Analysing Wi-Fi/LTE Coexistence to Demonstrate the Value of Risk-Informed Interference Assessment

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***Abstract*—Effective interference evaluation methods are crucial when making regulatory decisions about whether new wireless technologies should be allowed to operate. Such decisions are highly relevant for both DSA technologies in licensed bands and for technologies coexisting in unlicensed bands. In this paper we demonstrate the benefit of risk-informed interference assessment as an effective method that aids spectrum regulators in making decisions, and readily conveys engineering insight. We apply risk assessment to a Wi-Fi/LTE coexistence study in the 5 GHz unlicensed band. Our contributions are: (i) we apply, for the first time, risk assessment to a real-life problem of inter-technology spectrum sharing; and (ii) we demonstrate that risk assessment comprehensively quantifies the effect of interference in an intuitive manner. We perform extensive Monte Carlo simulations and we consider throughput degradation and fairness metrics to assess the risk of co- and adjacent channel interference for different network densities, numbers of available channels, and deployment scenarios. Our risk assessment results show that no regulatory intervention is needed to ensure harmonious technical coexistence between Wi-Fi/LTE in the unlicensed band. As an engineering insight, Wi-Fi coexists better with itself in locally dense deployments, but better with LTE in sparse deployments. For the large number of available channels typically expected in practice in the 5 GHz band, the risk of interference for Wi-Fi coexisting with LTE is negligible, rendering policy and engineering concerns largely moot.**

***Index Terms*—coexistence, interference, LTE, risk assessment, spectrum regulation, Wi-Fi.**

I. Introduction

Inter-technology spectrum sharing may generate coexistence problems in bands where mutual interference among different systems occurs. Dynamic spectrum access (DSA) techniques seek to solve such problems by allowing access to the spectrum on a primary-secondary basis, where the primary has priority over secondary systems [1]. This problem is managed by each technology individually in the unlicensed bands, where all systems have equal rights to access the spectrum.

Regardless of the spectrum access rights, inter-technology spectrum sharing raises a two-stage question: (i) which technologies should/can coexist based on the expected harm of mutual interference, and (ii) how to manage interactions between technologies on a moment-by-moment basis? In this paper we present an extended case study of applying risk assessment for Wi-Fi/LTE coexistence in the unlicensed bands, in order to evaluate the harm caused by interference.

Evaluating coexistence problems due to co- and adjacent channel interference is of interest to both spectrum regulators seeking to establish operational bounds and to engineers designing and managing systems for optimized performance within the regulatory restrictions. Assessing interference is not a trivial task; consequently, most of the studies manage this complexity by considering worst-case scenarios as the baseline. Nevertheless, it is not clear how often or under what conditions such worst-case scenarios would occur in practice. Making regulatory decisions based on worst-case analysis may even lead to a complete exclusion of new entrant technologies, so that the second question of interference management becomes irrelevant. As such, comprehensive interference assessment methods are essential for creating a regulatory environment that would enable the deployment of advanced spectrum-sharing techniques, e.g. for DSA-like scenarios. Effective interference assessment methods are equally important for the engineers who design, deploy, and manage networks of different technologies coexisting in shared bands, e.g. IEEE 802.11g and n, and Wi-Fi/LTE in the unlicensed bands. Coexistence performance optimization of such networks cannot be conducted under worst-case conditions only.

In this paper we demonstrate the benefit of risk assessment as a complement to worst-case interference analysis. Importantly, risk assessment is a very new method in the fields of communications engineering and spectrum regulation, although it has been used successfully in other fields (e.g. the nuclear industry [2]). We apply risk-assessment to a Wi-Fi/LTE coexistence study in the 5 GHz unlicensed band for different network densities, number of channels, and scenarios. Our contributions are: (i) we are the first to apply risk-informed interference assessment to a real-life, topical problem (dealing with inter-technology spectrum sharing with wide relevance for regulatory DSA-like scenarios); and (ii) we demonstrate the benefit of risk assessment as a method that comprehensively and quantitatively characterizes the harm caused by interference in an intuitive and illustrative manner, from both policy and engineering perspectives. Our analysis shows that no regulatory intervention is needed to ensure harmonious technical coexistence[1] between Wi-Fi/LTE in the

[1]Considering economic and policy coexistence issues, e.g. deploying LTE-in-unlicensed for anti-competitive practices, is out of the scope of this paper.

unlicensed bands. From an engineering perspective, we show that Wi-Fi coexists better with itself and worse with LTE in locally dense deployments, but the opposite holds in sparse deployments, due to the specifics of Wi-Fi's MAC. Also, given the large number of available channels expected in practice in the 5 GHz band, there is typically no risk of interference caused by LTE-in-unlicensed entrants, which renders both policy and engineering coexistence issues largely irrelevant.

This paper is organised as follows. Section II gives a brief overview of LTE-in-unlicensed and prior work on its coexistence with Wi-Fi. Section III presents the risk-informed interference assessment method. Section IV presents our simulation and throughput model. Section V illustrates and discusses the benefit of applying the risk assessment method for our Wi-Fi/LTE case study and Section VI concludes the paper.

II. LTE-in-Unlicensed: The Story so Far

LTE operation in the unlicensed 5 GHz band has recently been proposed by industry [3], [4]. Initially, the unlicensed band is aggregated only for user data transmissions, while the control traffic is sent over the licensed bands for reliability reasons [5]. Two main LTE-in-unlicensed variants with fundamentally different MAC mechanisms have emerged: (i) LTE-U proposed by the LTE-U Forum [3]; and (ii) Licensed Assisted Access (LAA) first standardized by 3GPP in Release 13 [5].

LTE-U is based on an adaptive duty cycle MAC mechanism, which adjusts the periodic transmission duration of the devices according to the number of other devices operating in the same channel, such that all devices have an equal share of the channel in time. However, LTE-U devices do not sense and defer to ongoing transmissions before starting their own transmissions, so collisions are likely. LTE-U is a pre-standard version intended for markets where listen-before-talk (LBT) is not required by regulators (e.g. the U.S.).

LAA is based on LBT, a MAC mechanism in which devices start transmitting only after detecting that the channel is unoccupied. LBT is required by spectrum regulators in some regions (e.g. Europe), so LAA was proposed as a globally applicable standard.

As Wi-Fi is currently the dominant technology in the 5 GHz band, it has been claimed by some parties (e.g. [6]) that introducing LTE-in-unlicensed would harm Wi-Fi operation. On the other hand, proponents have argued that LTE-in-unlicensed would actually improve Wi-Fi performance compared to Wi-Fi coexisting with itself [3], [4]. The debate between the two camps led the FCC to issue a Public Notice requesting comments on LTE coexistence in the unlicensed bands [7], implicitly raising the question of whether regulatory intervention is required to ensure harmonious technical coexistence between LTE-in-unlicensed and Wi-Fi.

Most existing Wi-Fi/LTE coexistence analyses are not thorough enough to answer the public policy question of whether LTE is a friend or a foe to Wi-Fi in the unlicensed band. Some existing work lacks a detailed description of algorithms and models (e.g. [3]), so that it is difficult to draw generalizable conclusions from the presented results. Other work considers only one main LTE-in-unlicensed variant (*cf.* classification of related work in [8]), so that the results only partially characterize the Wi-Fi/LTE coexistence problem. In our previous work [9] we presented results from a transparent, systematic, and extensive coexistence study and we showed that LTE-in-unlicensed is neither friend nor foe to Wi-Fi.

In this paper we extend our previous work by conducting, for the first time, a risk assessment of the Wi-Fi/LTE coexistence problem, in order to show the effectiveness of this method for deriving regulatory and engineering insight from quantitative results in a comprehensive, illustrative, and intuitive manner. Furthermore, we extend our throughput model from [8] by incorporating adjacent channel interference and we consider throughput fairness as an additional coexistence performance metric. Finally, we present more detailed results than in [8], [9] by showing the full distributions of our considered metrics.

III. Risk-Informed Interference Assessment

A. Introduction to Risk Assessment

Risk-informed interference assessment was introduced as a comprehensive, quantitative tool for a spectrum regulator seeking to balance the interests of incumbents, new entrants and the public when deciding whether and how to allocate new radio services [10]. It facilitates a balanced assessment of the adverse technical impact of new entrants on incumbents.

Engineering risk assessment, a well-established method used in many industries, considers the likelihood-consequence combinations for multiple hazard scenarios, and complements a "worst case" analysis that considers the single scenario with the most severe consequence, regardless of its likelihood. Charts that plot the severity of hazards against their likelihoods are frequently used to visualize and compare the risk of different hazards; see Fig. 2(b).

To date, quantitative risk assessment has not been used in spectrum management. The authors in [11] proposed a four-step method for performing risk-informed interference assessment: **(1)** make an inventory of all significant harmful interference hazard modes; **(2)** define a consequence metric to characterize the severity of hazards; **(3)** assess the likelihood and consequence of each hazard mode; and **(4)** aggregate them into a basis for decision making. In [10] it was shown how this method could be used to analyse the risk of cellular interference to weather satellite earth stations for a hypothetical general case. By contrast, we are the first to apply risk-informed interference assessment to a real-life problem and to inter-technology coexistence in the same spectrum band.

B. Applying Risk Assessment to Wi-Fi/LTE Coexistence

In this paper we address co- and adjacent channel interference from Wi-Fi/LAA/LTE-U entrants towards Wi-Fi incumbents by applying risk assessment. In Section IV we present the interference hazards corresponding to Step (1). In Section III-C we define the throughput consequence metrics to characterize hazard severity for Step (2). In Section V we demonstrate Steps (3) and (4) by assessing the hazard modes

TABLE I
SCENARIOS AND ENTRANT VARIANTS

PARAMETER \ SCENARIO		***Indoor/indoor*** **(indoor incumbent, indoor entrant)**	***Outdoor/outdoor*** **(outdoor incumbent, outdoor entrant)**
Network size		**incumbent**: 10 APs **entrant**: 1–30 APs	**incumbent**: 10 APs **entrant**: 1–10 APs
Maximum number of available channels (Europe)		19	11
Coexistence mechanism	**Channel selection**	**incumbent**: random *or* single channel **entrant**: random *or* sense (select channel with fewest incumbent APs) *or* single channel	
	MAC	**incumbent**: **Wi-Fi**: LBT, CS threshold of -82 dBm for co-channel Wi-Fi devices, and -62 dBm for co-channel non-Wi-Fi and all adjacent channel devices **entrant**: **LAA**: LBT, CS threshold of -62 dBm **LTE-U**: ON/OFF with adaptive duty cycle based on number of entrant & incumbent APs within CS range (CS threshold = -62 dBm) **Wi-Fi**: LBT, CS threshold of -82 dBm for co-channel Wi-Fi devices, and -62 dBm for co-channel non-Wi-Fi and all adjacent channel devices	
PHY		**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**: LTE spectral efficiency ρ_{LTE}, NF=9 dB **Wi-Fi**: IEEE 802.11n spectral efficiency ρ_{WiFi}, NF=15 dB	
LBT parameters & assumptions		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)	
LBT frame duration T_f		***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)	
Duty cycle ON-time		***LTE-U***: 100 ms (i.e. maximum ON-time specified in [4])	
User distribution		1 user per AP	
Traffic model		downlink full-buffered	
Channel bandwidth		20 MHz	
Frequency band		5 GHz (5150–5350 and 5470–5725 MHz)	
AP transmit power		23 dBm	

and by showing the effectiveness of risk assessment when making decisions of regulatory and engineering concern.

C. Consequence Metrics for Risk Assessment

In this section we define the consequence metrics to characterize the severity of the interference hazards. In the context of Wi-Fi/LTE coexistence we select two throughput metrics[2] that represent the hazard consequence for the incumbents: (i) the throughput degradation, which we consider the most relevant metric to quantify whether Wi-Fi gets a fair share of the channel and whether it experiences excessive interference when coexisting with LTE-in-unlicensed, and thus to answer the technical public policy coexistence question; and (ii) the throughput unfairness among incumbents, which gives insight into engineering optimization of inter-technology coexistence within the given regulatory context.

We define the throughput degradation of the incumbent access points (APs) when coexisting with entrant APs with respect to two different baselines: (i) the standalone Wi-Fi incumbent network, in order to capture the general throughput degradation due to network densification; and (ii) the Wi-Fi incumbent network coexisting with a Wi-Fi entrant network, in order to directly focus on the question of whether LTE is a better neighbour to Wi-Fi than Wi-Fi is to itself. For an incumbent AP x we estimate the throughput degradation as

$$\Delta R_x = \frac{R_{x,baseline} - R_x}{R_{x,baseline}}, \qquad (1)$$

where $R_{x,baseline}$ is the baseline throughput of x and R_x is the throughput of x when coexisting with a given entrant variant.

In order to quantify the throughput fairness among incumbent APs, we apply Jain's fairness index [13] for a set of incumbent throughput results corresponding to APs in a single network realization, given by

$$J = \frac{|\sum_{x=1}^{n} R_x|^2}{n \sum_{x=1}^{n} R_x^2}, \qquad (2)$$

where n is the number of incumbents in the network.

For consistency with data representation in a risk assessment chart (explained in Section V-A), we define the incumbent throughput unfairness as the consequence metric, given by

$$U = 1 - J. \qquad (3)$$

IV. Simulation & Throughput Models

A. Simulation Model

We assume a population of Wi-Fi incumbent APs coexisting with Wi-Fi/LAA/LTE-U entrant APs in two main scenarios, for realistic network densities, as summarized in Table I.

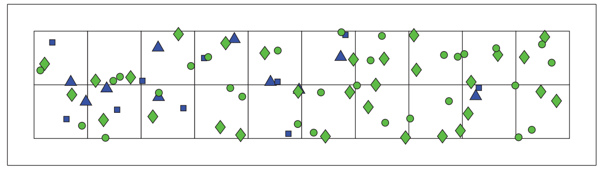
[2] We note that throughput has been the baseline network performance evaluation metric in general and is also considered the only or primary performance metric in important Wi-Fi/LTE coexistence studies, e.g. [3]. Although delay can be considered a relevant evaluation metric in some cases, it is typically applied for VoIP traffic [12], which does not represent the majority of the traffic.

We assume the incumbent APs and their associated users are always Wi-Fi devices implementing the IEEE 802.11n PHY layer and LBT[3] at the MAC layer with a carrier sense (CS) threshold of -82 dBm for deferring to co-channel Wi-Fi devices, and -62 dBm for adjacent channel Wi-Fi devices and co- and adjacent channel non-Wi-Fi devices. For the entrants, we assume either (i) LAA implementing the LTE PHY and the LBT MAC mechanism with -62 dBm CS threshold for deferring to all other devices, or (ii) LTE-U that adapts its duty cycle according to the number of detected APs based on the -62 dBm CS threshold. As the baseline entrant for answering the question of whether LTE-in-unlicensed is a friend or a foe to Wi-Fi, we also consider (iii) Wi-Fi entrants.

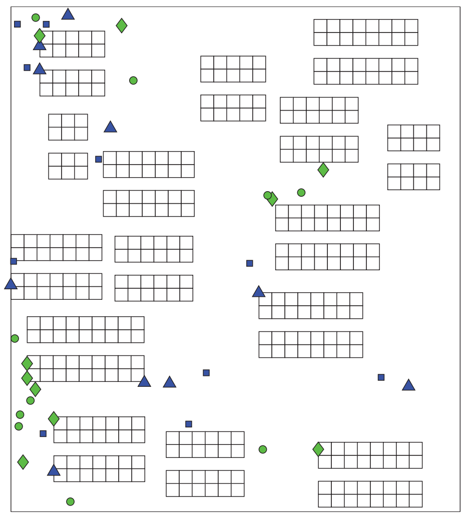
We consider two main scenarios, where each AP has one associated user, i.e. the *indoor/indoor* scenario where all incumbent and entrant devices are located indoors and the *outdoor/outdoor* scenario where all devices are located outdoors, as in Fig. 1. For the *indoor/indoor* scenario we assume a single-floor building, according to the 3GPP dual stripe model [14]. Each incumbent AP and its associated user are located randomly within a single apartment. The entrant APs and their associated users are first randomly located in unoccupied apartments and then randomly occupy apartments with only one other AP, until all apartments contain up to two APs. This results in network densities of 600–12000 APs/km^2, as (and more) dense as that seen in contemporary 2.4 GHz deployments, but not yet in 5 GHz [15]. For the *outdoor/outdoor* scenario we assume 20 real outdoor base station locations from central London [16] and we randomly overlay buildings over the area where the real outdoor locations were observed, resulting in network densities of 7–150 APs/km^2. The associated users are located within the coverage area of the respective APs and at a maximum distance of 50 m. As a worst-case interference scenario of low signal attenuation through walls resulting in high interference among APs, we also consider the *indoor/indoor* scenario *without internal walls*.

We assume each incumbent AP randomly selects one of the available channels. The entrants either randomly select a channel, i.e. *random*, or apply *sense*, i.e. they randomly select a channel unoccupied by incumbents. We assume the maximum number of channels in the 5 GHz band in Europe to be typically available in practice (i.e. 19 indoor and 11 outdoor channels), or only the 4 non-DFS channels, corresponding to less likely cases of either legacy devices that do not implement DFS, or devices with faulty DFS implementation (e.g. erroneously detecting radar channels as occupied). As a worst-case of high local AP density corresponding to a high level of interference, we also consider the *single channel* case.

We assume propagation models according to the indoor and outdoor links in our scenarios. For the indoor links we assume a multi-wall-and-floor model (MWF) model [19] and for the outdoor links we assume the ITU-R model for line-of-sight (LOS) propagation within street canyons and for non-line-of-sight (NLOS) with over roof-top propagation [20]. We assume log-normal shadowing with a standard deviation of 4 dB for indoor links and 7 dB for outdoor links [21].



(a) *Indoor/indoor* scenario: the incumbents and entrants 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 with up to two AP-user pairs. This figure shows an example of the most dense deployment.



(b) *Outdoor/outdoor* scenario: the incumbent and entrant APs are randomly allocated one real outdoor location and are placed at the roof-top level. 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, at a height of 1.5 m. 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 APs were observed.

Fig. 1. Example 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*, and (b) *outdoor/outdoor* scenarios, showing locations of incumbent APs (▲), incumbent users (■), entrant APs (♦), and entrant users (●).

We perform extensive Monte Carlo simulations in MATLAB with 3000 network realizations for the *indoor/indoor* scenario and *indoor/indoor* scenario *without internal walls*, and 1500 realizations for the *outdoor/outdoor* scenario. We assume downlink saturated traffic (i.e. most challenging coexistence case) and we evaluate the network performance based on the downlink throughput per AP, estimated at the associated user.[4]

B. Throughput Model

Our throughput and interference model for co-channel interference is described in detail in [8] and in this paper we

[3]We note that CSMA/CA is a specific variant of the more general LBT mechanism, so we refer to it as LBT. In this paper we assume LBT with binary exponential random backoff throughout.

[4]For multiple users associated to a single AP, the user throughput is obtained by dividing the per-AP throughput to the number of associated users.

TABLE II
PARAMETERS FOR THROUGHPUT AND INTERFERENCE MODEL

AP type / Parameter	**Incumbent**	**Entrant**
S_x	defined in [8]	$\begin{cases} \text{defined in [8]}, & \text{if W-Fi/LAA entrant} \\ 1, & \text{if LTE-U entrant} \end{cases}$
$r_{deg,x}$	$\begin{cases} 0, & \text{if Wi-Fi/LAA entrant} \\ \text{defined in [8]}, & \text{if LTE-U entrant} \end{cases}$	0
$AirTime_x$	$\begin{cases} \frac{1}{1+\lvert\mathbf{A}_x\rvert+\lvert\mathbf{B}_x\rvert}, \text{ if Wi-Fi/LAA entrant} \\ \prod_{y\in\mathbf{B}_x} \left(1-\frac{1}{1+\lvert\mathbf{C}_y\rvert+\lvert\mathbf{D}_y\rvert}\right) \times \frac{1}{1+\lvert\mathbf{A}_x\rvert}, \\ \text{if LTE-U entrant} \end{cases}$	$\frac{1}{1+\lvert\mathbf{A}_x\rvert+\lvert\mathbf{B}_x\rvert}$
ρ_x	ρ_{WiFi} [17]	$\begin{cases} \rho_{WiFi}, & \text{if Wi-Fi entrant} \\ \rho_{LTE} \text{ [18]}, & \text{if LAA/LTE-U entrant} \end{cases}$
I_u^{co}	$\sum_{z\in(\mathbf{A}^{co}\setminus\mathbf{A}_x^{co})\cup(\mathbf{B}^{co}\setminus\mathbf{B}_x^{co})} \frac{P_z \times AirTime_z}{L_{u,z}}$	$\begin{cases} \sum_{z\in(\mathbf{A}^{co}\setminus\mathbf{A}_x^{co})\cup(\mathbf{B}^{co}\setminus\mathbf{B}_x^{co})} \frac{P_z \times AirTime_z}{L_{u,z}}, & \text{if Wi-Fi/LAA entrant} \\ \sum_{z\in(\mathbf{A}^{co}\setminus\mathbf{A}_x^{co})\cup(\mathbf{B}^{co})} \frac{P_z \times AirTime_z}{L_{u,z}}, & \text{if LTE-U entrant} \end{cases}$
I_u^{adj}	$\sum_{z\in(\mathbf{A}^{adj}\setminus\mathbf{A}_x^{adj})\cup(\mathbf{B}^{adj}\setminus\mathbf{B}_x^{adj})} \frac{P_z \times AirTime_z}{L_{u,z} \times ACIR_{u,z}}$	$\begin{cases} \sum_{z\in(\mathbf{A}^{adj}\setminus\mathbf{A}_x^{adj})\cup(\mathbf{B}^{adj}\setminus\mathbf{B}_x^{adj})} \frac{P_z \times AirTime_z}{L_{u,z} \times ACIR_{u,z}}, & \text{if Wi-Fi/LAA entrant} \\ \sum_{z\in(\mathbf{A}^{adj}\setminus\mathbf{A}_x^{adj})\cup(\mathbf{B}^{adj})} \frac{P_z \times AirTime_z}{L_{u,z} \times ACIR_{u,z}}, & \text{if LTE-U entrant} \end{cases}$

apply it to both co- and adjacent channel interference.

For Wi-Fi and LAA, we assume the LBT mechanism does not allow co- and adjacent channel APs within CS range[5] of each other to transmit simultaneously. Each of these APs is thus allowed to transmit for only an approximately equal fraction of time. The co- and adjacent channel APs located outside the CS range interfere by decreasing the signal-to-interference-and-noise-ratio (SINR) at the associated user.

For LTE-U, the adaptive duty cycle MAC mechanism adjusts the duty cycle of each AP based on the number of co- and adjacent channel APs detected within the CS range. However, the LTE-U APs within the same CS range may interfere with each other, as they do not check if the channel is unoccupied before transmitting. Instead, they transmit periodically, where we assume uncoordinated LTE-U APs that randomly select the starting moment of their duty cycle period, so that their transmissions may overlap in time. The Wi-Fi incumbents sense the medium unoccupied by coexisting LTE-U entrants for a duration determined by the entrants' adaptive duty cycle, and the likelihood of their overlapping transmissions. Consequently, when coexisting with LTE-U entrants, the incumbents detect the medium unoccupied for a different fraction of time than when coexisting with LAA entrants. The co- and adjacent channel LTE-U APs located outside the CS range decrease the SINR at the associated incumbent or entrant user.

In general we estimate the downlink throughput of an AP x according to our model in [8] as

$$R_x = S_x \times (1 - r_{deg,x}) \times AirTime_x \times \rho_x(SINR_u), \tag{4}$$

[5]The CS range within which co- and adjacent channel APs are located is defined according to the respective CS thresholds given in Section IV-A.

where S_x is the LBT MAC protocol efficiency accounting for sensing time and collisions between LBT frames based on Bianchi's model [22], $r_{deg,x}$ is the additional throughput degradation due to collisions between LBT and duty cycle frames, $AirTime_x$ is the fraction of time that AP x is allowed to transmit according to its own and the other within-CS-range APs' MAC mechanisms, ρ_x is the auto-rate function mapping the SINR to the bit rate, and $SINR_u$ is the SINR at the associated user u of x. A mathematical description of these parameters in given in Table II, where $\mathbf{A}_x$ is the set of co- and adjacent channel incumbent APs within CS range of x, $\mathbf{B}_x$ is the set of co- and adjacent channel entrant APs within CS range of x, $|\mathbf{A}_x|$ is the number of co- and adjacent channel incumbent APs within the CS range of x, $|\mathbf{B}_x|$ is the number of co- and adjacent channel entrant APs within the CS range of x, $|\mathbf{C}_y|$ is the number of co- and adjacent channel incumbent APs within CS range of AP y, and $|\mathbf{D}_y|$ is the number of co- and adjacent channel entrant APs within CS range of AP y.

We estimate the SINR at the associated user u as

$$SINR_u = \frac{P_x (L_{u,x})^{-1}}{I_u^{co} + I_u^{adj} + N_0}, \tag{5}$$

where P_x is the transmit power of AP x, $L_{u,x}$ is the propagation loss between user u and AP x, I_u^{co} is the interference from co-channel APs, I_u^{adj} is the interference from adjacent channel APs, and N_0 is the background noise (assumed -174 dBm/Hz). A mathematical description of these terms is given in Table II, where $\mathbf{A}^{co}$ is the set of all co-channel incumbent APs of x, $\mathbf{A}_x^{co}$ is the set of co-channel incumbent APs within CS range of x, $\mathbf{B}^{co}$ is the set of all co-channel entrant APs of x, $\mathbf{B}_x^{co}$ is the set of co-channel entrant APs within CS range of x, $\mathbf{A}^{adj}$ is the set of all adjacent channel incumbent APs of x, $\mathbf{A}_x^{adj}$ is the set of adjacent channel incumbent APs within CS range of x, $\mathbf{B}^{adj}$ is the set of all adjacent channel entrant APs of x, $\mathbf{B}_x^{adj}$ is the set of adjacent channel entrant APs within CS range of x, P_z is the transmit power of AP z, $AirTime_z$ is the fraction of time AP z may transmit (defined similarly as $AirTime_x$), $L_{u,z}$ is the propagation loss between z and u, and $ACIR_{u,z}$ is the adjacent channel interference ratio given by z's transmitter at u's receiver when operating on adjacent channels. We assume the model in [5] defining $ACIR_{u,z}$ as

$$ACIR_{u,z} = \frac{1}{\frac{1}{ACLR_z} + \frac{1}{ACS_u}}, \tag{6}$$

where $ACLR_z$ is the adjacent channel leakage ratio of transmitter z and ACS_u is the adjacent channel selectivity of receiver u. For Wi-Fi APs and users we assume $ACLR_z$=26 dBm and ACS_x=ACS_u=22 dBm, corresponding to the least efficient Wi-Fi transmitter and receiver,[6] whereas for the LTE-in-unlicensed variants we assume $ACLR_z$=45 dBm, ACS_x=46 dBm, and ACS_u=22 dBm [5], corresponding to the most efficient LTE AP transmitter and receiver, and the same LTE user receiver as for Wi-Fi.

V. Results & Analysis

In this section we present a selection of our simulation results that illustrate the effectiveness of risk assessment for Wi-Fi/LTE coexistence. Specifically, we evaluate the risk of co- and adjacent channel interference for the Wi-Fi incumbents[7] and we show its relevance for spectrum regulators, i.e. in deciding whether regulatory action is required to ensure harmonious inter-technology coexistence, and for engineers designing and optimizing such networks.

We apply the consequence metrics defined in Section III-C as follows. The throughput degradation is estimated for each incumbent AP in each Monte Carlo network realization, resulting in a distribution of throughput degradation over all incumbents in all network realizations. Jain's unfairness is estimated for each network realization, over the set of incumbent throughput values within a single network realization, resulting in a distribution of unfairness over all network realizations.

In this section we first discuss how to read risk assessment charts in general and for our case study. Then we focus on individually assessing the risk of interference for different network densities, channel availability, and deployment scenarios.

A. Reading Risk Assessment Charts

Risk assessment representations in general are likelihood-consequence charts where the curves show an increasing risk of harm from the lower left corner to the upper right corner, as indicated by the red arrow in the example of Fig. 2(b). For the Wi-Fi/LTE coexistence case, the likelihood-consequence charts illustrate the risk of interference that the incumbents suffer when coexisting with different entrants, by following the general rule of increased risk towards the upper right corner. We represent the likelihood as the CCDF of the throughput consequence metrics, for consistency with this rule.

In our figures showing throughput degradation, e.g. Figs. 2(b) and 2(c), a positive throughput degradation shows an actual decrease in throughput compared with the considered baseline, whereas a negative throughput degradation shows an increase in throughput.

B. Effect of Network Density

In this section we demonstrate the advantage of risk over conventional representation of our coexistence study results when assessing interference for various network densities.

Fig. 2 shows an example of conventional and risk representations of incumbent throughput performance results, for the *indoor/indoor* scenario with 10 incumbents and 0–30 entrants, for *single channel* (i.e. co-channel interference only). Specifically, Fig. 2(a) shows an example of a conventional representation as the CDF of the incumbent AP throughput R_x. When the number of entrants increases from 0 to 30, the incumbent throughput decreases from e.g. 10 to 2.5 Mbps for the median value. Also, Fig. 2(a) shows that for a fixed number of entrants, the throughput of incumbents coexisting with Wi-Fi entrants is sometimes higher and sometimes lower than when coexisting with LAA/LTE-U entrants. This suggests that LAA/LTE-U entrants are sometimes friend and sometimes foe to Wi-Fi, but does not readily provide further insightful information. Although such a representation of the absolute throughput is important for coexistence cases since it provides the baseline for calculating the throughput degradation as a relative metric, the performance degradation caused by various entrants cannot be quantified in a straightforward way.

Fig. 2(b) shows the results in Fig. 2(a) in the form of a likelihood-consequence chart, i.e. the CCDF vs. incumbent throughput degradation with the standalone incumbent throughput (i.e. no entrant) as baseline. Fig. 2(b) shows in general that the risk increases significantly when the number of entrants increases, irrespective of the entrant technology. The median incumbent throughput degradation increases from 0% to 75% for 0 to 30 entrants. Also, for each number of entrant APs there is a switching point where the order of the curves corresponding to Wi-Fi and LAA/LTE-U is reversed. Consequently, the risk of incumbent throughput degradation when coexisting with Wi-Fi entrants is sometimes higher and sometimes lower than when coexisting with LAA/LTE-U. LTE-in-unlicensed is thus neither consistently friend nor foe to Wi-Fi, suggesting the engineering policy question is moot.

From a more detailed engineering perspective, it is evident from Fig. 2(b) that the Wi-Fi entrants pose greater risk in case of lower negative impact, whereas the LAA/LTE-U entrants pose greater risk in case of higher negative impact. Let us consider the example case of 30 entrants, where the switching point occurs at a throughput degradation of 72%. For a throughput degradation lower than 72%, the risk posed

[6]We note ACS_x is needed as the power received from adjacent channels is also estimated at AP x, since its level may be high enough, such that x may detect the channel busy and may share its channel in time with (or adapt its duty cycle according to) transmissions in the adjacent channels.

[7]In this paper we seek to illustrate the benefit of risk-informed interference assessment by means of example and we focus on the incumbent performance. We thus omit entrant throughput results as they are not presently relevant, but entrant results are reported in our previous work [8], [9].

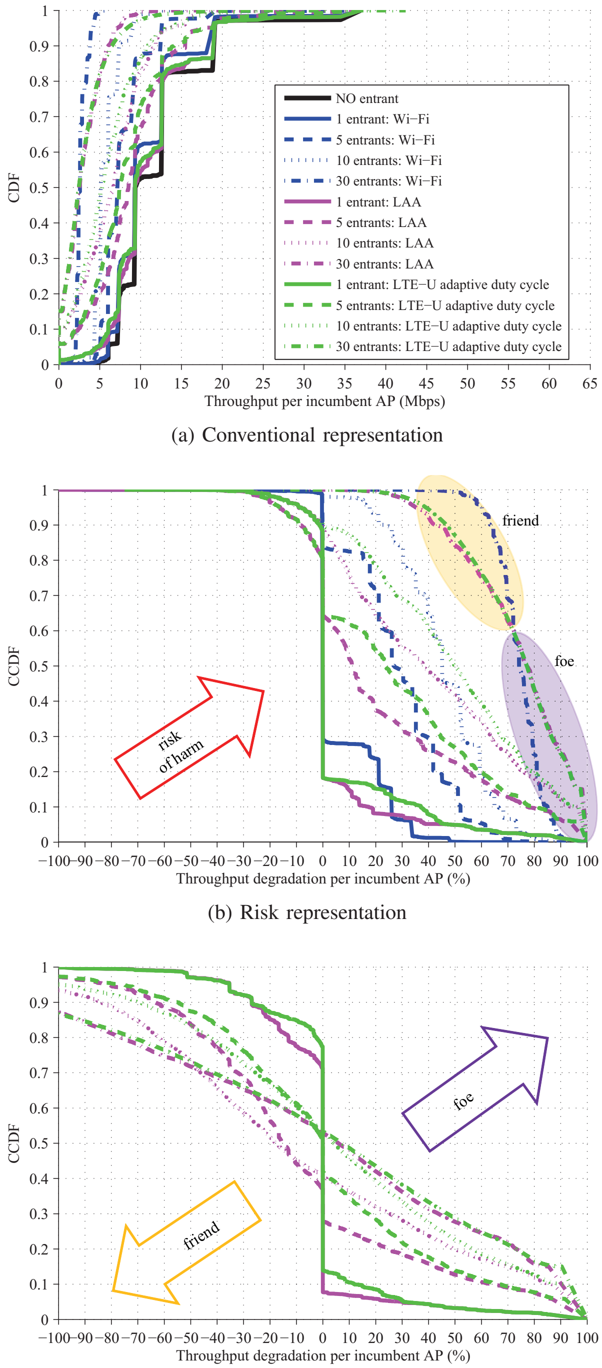
by Wi-Fi entrants is higher than for LAA/LTE-U entrants, whereas for a throughput degradation higher than 72% the opposite holds. This effect occurs due to the value of the CS threshold according to which the incumbent APs defer to the entrants, i.e. the incumbents apply a -82 dBm and -62 dBm threshold to defer to Wi-Fi and LAA/LTE-U entrants, respectively (*cf.* IEEE 802.11). For the lower CS threshold the incumbents are more conservative and avoid strong interference, by deferring to more entrants and transmitting less often. A lower CS threshold is thus suitable for (locally) dense deployments with strong interference, whereas it causes the incumbents to defer unnecessarily in sparse deployments with low interference. The opposite holds for a higher CS threshold.

Fig. 2(b) also shows that for a fixed number of entrants, the throughput degradation from LTE-U and LAA is similar, so LTE-U and LAA are almost equally good neighbours to Wi-Fi. The risk is somewhat higher from LTE-U than LAA, due to the additional collisions in term $r_{x,deg}$ and the adjustment of the entrant duty cycle based on the number of devices detected by the entrants only. Consequently, some incumbents are allowed to transmit for a lower fraction of time than their equal share when considering the number of APs in their own CS range.[8]

Finally, Fig. 2(b) shows that some of the incumbents have a negative throughput degradation when coexisting with entrants compared with the standalone (i.e. no entrant) network. These cases are due to hidden nodes that are continuous sources of interference in the standalone incumbent network, but that interfere only for a fraction of time when they defer to entrants deployed in the coexistence cases. Also, the negative throughput degradation is in some cases an artefact of our throughput model, where the MAC efficiency term S_x is averaged over the entire CS range, sometimes resulting in higher average values for the incumbents when LTE-in-unlicensed entrants with higher S_x are located within the CS range.

In order to focus directly on the question of whether LTE-in-unlicensed is friend or foe to Wi-Fi, Fig. 2(c) shows an alternative risk representation of Fig. 2(b), where the baseline for incumbent throughput degradation is the incumbent throughput when coexisting with Wi-Fi entrants. A positive throughput degradation thus corresponds to LTE being foe, whereas a negative throughput degradation corresponds to LTE being friend to Wi-Fi in unlicensed bands. For a given number of entrants, the percentage of incumbents for which the entrants are friends or foes is similar, with up to 50% being friends and 50% foes for 30 entrants. This clearly shows that for the typical *indoor/indoor* scenario no regulatory intervention is required. In the rest of this paper we focus on the throughput degradation with only the standalone incumbent network as baseline (as in Fig. 2(b)), as this case provides better insight into the more general network densification problem.

Let us now consider the second consequence metric, i.e. Jain's unfairness. Fig. 3 shows an example of conventional and risk representations of Jain's fairness/unfairness among incumbents, for the *indoor/indoor* scenario with 10 incumbents and 0–30 entrants, corresponding to the throughput degradation in Fig. 2. Specifically, Fig. 3(a) shows a conventional represen-



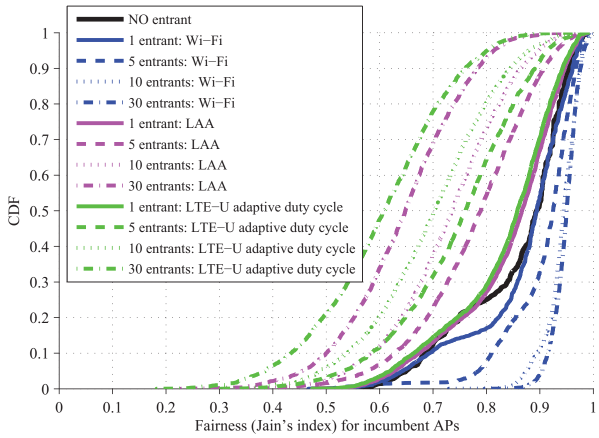
(a) Conventional representation

(b) Risk representation

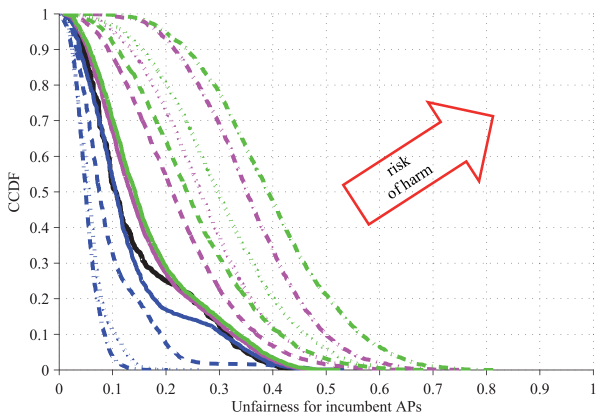
(c) Risk representation

Fig. 2. Example of conventional (a) and risk (b) and (c) representations of incumbent AP performance results for the *indoor/indoor* scenario, for *single channel*, for 10 incumbent and 0–30 entrant APs, as (a) distribution of throughput per incumbent AP; (b) distribution of throughput degradation per incumbent AP with the standalone incumbents as baseline; and (c) distribution of throughput degradation per incumbent AP with the incumbents coexisting with Wi-Fi entrants as baseline.

[8]The opposite effect was shown in [8] for low incumbent and high entrant densities, where the likelihood of short duty cycles and overlapping entrant transmissions is higher, such that the incumbents find the medium unoccupied by entrants for a longer fraction of time.



(a) Conventional representation



(b) Risk representation

Fig. 3. Example of conventional (a) and risk (b) representations of incumbent AP performance results for the *indoor/indoor* scenario, for *single channel*, for 10 incumbent and 0–30 entrant APs, as (a) distribution of Jain's fairness index for incumbent APs in each network realization; and (b) distribution of Jain's unfairness index for incumbent APs in each network realization.

tation as the CDF of the fairness index J. For consistency with the likelihood-consequence charts, Fig. 3(b) shows the same results as Fig. 3(a) in the form of CCDF of throughput unfairness U, where the risk increases towards the upper right corner. We will thus comment only on Fig. 3(b). For a fixed number of entrants, the risk of incumbent unfairness is higher for LAA/LTE-U entrants than for Wi-Fi entrants, consistent with our results in Fig. 2(b), which show that the risk of high throughput degradation is higher for LAA/LTE-U, resulting in larger variation of the throughput degradation. Also, the risk of unfairness increases with the number of entrants for LAA/LTE-U, whereas it decreases for Wi-Fi, given the different CS thresholds that the incumbents apply. Moreover, the risk of unfairness decreases for Wi-Fi below the risk for the standalone incumbent network. Also, LTE-U has a higher risk of unfairness compared with LAA, consistent with its higher throughput degradation for only some incumbents.

Importantly, our results show that for *single channel* the risk is qualitatively different for the two considered consequence metrics. The risk of throughput degradation (relevant for the engineering policy question) in Fig. 2(b) is sometimes higher and sometimes lower for coexistence with LAA/LTE-U than with Wi-Fi (i.e. LAA/LTE-U is sometimes friend and sometimes foe). By contrast, the risk of Jain's unfairness among incumbents (relevant for engineering performance optimization) in Fig. 3(b) is always higher with LAA/LTE-U than with Wi-Fi (i.e. with Wi-Fi, all incumbents are affected in a similar way). This illustrates the importance of choosing a metric that effectively quantifies policy goals, as different metrics, encoding different values, may lead to different conclusions.

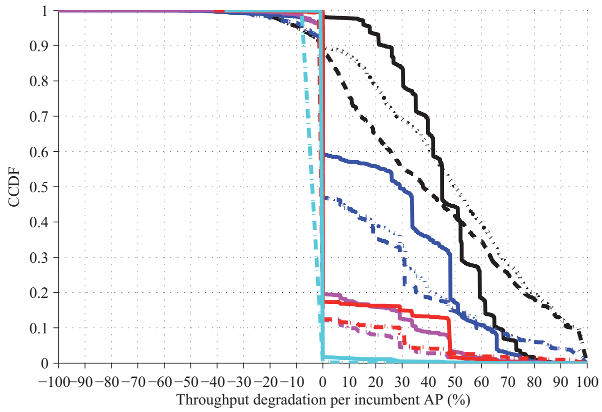
C. Effect of Channel Availability

In this section we assess the risk of interference for the Wi-Fi/LTE coexistence case, for different numbers of channels (i.e. with co- and adjacent channel interference) and channel selection schemes. Fig. 4 shows the incumbent throughput degradation and Jain's unfairness, for the *indoor/indoor* scenario, for 10 incumbents and 10 entrants (i.e. an example with a single AP in each apartment), and 1, 4 and 19 channels with *sense* and *random*. The risk of throughput degradation in Fig. 4(a) increases when the number of channels decreases, from 0% median throughput degradation for 19 channels to 40-50% median throughput degradation for *single channel*.

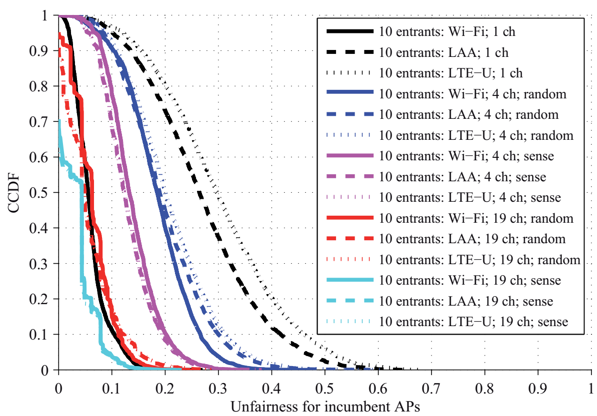
For *sense* with the maximum number of 19 channels (typically available in practice), near-perfect coexistence is ensured between incumbents and entrants (i.e. 0% incumbent throughput degradation), due to the large number of unoccupied channels that the entrants can select from. Also, *random* with 19 channels has similar performance, with only a small percentage of incumbent APs suffering a rather low throughput degradation. This shows that no regulatory or engineering action is needed to ensure harmonious coexistence. As an engineering insight, Fig. 4 reveals that *sense* does not bring significant benefit for such a high number of channels.

For non-DFS devices operating on 4 channels with the entrants implementing *sense*, the throughput degradation is similar to the one for 19 channels, whereas for 4 channels with *random* the throughput degradation increases significantly, showing that engineers should implement *sense* for the rare cases of such a low number of channels. Also, the switching point delimiting the friend/foe entrants (explained in Section V-B) is visible for 4 channels *random* and for *single channel*; for the other cases LAA/LTE-U is an equally good or better neighbour to Wi-Fi than Wi-Fi is to itself.

Fig. 4(b) shows the CCDF of Jain's incumbent unfairness for 1 to 19 channels, where the unfairness increases when the number of channels decreases, with the exception of Wi-Fi, for *single channel*. The highest unfairness is caused by the LAA/LTE-U entrants for *single channel*, but for 4 and 19 channels the unfairness is similar to the one caused by Wi-Fi entrants, consistent with the similar throughput degradation results for all entrant technologies for these number of channels. Importantly, for the typical 19 and also for 4 non-DFS available channels, both consequence metrics consistently show that there is no coexistence problem relevant for engineering policy or engineering optimization.

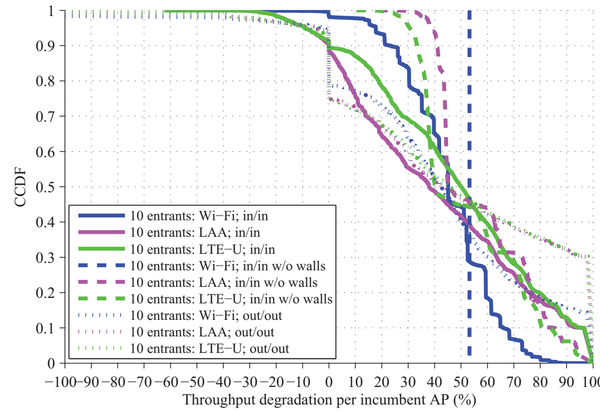


(a)

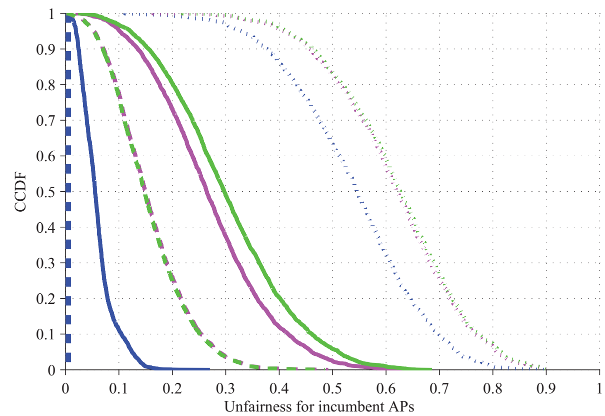


(b)

Fig. 4. Risk representation of incumbent AP performance results for the *indoor/indoor* scenario, for **different number of channels**, for 10 incumbent and 10 entrant APs, as (a) distribution of throughput degradation per incumbent AP with the standalone incumbents as baseline; and (b) distribution of Jain's unfairness index for incumbent APs in each network realization.



(a)



(b)

Fig. 5. Risk representation of incumbent AP performance results for the ***indoor/indoor***, ***indoor/indoor without internal walls***, and ***outdoor/outdoor*** scenarios, for *single channel*, for 10 incumbent and 10 entrant APs, as (a) distribution of throughput degradation per incumbent AP with the standalone incumbents as baseline; and (b) distribution of Jain's unfairness index for incumbent APs in each network realization.

D. Effect of Deployment Scenario

This section shows the benefit of risk assessment when quantifying the harm of interference in different scenarios, i.e. *indoor/indoor*, *indoor/indoor without internal walls*, and *outdoor/outdoor*. Fig. 5 shows how different scenarios affect the incumbent throughput degradation and Jain's unfairness for *single channel*, for 10 incumbents and 10 entrants. Importantly, Fig. 5(a) shows a consistent switching point between Wi-Fi and LAA/LTE-U curves across different scenarios at 40-50% degradation. LTE-in-unlicensed is thus consistently sometimes friend and sometimes foe to Wi-Fi, regardless of the scenario.

When comparing different scenarios for a given entrant technology in Fig. 5(a), we observe the following engineering insights: (i) the lowest risk of low throughput degradation is achieved for the *outdoor/outdoor* scenario and the highest risk of low degradation for the *indoor/indoor* scenario *without internal walls*; (ii) the highest risk of high throughput degradation is achieved for the *outdoor/outdoor* scenario and the lowest risk of high degradation for the *indoor/indoor* scenario *without internal walls*; and (iii) for the *indoor/indoor* scenario there is a moderate risk of high and low throughput degradation. This shows that the variation of incumbent throughput is highest in the *outdoor/outdoor* scenario, moderate for the *indoor/indoor* scenario, and low for the *indoor/indoor* scenario *without internal walls*. This effect is consistent with the interference conditions in each scenario. For the *indoor/indoor* scenario *without internal walls* where the interference is high and the APs are located close to each other, the incumbents detect more entrants and are able to better avoid strong interference by deferring to them, at the expense of sharing the channel in time. Specifically, almost all incumbents suffer a degradation of at least 20%, and for coexistence with Wi-Fi entrants the incumbent degradation is constant and equal to 52%, as every incumbent detects all incumbents and entrants within CS range and the MAC efficiency also changes accordingly. In the *outdoor/outdoor* scenario the AP network deployment is more sparse and the users are located at a wider range of distances from the APs that they are associated with. Consequently, users close to their corresponding APs experience low risk of degradation, but users far from their corresponding APs may face hidden node problems (i.e. at least 15% of the APs have a throughput degradation of 100%). The interference in the *indoor/indoor* scenario where the APs are separated by walls is moderate compared with the other scenarios.

We note that in our previous work [8], [9] we observed that in the *indoor/outdoor* scenario, i.e. where the incumbents are located indoors and the entrants are located outdoors, the incumbents and entrants are isolated from each other, due to the high attenuation through the external walls. The corresponding risk of interference from the entrants to the incumbents would therefore be zero, so we do not present results for this scenario in this paper.

Fig. 5(b) shows Jain's throughput unfairness among incumbents for different scenarios. Consistent with our results in Fig. 5(a) and the corresponding discussion, the lowest unfairness is achieved for the *indoor/indoor* scenario *w/o internal walls* with down to zero unfairness for incumbents coexisting with Wi-Fi entrants. A moderate risk of unfairness is shown for the *indoor/indoor* scenario, whereas for the *outdoor/outdoor* scenario the unfairness is large. Also, for each specific scenario, the unfairness when coexisting with Wi-Fi entrants is lower than when coexisting with LAA/LTE-U entrants, consistent with the values of the CS threshold that the incumbents implement.

VI. Conclusions

In this paper we presented a case study of Wi-Fi/LTE coexistence in the 5 GHz band, in order to demonstrate the value of risk-informed interference assessment in making regulatory decisions and for providing engineering insight. We applied risk assessment methods to this coexistence problem by (i) identifying co- and adjacent channel interference as hazard modes, (ii) defining the throughput degradation and Jain's throughput unfairness as consequence metrics, and (iii) assessing the likelihood and consequence for different network densities, numbers of available channels, and scenarios (i.e. *indoor/indoor*, *indoor/indoor without internal walls*, and *outdoor/outdoor*). We performed extensive Monte Carlo simulations for Wi-Fi incumbents coexisting with Wi-Fi/LAA/LTE-U entrants and we estimated the downlink throughput by considering co- and adjacent channel interference.

Our analysis showed that risk assessment is an effective method for evaluating the harm caused by interference in a comprehensive and intuitive manner. This method clearly showed that LTE-in-unlicensed is neither friend nor foe to Wi-Fi in general, and thus that no regulatory intervention is needed to ensure harmonious technical coexistence. From an engineering perspective, our analysis showed that Wi-Fi incumbents suffer a lower risk of interference when coexisting with Wi-Fi entrants compared with LTE-in-unlicensed entrants in locally dense deployments, but the opposite holds for sparse deployments, due to the Wi-Fi MAC design. Also, for the high number of available channels expected in practice, there is a negligible risk of interference for Wi-Fi incumbents from LTE-in-unlicensed entrants, which renders both policy and engineering coexistence issues largely irrelevant.

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