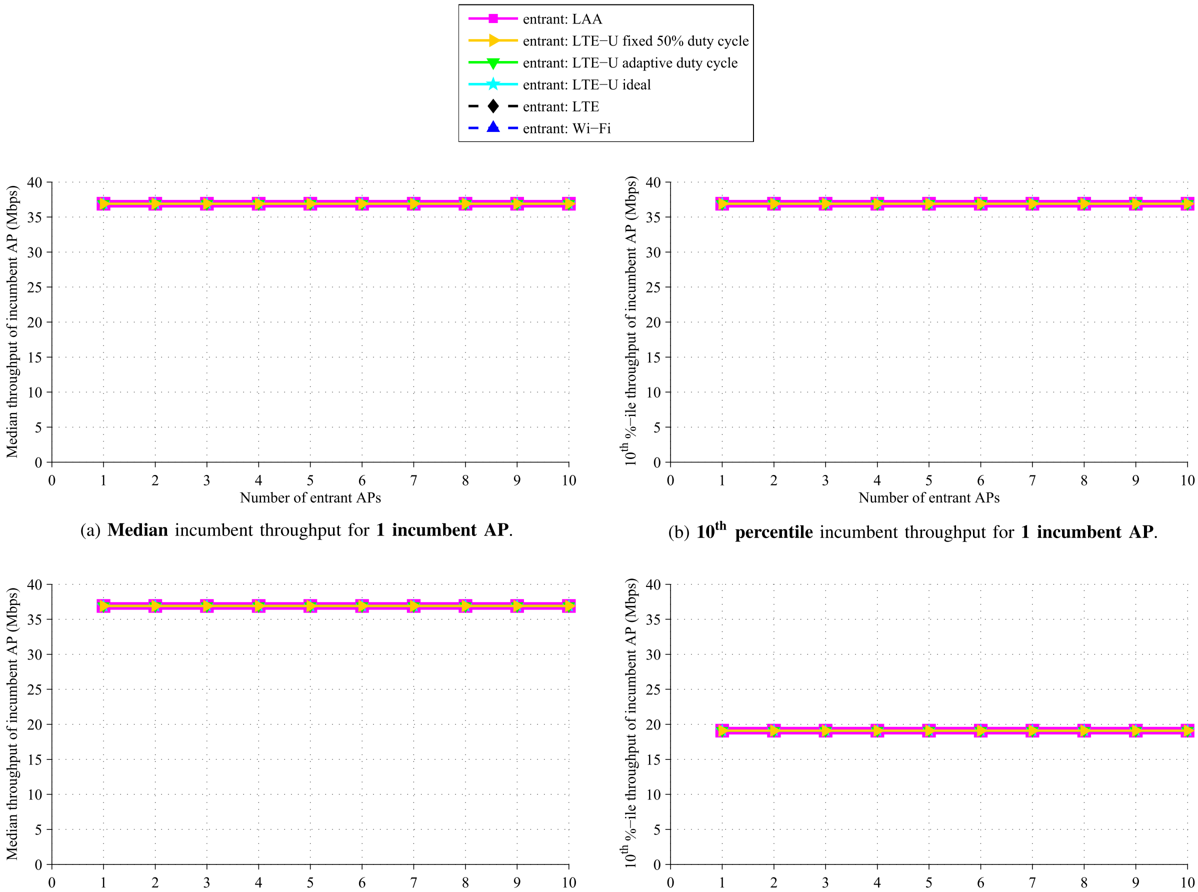
A. TYPICAL IMPACT OF ENTRANT ON Wi-Fi INCUMBENT

Fig. 3 shows the *Wi-Fi* incumbent AP throughput when 1 or 10 incumbent APs coexist with an increasing number of entrant APs in the *indoor/indoor* scenario, for different entrant technologies using *sense* channel selection. Figs. 3(a) and 3(c) show the median throughput, whereas Figs. 3(b) and 3(d) show the 10th percentile throughput (over all Monte Carlo network realizations).[10] For 1 incumbent AP coexisting with the entrant APs in Figs. 3(a) and 3(b), a constant throughput of 37 Mbps is achieved regardless of the number of entrant APs or entrant variant. For 10 incumbent APs in Figs. 3(c) and 3(d), a constant throughput of 37 Mbps and 19 Mbps is achieved regardless of the number of entrant APs or entrant variant, for the median and 10th percentile case, respectively. We note that we observed the identical trend of constant incumbent throughput also in the *indoor/outdoor* and *outdoor/outdoor* scenarios when the entrant APs use *sense* channel selection.[11] Therefore, our results demonstrate that the performance of the *Wi-Fi* incumbent is entirely independent of the entrant, as long as the entrant implements *sense* channel selection such that it operates in a channel unoccupied by an incumbent whenever possible. Moreover, our results for the *indoor/indoor*, *indoor/outdoor*, and *outdoor/outdoor* scenarios using *random* channel selection also exhibit the same trend of constant median incumbent throughput (and a similar trend for the 10th percentile throughput).

This is an important result: at the realistic network densities considered, near-perfect coexistence between the *Wi-Fi* incumbent networks and LTE-in-unlicensed entrant networks is ensured simply by virtue of the large number of available channels in the 5 GHz band, such that co-channel operation is easily avoided. We note that in practice there may be cases of legacy incumbent Wi-Fi devices that do not perform DFS and thus have a more restricted set of available channels to operate on, i.e. only four non-DFS channels [19], [20] (support for DFS is standard in the majority of modern commercial Wi-Fi APs). It remains reasonable to assume that the entrant APs, being at least as sophisticated as modern Wi-Fi devices, will have DFS capabilities and be able to implement *sense*, as required in [1]. In such a case, the incumbent/entrant coexistence conditions would in fact improve, since perfect isolation between incumbents and entrants would be ensured by the entrant APs always selecting the DFS channels unoccupied by the incumbents. For the even less likely case where neither the incumbents, nor the entrants have DFS capabilities (corresponding to rare cases of e.g. faulty DFS implementation by

[10]Throughout, we present our simulation results in terms of the median and 10th percentile throughput of the ensemble distribution of all Monte Carlo network realizations as specified in Section III, in order to provide both the representative and worst-case throughput experienced by the APs, respectively, in the various considered coexistence scenarios.

[11]For the sake of brevity, we focus on explicitly presenting only a representative selection of the results for all studied scenarios in Table 1, and discuss our overall simulation results with respect to these.



(a) **Median** incumbent throughput for **1 incumbent AP**.

(b) **10th percentile** incumbent throughput for **1 incumbent AP**.

(c) **Median** incumbent throughput for **10 incumbent APs**.

(d) **10th percentile** incumbent throughput for **10 incumbent APs**.

FIGURE 3. Median and 10th percentile throughput of incumbent *Wi-Fi* AP when coexisting with different entrant technologies, for the *indoor/indoor* scenario with *sense* entrant channel selection of 1 of 19 indoor channels. (The trend of constant incumbent AP throughput, regardless of entrant number or variant, shown here, was also observed in our simulation results for the *indoor/outdoor* and *outdoor/outdoor* scenarios.)

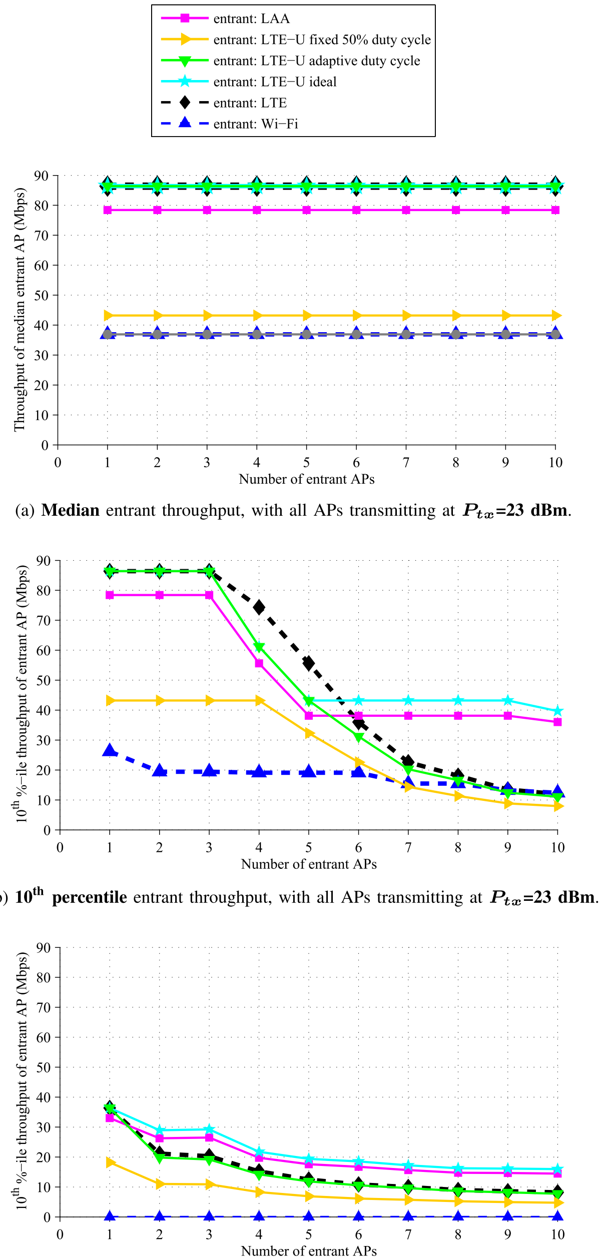
entrant devices), we discuss in Section IV-C the worst-case scenario where incumbent and entrant APs locally operate on the same channel, i.e. the *forced co-channel* case.

B. TYPICAL IMPACT OF LTE-IN-UNLICENSED ENTRANT TECHNOLOGIES

Having established that the LTE-in-unlicensed entrant variant makes no difference to the incumbent throughput in the above scenarios, we now consider what incentives the entrant may have for adopting different LTE-in-unlicensed technologies. Fig. 4 presents the throughput of the entrant AP for the *outdoor/outdoor* scenario with *sense* channel selection. Fig. 4(a) shows that the median entrant AP throughput is independent of the number of entrant APs, which is consistent with the avoidance of co-channel operation enabled by the large number of available channels, as observed for the incumbents in Fig. 3. It follows that since there are no other co-channel APs within CS range, the entrant AP throughput in Fig. 4(a) is simply determined by the single-link PHY and MAC layer efficiency of the entrant variant. The entrants *LTE-U ideal* and *LTE-U adaptive duty cycle* achieve the maximum single-link *LTE* throughput of 86 Mbps; the *LAA* entrant achieves a slightly lower throughput than *LTE*, of 78 Mbps, due to the LBT MAC overhead term S; the *LTE-U fixed 50% duty cycle* achieves exactly half the *LTE* throughput; and the *Wi-Fi* entrant achieves the lowest throughput of 37 Mbps due to its lower PHY layer efficiency than *LTE* (and slightly higher LBT MAC overhead than *LAA*). We note that the median throughput results for the *indoor/indoor* and *indoor/outdoor* scenarios, for all considered incumbent network densities, are identical to those in Fig. 4(a).

The coexistence mechanism implemented by the LTE-in-unlicensed variant only starts to play a role in the achieved entrant throughput once the likelihood of co-channel operation by entrant APs within CS range increases significantly,[12] as demonstrated by the

[12] We note that this differs from the incumbent AP throughput results in Fig. 3, because the entrant AP using *sense* channel selection will avoid operating in a channel occupied by an incumbent AP if possible, but is more likely to randomly select the same channel as another entrant AP (once the number of entrant APs is high enough).



(a) **Median** entrant throughput, with all APs transmitting at P_{tx}=23 dBm.

(b) **10th percentile** entrant throughput, with all APs transmitting at P_{tx}=23 dBm.

(c) **10th percentile** entrant throughput, with all APs transmitting at P_{tx}=30 dBm.

FIGURE 4. Median and 10th percentile throughput of entrant AP coexisting with 1 incumbent *Wi-Fi* AP, for different entrant technologies, for the *outdoor/outdoor* scenario with *sense* selection of one of 11 outdoor channels, and different AP transmit powers.

10th percentile entrant throughput in Figs. 4(b) and 4(c). Specifically, Fig. 4(b) shows that the ordering of the LTE variant curves changes once the entrant network density reaches a critical value (of around 5–7 APs) where the likelihood of co-channel operation becomes significant, and mechanisms to avoid interference thus become useful. The results in Fig. 4(c) show that this *critical network density* is only around 1–2 entrant APs with a higher transmission power P_{tx}, due to a higher corresponding CS range, and thus higher likelihood of co-channel interference for neighbouring APs. We note that we observed a similar trend of *two distinct regimes for entrant variant ranking* also for other scenarios, but with different critical network densities.

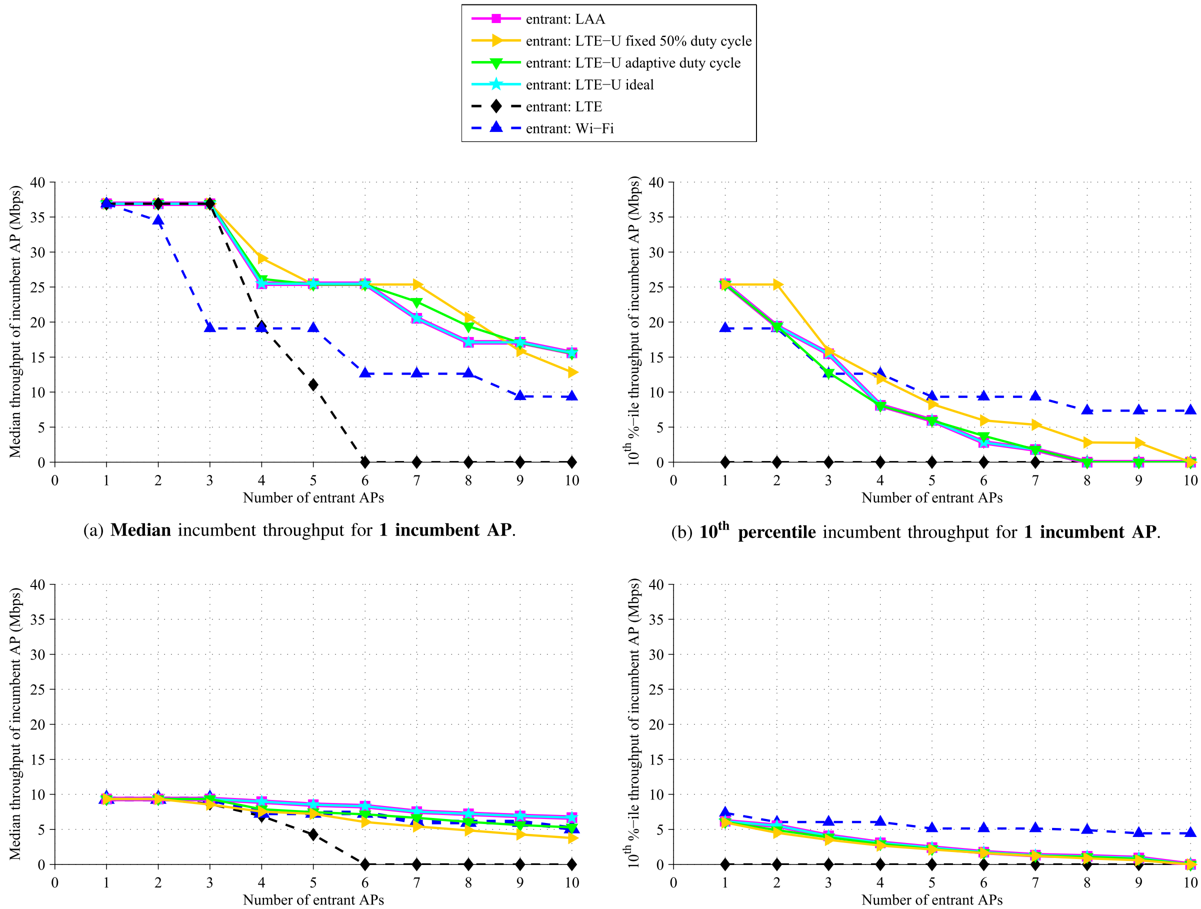
In this second regime beyond the critical network density, where interference starts to occur, the *LTE-U ideal* variant achieves the highest entrant AP throughput, consistent with its superior PHY layer and maximum MAC layer coordination. The *LAA* entrant achieves only a slightly lower throughput than *LTE-U ideal* due to the MAC layer overhead of LBT. By contrast, the other LBT entrant *Wi-Fi* achieves the lowest throughput of all entrant variants, simply due to a lower PHY layer spectral efficiency than *LAA*.[13] Finally, the *LTE* and *LTE-U duty cycle* variants exhibit a decreasing entrant throughput with increasing (SINR-reducing) interference in dense networks, consistent with their implementing either no or ineffective interference coordination mechanisms at the MAC layer. It is therefore only in this *regime of likely interference*—i.e. situations when co-channel APs are situated within CS range of each other—that distributed interference coordination, as facilitated by the LBT MAC mechanism of the *Wi-Fi* incumbent, becomes necessary to prevent a ''tragedy of the commons'' in an unlicensed spectrum band.

C. WORST-CASE IMPACT OF ENTRANT ON Wi-Fi INCUMBENT

Finally, let us consider the impact of different LTE-in-unlicensed entrant variants on the incumbent throughput in situations where the incumbent APs are also affected by the *regime of likely interference* observed for the entrants in Fig. 4 after a critical network density. We emphasize that although our results in Fig. 3 demonstrate that such situations are expected to occur infrequently, they are nonetheless important, as even such rare cases of coexistence problems have the potential to motivate calls for regulatory intervention (as discussed in Section II-A). To this end, Fig. 5 shows the *Wi-Fi* incumbent AP throughput in the *indoor/indoor* scenario for the worst-case coexistence situation where the incumbent and entrant APs all operate on a single channel (i.e. *forced co-channel*).

We observe from Fig. 5 that the *LTE* entrant, which implements no coexistence mechanism whatsoever, results in a severe deterioration of incumbent performance, reducing the median incumbent AP throughput to zero when there are more than 6 co-channel entrant APs and for all entrant densities in the 10th percentile case. Thus Fig. 5 makes it clear that some kind of coexistence mechanism is necessary to avoid disrupting the incumbent. However, Fig. 5 also shows that the difference in impact on the incumbent's performance among the other LTE-in-unlicensed variants (i.e. *LAA* and *LTE-U*) is typically under 1 Mbps, and at most 3 Mbps. This result has important policy implications, as it suggests that, contrary to arguments and claims made in many recent heated industry

[13] We note *Wi-Fi* LBT also implements a more conservative CS threshold than *LAA*. However, we have observed in our other simulation results [5] that *Wi-Fi*'s lower CS threshold is somewhat beneficial in the *outdoor/outdoor* scenario; nonetheless, it is important to choose a well-tuned CS threshold to maximize network throughput of LBT technologies in shared spectrum.



(a) **Median** incumbent throughput for **1 incumbent AP**.

(b) **10th percentile** incumbent throughput for **1 incumbent AP**.

(c) **Median** incumbent throughput for **10 incumbent APs**.

(d) **10th percentile** incumbent throughput for **10 incumbent APs**.

FIGURE 5. Median and 10th percentile throughput of incumbent AP when coexisting with different entrant technologies, for the *indoor/indoor* scenario with *forced co-channel* operation of all APs.

and regulatory debates [1]–[3], [6], in practice it does not make a difference to the incumbent what kind of coexistence mechanism is added to *LTE* operating in unlicensed bands, as long as one is in place. In other words, the debate over whether LAA should be mandatory or LTE-U may be allowed [6], is immaterial to the policy goal of ensuring coexistence with the Wi-Fi incumbent; the choice of LAA or LTE-U should be made by the LTE-in-unlicensed operator, based on the resulting performance for the entrant, and is of no concern for the spectrum regulator.

Importantly, Fig. 5 answers our original motivating research question: LTE is neither friend nor foe to Wi-Fi in the unlicensed bands *in general*. Fig. 5(a) shows that in some cases the LTE-in-unlicensed variants are indeed better neighbours to the *Wi-Fi* incumbent than the baseline *Wi-Fi* entrant itself. This is consistent with existing claims by e.g. the LTE-U forum [1], [2]. The opposite holds in the cases of Figs. 5(b) and 5(d). This result stems simply from the fact that the *Wi-Fi* incumbent applies a lower CS threshold when deferring to *Wi-Fi* than when deferring to another technology (e.g. the LTE-in-unlicensed entrants), of −82 dBm and −62 dBm, respectively. The lower CS threshold is poorly tuned for networks with low effective density, and well tuned for dense networks. Accordingly, in Fig. 5(a) the *Wi-Fi* incumbent is unnecessarily "polite" to the *Wi-Fi* entrant, to the detriment of its throughput, and achieves a higher median throughput when it defers less to equivalently far away LTE-in-unlicensed entrants. On the other hand, a higher level of politeness starts to pay off in the cases of higher effective node density in Figs. 5(b)-(d): the likelihood of a large number of nearby APs causing harmful interference to the incumbent increases in the order of Fig. 5(c) to Fig. 5(b) to Fig. 5(d), matched by the trend of increasing superiority of *Wi-Fi*'s coexistence with itself compared to with LTE-in-unlicensed. In the most extreme case of the 10th percentile throughput of 10 incumbent APs coexisting with 10 entrant APs shown in Fig. 5(d), all LTE-in-unlicensed variants completely prevent the *Wi-Fi* incumbent from transmitting, whereas the all-*Wi-Fi* network still achieves a throughput of around 5 Mbps.

Finally, we note that for all *outdoor/outdoor* scenarios we observed the same qualitative results as in Fig. 5, whereas for the *indoor/outdoor* scenarios we observed the same results as in Fig. 3, since the entrant and incumbent networks remain independent even in the *forced co-channel* case due to the isolation afforded by high external building material losses [21].

V. CONCLUSIONS

We presented a coexistence study of Wi-Fi and LTE in the 5 GHz unlicensed band, surveying a large parameter space of coexistence mechanisms and a range of network scenarios. We thereby sought to identify whether situations warranting regulatory intervention to protect the incumbent Wi-Fi technology from the new LTE entrant are likely to arise. Our results show that, for typical network densities, harmonious coexistence between Wi-Fi and LTE is ensured by the large number of 5 GHz channels which mean that co-channel operation is easily avoided. For the worst-case scenario of *forced co-channel* operation, LTE is sometimes a better neighbour to Wi-Fi than a Wi-Fi entrant— when effective node density is low—but sometimes worse—when the density, and the potential for interference, is high. We also showed that it does not make a difference to the Wi-Fi incumbent which LTE coexistence mechanism is implemented (i.e. LTE-U or LAA), as long as one is in place. Therefore, we conclude that LTE is neither friend nor foe to Wi-Fi in the unlicensed bands *in general*, contrary to the claims of both lobbying camps. We argue that the systematic engineering analysis demonstrated by our Wi-Fi/LTE case study is a best-practice approach for supporting evidence-based rulemaking by the regulator.

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