LTE Transmission in Unlicensed Bands: Evaluating The Impact Over Clear Channel Assessment

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Abstract—**Among the significant advances in mobile network technology, as evident in the latest 3GPP releases, one of the most notable is the possibility to do aggregation between licensed and unlicensed carriers. With LTE transmitting over unlicensed bands, obvious concerns of a fair co-existence with other pre-existing technologies have risen up. In this study, we aim to evaluate the impact of LTE transmission on the key mechanism of Clear Channel Assessment (CCA), which is common to several unlicensed systems, amongst which Wi-Fi is the most notable. Relying on the statistical tool of stochastic geometry and a semi-analytical approach, we will obtain the probabilities of Wi-Fi preamble false alarm and detection under a wide set of realistic propagation effects, such as path-loss and Rayleigh distributed fading. Above all, we will model the effect of a single LTE down-link interfering transmission, as well as the aggregate interference effect. Hence, we shall be able to evaluate the modified energy detection threshold that has been long debated between 3GPP and IEEE 802.11 Working Groups.**

I. Introduction

In recent years the mobile network technology has undergone to a major revolution known as 5G. In the endeavor to reach dramatic performance improvements, several new features have been introduced by 3GPP even before the full fledged 5G solution is unveiled. Notably, in Releases 12, 13 and 14 (i.e. for LTE technology), 3GPP introduced the new feature of using unlicensed spectrum as a supplement to costly and scarce licensed carriers.

As summarized in [1], two main forms of LTE in unlicensed spectrum were developed by 3GPP: LTE-Unlicensed (LTE-U), and Licensed Assisted Access (LAA). Initially designed for transmitting the down-link communication channels, in Rel. 14 this feature has been extended also to specific up-link channels. Both systems are meant to be deployed in the 5 GHz band, although this lacks worldwide harmonization. Another interesting approach was introduced with MulteFire [2], an industry led initiative driven by the MulteFire Alliance in which only unlicensed spectrum is used by the mobile network technology.

Depending upon the channel access scheme adopted, the behavior of an unlicensed LTE system could have been more or less aggressive towards other pre-existing radio technologies. Among the systems that could be affected by unlicensed LTE transmissions, this study involves the effect of letting LTE proliferate on the 5 GHz unlicensed band, considering Wi-Fi as the victim system. With LTE transmitting in the 5 GHz unlicensed band, obvious concerns of coexistence with other wireless technologies have risen up. In this regard, Wi-Fi, probably the most popular unlicensed technology, has become a major concern. Therefore, 3GPP began investigating improved LTE, Wi-Fi coexistence.

One challenge consists of determining the impact of LTE transmissions over the crucial Clear Channel Assessment (CCA) mechanism that is typically carried out by Wi-Fi devices prior to transmitting packets over the wireless medium. CCA relies on an energy detection (ED) operation that is done on specific symbols of the whole preamble sequence, and this is common not only in Wi-Fi but to other unlicensed protocols as well (e.g. IEEE 802.15.4).

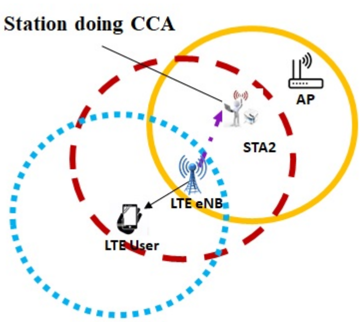
Regarding this topic, the contribution of this work is manifold. First, relaying on the powerful tool of stochastic geometry, we will obtain the probabilities of false alarm and detection that characterize the energy detection during CCA when we target the preamble structure of the IEEE 802.11n standard. To do this, we rely on a semi-analytical approach that is based on the characteristic function (CF) of the ED decision variable when LTE interference affects the CCA operation. This method proves to be very general, and it allows modeling the path-loss affecting both useful (i.e. Wi-Fi transmission) and interfering signals (i.e. down-link LTE transmission), as well as channel fading. Second, we model interference with exactly one LTE interferer, whereas to model the aggregate LTE interference effect we resort to mathematically tractable Poisson Point Processes (PPPs). Finally, we will obtain the new Wi-Fi energy detection threshold when LTE interference affects CCA. If the ED threshold usually is selected to minimize preamble false alarm and maximize the detection, fulfill both is not always possible when the energy detection is affected by interference. Therefore, we aim to identify effective design to improve the coexistence situation. To the best of the authors' knowledge, this is the first research work that makes the attempt to develop a general model to LTE, Wi-Fi coexistence that can be used to compute the ED threshold in different scenarios and propagation conditions.

The rest of the paper organized as follow. Section II presents a review of the related work. We describe the system model in Section III, and system analysis in Section IV, respectively.

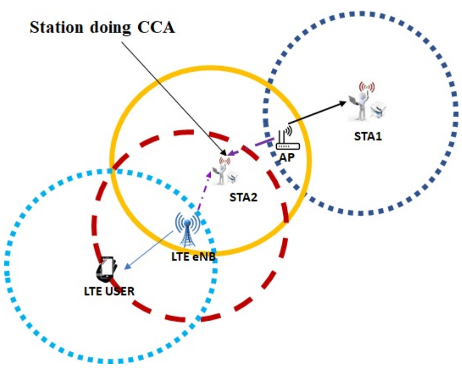
Numerical results are shown in Section V, whereas Section VI provides the concluding remarks fo the paper.

II. Related work

Despite it is a fairly recent topic, LTE, Wi-Fi coexistence has already been studied in several research papers. In [3], the authors propose a simple approach that requires minimal changes to the current LTE protocols by adopting a discontinuous transmission pattern, whereas in [4], the authors tried to avoid interference to Wi-Fi by limiting LTE presence on the bandwidth through allocating only a fraction of the air time for it. Listen Before Talk (LBT), used in LTE LAA, was proposed in [5] in which a random back-off is drawn within a fixed contention window size. Moreover, in [6], the authors analyze three different co-existence scenarios of continuous and non-continuous LTE transmission resorting to stochastic geometry. As evidenced in [7], a debate between 3GPP and the IEEE 802.11 Working Group started around different ED threshold values to use in LTE-LAA or 802.11ax, which stresses the importance of adjusting the threshold for either of these technologies. Regarding the way of modeling the interference distribution from an analytical standpoint, we rely on the rich existing literature that already demonstrated that the aggregate interference behaves as a shot noise process [8], [9], [10], and the simple Gaussian distribution used extensively in the past is not adequate to characterize accurately the random interfering process.



(a) Preamble false alarm case



(b) Preamble detection case

Fig. 1: Hidden LTE transmitter scenarios for studying false alarm (a) and detection (b).

III. System Model

In this work, we assume LTE base station (i.e. small cell eNodeB in this paper) transmissions interfere with the CCA operation of a Wi-Fi station. While LTE-U dose not have any specific mechanism to address the status of the channel and the interference with Wi-Fi is very probable, the LBT mechanism of LAA, which senses the channel before transmitting, still could cause interference to Wi-Fi as in the typical hidden node problem; When an LTE user is out of Wi-Fi transmission range while LTE eNB is located withing that range. The general scenario for studying false alarm and miss-detection is shown in Fig. 1.

The general spatial configuration of terminals is shown in Fig. 2, in which the test Wi-Fi terminal doing CCA is located at the center of the two-dimensional reference system. Interfering LTE nodes are independently and randomly distributed over space and all links are affected by path-dependent loss with exponent α. Moreover, the path-loss model assumed in this work is such that $l(x, y) = ||x-y||^{\alpha}$. In Fig. 2, $r_{\rm s}$ denotes the sensing range of the CCA station. The active Wi-Fi link is interchangeably referred to as the useful link, while an LTE transmission as interfering link. The spatial configuration that we use to study the probability of false alarm ($P_{\rm fa}$), in which there is no useful link, but the node doing CCA wrongly detects the channel busy due to the existence of interference is shown in Fig. 1(a), whilst the scenario for deriving the probability of detection ($P_{\rm d}$), in which the node will sense the channel busy upon detecting the preamble, in Fig. 1(b).

The CCA operations uses the simple non-coherent energy detection on specific symbols of the whole preamble sequence. Communication links (useful and interfering) are assumed statistically independent and corrupted by Additive White Gaussian Noise (AWGN) that is assumed a circularly symmetric complex ($\mathcal{CN}$) random variable (r.v.) $n(t)$ with zero mean and variance σ^2, and are affected by Rayleigh distributed amplitude channel fading. In other words, communications are affected by exponential power fading. All power fading coefficients, denoted by g, are assumed independent and identically distributed (i.i.d.), random variables (r.vs.) with a unit mean.

Regarding LTE transmissions, we are interested in studying the case of single LTE interferer and generalize it to the case of aggregate LTE interference. This allows us to study two extreme conditions of mild and severe interference that may affect the CCA operation of Wi-Fi. As mentioned, the aggregate interference is modeled through a PPP with spatial density λ_s. Particularly, we denote by Ω the set of active LTE transmitters, i.e., an LTE interferer located in point X of the spatial point process contributes to the interference *iff* it belongs to Ω.

The semi-analytical approach consists of developing the characteristic function of the ED decision variable (d.v.) Y. Conditioning upon the distribution of the interference, channel fading and distance-dependent loss this is known to follow a Chi-Square distribution. Using the Characteristic Function

(CF), we manage to remove the statistical dependence upon the position of the LTE interfering devices, as well as the channel fading. Finally, we manage to compute $P_{\rm fa}$ and $P_{\rm d}$ inverting the CF by means of a numerical integration. To do this, we rely on the standard definition of these two probabilities as follows

$$P_{\rm fa} := P_{\rm r}\{Y > \lambda|\mathcal{H}_0\}, P_{\rm d} := P_{\rm r}\{Y > \lambda|\mathcal{H}_1\} \ , \qquad (1)$$

where $\mathcal{H}_0$ and $\mathcal{H}_1$ stand for the two statistical hypotheses of absence and presence of useful signal, respectively, and λ is the energy detection threshold. We observe that with interference the Chi-Square distribution is always non-central with a non-centrality parameter (μ) that can be distinguished depending on the test hypothesis.

A. Transmitted Signals Representation

Since both Wi-Fi and LTE use OFDM modulation, the low-pass representation of the both signals relies on the expression used in [11]. For the Wi-Fi signal this is as follows

$$s(t) = \mathcal{R}\Big\{\sum_{n=0}^{N-1} A_n p(t) e^{j2\pi f_n t}\Big\} \ , \qquad (2)$$

where $\mathcal{R}\{\cdot\}$ stands for the real part operator, $p(t)$ is the waveform with unitary energy, N is the number of OFDM sub-carriers, $f_n = \Delta f(n - \frac{N-1}{2})$, with $\Delta f = 1/t_{\rm s}$ the sub-carrier spacing (i.e. 312.5 kHz in Wi-Fi), $t_{\rm s}$ the preamble symbol duration and A_n the nth complex transmitted preamble symbol. Based on the expression shown in eq. (2) we can provide the expression of the Wi-Fi preamble sequence

$$S(t) = \sum_{k=1}^{N_{\rm s}}\sum_{n=0}^{N-1} a_n^{(k)} p(t - kt_{\rm s}) e^{j2\pi f_n t} = \sum_{k=1}^{N_{\rm s}} x_n(t - kt_{\rm s}) \ , \qquad (3)$$

with $N_{\rm s}$ the number of preamble symbols used during CCA, $|a_n^{(k)}| = \sqrt{\frac{\varepsilon_{\rm s}}{N}}$ is the signal amplitude of the kth preamble symbol on the nth sub-carrier and $\varepsilon_{\rm s}$ is the transmitted symbol energy. In this work, we chose Wi-Fi nodes that use the IEEE 802.11n standard in mixed mode. In other words, the CCA operation is done in one Legacy Short Training OFDM symbol (L_SFT) that is identical to a IEEE 802.11a OFDM symbol [12]. Similarly, the low-pass representation of the LTE interfering signal can be written as

$$\xi(t) = \mathcal{R}\Big\{\sum_{m=0}^{M-1} A_m b(t) e^{j2\pi f_m (t-\tau)+\varphi}\Big\} \ , \qquad (4)$$

where $M \neq N$ denotes the number of OFDM sub-carriers, $f_m = \Delta F(m - \frac{M-1}{2})$ and ΔF is the sub-carrier spacing (15 kHz for LTE), A_m is the mth complex LTE transmitted symbol, $b(t)$ is the transmitted waveform with unitary energy, τ is a random delay time that takes into account that the LTE transmission is asynchronous with respect to the useful Wi-Fi signal, and φ is a uniformly distributed r.v. in the interval $[0, 2\pi)$. Similar to the case of useful signal, we can rewrite eq. (4) as follows

$$\xi(t) = \sum_{m=0}^{M-1} a_m b(t-\tau) e^{j2\pi f_m (t-\tau)+\varphi} = \sum_{m=0}^{M-1} x_m(t-\tau, \varphi) \ , \qquad (5)$$

where $|a_m| = \sqrt{\frac{\varepsilon_{\rm I}}{M}}$ is the per sub-carrier energy with $\varepsilon_{\rm I}$ the transmitted LTE symbol energy. Finally, the case of aggregate interference can be obtained from eq. (5) straightforwardly as follows $I(t) = \sum_{X\in\Omega} \xi_X(t)$, where ξ_X stands for the interfering signal caused by the active LTE transmitter located at point X in the spatial point process.

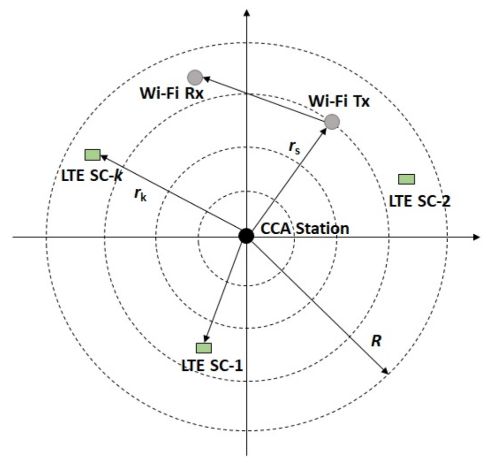


Fig. 2: General scenario for studying interference

IV. System Analysis

In this section, we provide the detailed analysis of the false alarm and detection probabilities when LTE interference affects the CCA operation by means of developing first the CF of the d.v. in each case of interest, and subsequently doing a numerical integration. The CF of a r.v. x is defined as $\Psi(v) := \mathbb{E}\{e^{jvx}\}$. It is worth providing the following expression as the general way to write the received signal with interference, corrupted by additive noise and fading:

$$r(t) = h_{\rm s} S(t) + h_{\rm I} \mathbb{1}_\Omega I(t) + n(t) \ , \qquad (6)$$

where $\mathbb{1}_\Omega(X)$ is an indicator r.v. that is one when the interfering signal $I(t)$ is present and zero otherwise. The latter case will be used to obtain the benchmark performance for CCA affected only by path-loss and fading. As mentioned, $I(t)$ reduces to $\xi(t)$ in case exactly one LTE interferer is active. In our study, the signal $S(t)$ is the ongoing preamble transmitted by a Wi-Fi node $r_{\rm s}$ apart that the test Wi-Fi station must detect. The terms $h_{\rm s}$ and $h_{\rm I}$ respectively denotes the effect introduced by the channel fading for useful and interfering signals and $h := \theta e^{j\phi(t)}$, which is such that $|h|^2 = g$ after the squaring operation of the ED receiver. Complying with the two typical statistical hypothesis for false alarm and detection, we denote by r_0 the received signal when no useful Wi-Fi transmission is on the air (i.e. hypothesis $\mathcal{H}_0$), and with r_1 the received signal when the useful transmission is present (i.e. hypothesis $\mathcal{H}_1$). Before deriving the false alarm and detection probabilities in the different cases of interference, it is worth so clarify that after obtaining the CF of the decision variable in each case, we will make use of the Gil-Pelaez inversion theorem [13] to compute the complementary probability

$$P_{\mathrm{r}}\{X > x\} = \frac{1}{2} + \frac{1}{\pi}\int_0^\infty \mathrm{Im}\left(\frac{\Psi(v)e^{-jvx}}{v}\right)dv \ , \qquad (7)$$

with $\mathrm{Im}(\cdot)$ that denotes the imaginary operator. The received signal under the two statistical hypotheses when exactly one LTE interfering signal affects the CCA operation can be written as

$$r_0(t) = h_{\mathrm{I}}\xi(t) + n(t) = X_{\mathrm{I}}(t) + n(t), \text{ under } \mathcal{H}_0$$

$$\begin{aligned} r_1(t) &= h_{\mathrm{s}}S(t) + h_{\mathrm{I}}\xi(t) + n(t) \\ &= X_{\mathrm{S}}(t) + X_{\mathrm{I}}(t) + n(t), \text{ under } \mathcal{H}_1 \ . \end{aligned} \qquad (8)$$

Relying on [14], the analog d.v. Z (in the continuous time domain) can be found by applying the following operation to the received signal: $Z = \frac{1}{2\sigma^2}\int_0^T |r(t)|^2 dt$, where T is the integration time and $\sigma^2 = \frac{N_0}{2}$ is the variance of the two-sided white Gaussian noise. After sampling at the Nyquist rate the continuous time problem, we obtain the d.v. Y for the discrete time version of the variable Z as follows

$$Y = \frac{1}{2\sigma^2}\sum_{q=1}^{2Q}\frac{r_q^2}{2W} \ , \qquad (9)$$

where $Q = WT$ denotes the number of degrees of freedom of the Chi-Square distribution with W the signal bandwidth. We point out that due to the assumption that all links are independent, the cross-terms are neglected and we distinguish the d.v. based on the test hypotheses $\mathcal{H}_0$ and $\mathcal{H}_1$ as

$$\begin{aligned} Y_0 &\simeq \frac{1}{2\sigma^2}\sum_{q=1}^{2Q}\left(\frac{X_{Iq}^2 + n_q^2}{2W}\right), \\ Y_1 &\simeq \frac{1}{2\sigma^2}\sum_{q=1}^{2Q}\left(\frac{X_{sq}^2 + X_{Iq}^2 + n_q^2}{2W}\right) \ . \end{aligned} \qquad (10)$$

Since with interference the d.v. follows a non-central Chi-Square distribution, we are able to write the non-centrality parameters based on the two test hypotheses.

$$\mu_0 = \frac{1}{2\sigma^2}\sum_{q=1}^{2Q} X_{\mathrm{I}q}^2 = \frac{1}{2\sigma^2}\sum_{m=0}^{M-1}\sum_{q=1}^{2Q}\left(h_{\mathrm{I}m,q}x_{m,q}\right)^2 = g_{\mathrm{I}}\frac{a_{r\mathrm{I}}^2}{2\sigma^2} \qquad (11)$$

$$\begin{aligned} \mu_1 &= \frac{1}{2\sigma^2}\sum_{q=1}^{2Q}\left(X_{\mathrm{s}q}^2 + X_{\mathrm{I}q}^2\right) = \frac{1}{2\sigma^2}\Bigg[\sum_{k=1}^{N_{\mathrm{s}}}\sum_{n=0}^{N-1}\sum_{q=1}^{2Q}\left(h_{\mathrm{s}n,q}x_{n,q}\right)^2 \\ &+ \sum_{m=0}^{M-1}\sum_{q=1}^{2Q}\left(h_{\mathrm{I}m,q}x_{m,q}\right)^2\Bigg] = g_{\mathrm{s}}N_{\mathrm{s}}\frac{a_{r\mathrm{s}}^2}{2\sigma^2} + c \times g_{\mathrm{I}}\frac{a_{r\mathrm{I}}^2}{2\sigma^2} \ , \end{aligned} \qquad (12)$$

where $a_{r_{\mathrm{s}n}} = \sqrt{\varepsilon_{r\mathrm{s}}/N}$, $\varepsilon_{r\mathrm{s}} = \varepsilon_{\mathrm{s}} r_{\mathrm{s}}^{-\alpha}$ and $a_{r_{\mathrm{I}m}} = \sqrt{\varepsilon_{r\mathrm{I}}/M}$, $\varepsilon_{r\mathrm{I}} = \varepsilon_{\mathrm{I}} r^{-\alpha}$ are the per sub-carrier received useful and interfering signals energy, respectively. We recall that the distance r_{s} stands for the distance separating the CCA station from a Wi-Fi station transmitting the preamble. On the other hand, the distance r denotes the random distance separating the CCA station from an LTE interferer. The factor c (shown later in Sect. V) is an oversampling factor that takes into account that an OFDM symbol in LTE has a different duration ($\sim$71 μs) compared to a preamble symbol (0.8 μs) and that sampling rates are different in the two systems.

Before showing the CF of the d.v. Y with single LTE interferer, we will provide few more useful facts. Referring to Fig. 2, the random distance separating an LTE interfering transmitter and the CCA station is assumed to follow a 2-dimensional uniform distribution in the interval $[r, r + dr)$ with probability $\frac{2r}{R^2}dr$ for some radius $R > 0$. The CF of the non-central Chi-Square distributed r.v. is $\Psi(v) = \big(1 - j2v\big)^{-Q}\exp\big(\frac{jv}{1-j2v}\mu\big)$, and the Poisson distribution in a measurable set $\mathcal{A}$ of area A has the expression:

$$P_{\mathrm{r}}\{\kappa = K\} = \frac{\big(\lambda_{\mathrm{s}}A\big)^K}{K!}\exp\big(-\lambda_{\mathrm{s}}A\big) \ . \qquad (13)$$

For the sake of computing subsequent derivations, we emphasize that all probabilities are obtained through the Gil-Pelaez inversion theorem in eq. (7). Since the power fading is exponential with $\mathbb{E}\{g\} = 1$, the CF is $\big(1 - jv\big)^{-1}$. Hence, the overall CF of the d.v. Y with fading is as follows

$$\Psi(v) = \frac{1}{(1 - j2v)^Q} \times \frac{1}{1 - \frac{jv}{1-2jv}\mu} \ . \qquad (14)$$

A. False alarm and Detection in No Interference Case

In the no interference case, the false alarm probability (under statistical hypothesis $\mathcal{H}_0$) is simply computed as $P_{\mathrm{fa}} = \Gamma(Q, \lambda/\sigma^2)/\Gamma(Q)$ [15]. When only fading and path-loss are taken into account, the detection probability is computed through the CF approach using eq. (14) with $\mu = N_{\mathrm{s}}\frac{a_{r\mathrm{s}}^2}{2\sigma^2} = N_{\mathrm{s}}\frac{\varepsilon_s}{N_0}r_{\mathrm{s}}^{-\alpha}$. Plugging the CF in eq. (7) P_{d} can be evaluated numerically.

B. Characteristic Function in a Single Interferer Network

In this interference case exactly one LTE interferer is active. Since false alarm is studied under the statistical hypothesis $\mathcal{H}_0$, the d.v. is non-Central Chi-Square distributed with non-centrality parameter μ_0 provided in (11). Relying on the general expression of the CF of a Chi-Square r.v. we are able to rewrite it conditioning upon the fading and distance distributions.

$$\Psi_0(v \mid g, r) = \frac{1}{(1 - j2v)^Q}\mathrm{e}^{\frac{jv}{1-2jv}gc\frac{\varepsilon_{\mathrm{I}}}{N_0}r^{-\alpha}} \ .$$

To obtain the unconditional expression of the CF it suffices to compute $\mathbb{E}_g\mathbb{E}_r\Psi(v \mid g, r) = \Psi(v)$. We remove first the conditioning on g by means of the CF of an exponential r.v. already mentioned above. After doing a sign change we obtain:

$$\Psi_0(v \mid r) = \frac{1}{(1-2jv)^Q} \times \frac{1}{1 + \frac{jv}{-1+j2v} c \frac{\varepsilon_{\mathrm{I}}}{N_0} r^{-\alpha}} ,$$

where the above expression was obtained computing eq. (14) in $c \times \big(\varepsilon_{\mathrm{I}}/N_0\big) r^{-\alpha}$. To derive the CF of the d.v. under single LTE interferer condition, we rely also on the following result.

Lemma 1: For any complex constant $G \in \mathbb{C}$, path-loss exponent $\alpha > 2$ and $R > 0$ the following integral holds:

$$\int_0^R \frac{1}{1+Gr^{-\alpha}} \frac{2r}{R^2} dr = \frac{2R^{\alpha} {}_2F_1(1, \frac{2+\alpha}{\alpha}; 2+\frac{2}{\alpha}; -\frac{R^{\alpha}}{G})}{G(2+\alpha)} ,$$

where this result was obtained using the tool of Mathematica.

Assuming that $G = \frac{jv}{-1+j2v} c \times \big(\frac{\varepsilon_{\mathrm{I}}}{N_0}\big)$ and using the result in Lemma 1, we obtain the CF of the d.v. under statistical hypothesis $\mathcal{H}_0$ as follows

$$\Psi_0(v) = \frac{1}{(1-j2v)^Q} \times \frac{2R^{\alpha}}{c \times \frac{\varepsilon_{\mathrm{I}}}{N_0} \frac{jv}{j2v-1}(2+\alpha)} \times {}_2F_1\left(1, \frac{2+\alpha}{\alpha}, 2+\frac{2}{\alpha}, \frac{R^{\alpha}}{\frac{\varepsilon_{\mathrm{I}}}{N_0}\big(\frac{jv}{1-2jv}\big)}\right) , \quad (15)$$

with ${}_2F_1(\cdot)$ the hyper-geometric function.

Similarly, to compute the CF of the d.v. under hypothesis $\mathcal{H}_1$, it suffices to follow similar steps but replacing the non-centrality parameter with μ_1 provided in eq. (12). As before, we have to remove the dependence upon the independent fading coefficients and the random distance: $\Psi_1(v) = \mathbb{E}_{g_{\mathrm{s}}} \mathbb{E}_g \mathbb{E}_r \Psi(v \mid g_{\mathrm{s}}, g, r)$. Repeating similar step, we obtain

$$\Psi_1(v) = \frac{1}{(1-j2v)^Q} \times \frac{1}{1 - \frac{jv\varepsilon_{\mathrm{s}}}{1-j2vN_0} r_{\mathrm{s}}^{-\alpha}} \times \frac{2R^{\alpha}}{c\frac{\varepsilon_{\mathrm{I}}}{N_0}\frac{jv}{j2v-1}} \times \frac{{}_2F_1\left(1, \frac{2+\alpha}{\alpha}, 2+\frac{2}{\alpha}, \frac{R^{\alpha}}{\frac{\varepsilon_{\mathrm{I}}}{N_0}\big(\frac{jv}{1-2jv}\big)}\right)}{2+\alpha} , \quad (16)$$

where r_{s} is a parameter that can be varied for the sake of showing results in Sect. V.

C. Characteristic Function with Aggregate Interference

For the aggregate LTE interference case, conditioning upon exactly K independent LTE active transmitters we rewrite the overall aggregate interfering process $I_K(t) = \sum_{k=0}^{K} \xi_k(t)$. Similar to the single interferer case, each interfering transmission is written as $\xi_k = c_k \times g_k \varepsilon_{\mathrm{I}_k} r_k^{-\alpha}$, where g_k are the i.i.d. channel power fading coefficients, and r_k the random distance of the kth interferer from the CCA station in the 2-dimensional plane. Conditioning upon the aggregate interference distribution, under statistical hypothesis $\mathcal{H}_0$, the distribution of the d.v. Y is non-central Chi-squared with a non-centrality parameter: $\mu_0 = \frac{1}{2\sigma^2}\sum_{k=0}^{K} c_k g_k \varepsilon_{\mathrm{I}_k} r_k^{-\alpha}$. This is plugged in the CF of the non-Central Chi-square distributed d.v. as follows

$$\Psi_{0|k}(v) = \frac{1}{(1-j2v)^Q} \exp\left(\frac{jv}{1-j2v}\frac{1}{2\sigma^2}\sum_{k=0}^{K} c_k g_k \varepsilon_{\mathrm{I}k} r_k^{-\alpha}\right) .$$

The previous expression can be rewritten as

$$\Psi_{0|K}(v \mid g_k, r_k) = \frac{1}{(1-2jv)^Q} \prod_{k=1}^{K} \exp\left(-a_k g_k r_k^{-\alpha}\right) ,$$

where $a_k = a = \frac{jv}{-1+j2v}\frac{c \times \varepsilon_{\mathrm{I}}}{2\sigma^2}$, $\forall k$ since the energy of each signal and the scaling factor c are the same for each interferer. The characteristic function is conditioned upon the specific realization of the fading and distances g_k and r_k, respectively. The following step consists of removing the dependence upon the fading and distance as $\Psi_{0|K}(v) = \mathbb{E}_{g_k}\mathbb{E}_{r_k}\Psi_{0|K}(v \mid g_k, r_k)$. Since all r.vs. are statistically independent and the expectation is a linear operator, we can change the order of the expectations to remove first the conditioning upon the r.v. g_k. Relying on the assumption of exponential fading with $\mathbb{E}g = 1$, we obtain $\Psi_{0|K}(v \mid r_k) = \frac{1}{(1-j2v)^Q}\prod_{k=1}^{K}\big(1 + sr_k^{-\alpha}\big)^{-1}$, where the last expression is computed in $s = a$. Dropping the index k in the distance we are able to rewrite: $\Psi_K(v \mid r) = \frac{1}{(1-j2v)^Q} \times (\frac{1}{1+sr^{-\alpha}})^K$.

Since the r.v. K is Poisson distributed, we can use eq. (13) to remove the dependence on it. For a real-valued measurable function f that takes values on the point process Φ it holds that $\prod_{x\in\Phi} f(x) = \exp\big(-\lambda_s \int_{\mathbb{R}^2}\big(1 - f(x)\big)dx\big)$, which is an important result in stochastic geometry that yields:

$$\begin{aligned}\Psi_0(v) &= \frac{1}{(1-j2v)^Q}\exp\big(-\lambda_s\int_{\mathbb{R}^2}(1 - \frac{1}{1+sr^{-\alpha}})dr\big) \\ &= \frac{1}{(1-j2v)^Q}\exp\big(-\lambda_s\int_{\mathbb{R}^2}(\frac{1}{1+s^{-1}r^{\alpha}})dr\big).\end{aligned}$$

Lemma 2: For any $s \in \mathbb{C}$, path-loss exponent $\alpha > 2$ and $R > 0$ the following integral holds:

$$\int_0^{\infty}\frac{1}{1+s^{-1}r^{\alpha}}\frac{2r}{R^2}dr = \frac{2\pi s^{2/\alpha}\csc(\frac{2\pi}{\alpha})}{\alpha R^2} , \quad (17)$$

where in the integral above we have used the 2-dimensional uniform distribution provided before. Eq. (17) is proved in appendix A.

The last part of the proof consists of using the result in Lemma 2 for $s = a = \frac{jv}{-1+j2v}\frac{c\times\varepsilon_{\mathrm{I}}}{2\sigma^2}$. Hence, under the statistical hypothesis $\mathcal{H}_0$, the CF of the d.v. is

$$\Psi_0(v) = \frac{1}{(1-2jv)^Q}\exp\left(-\lambda_{\mathrm{s}}\big(\frac{jv}{-1+j2v}\frac{c\varepsilon_{\mathrm{I}}}{N_0}\big)^{2/\alpha} \times \frac{2\pi^2}{\alpha}\csc(\frac{2\pi}{\alpha})\right) . \quad (18)$$

Considering now the statistical hypothesis $\mathcal{H}_1$, the d.v. is also non-central Chi-square distributed with the non-centrality parameter μ_1 provided already in eq. (12). In this case, the conditional characteristic function of the non-Central Chi-Squared distributed r.v. is $\Psi_1(v \mid g_{\mathrm{s}}, g, r) = \frac{1}{(1-j2v)^Q}e^{\frac{jv}{1-2jv}\mu_1}$. As done already, the subsequent steps consist of removing the conditioning upon the fading of both useful signal and interference, as well as the conditioning upon the random distance separating an interferer and the CCA station: $\Psi(v) = \mathbb{E}_{g_{\mathrm{s}}}\mathbb{E}_g\mathbb{E}_r\Psi(v \mid g, g_0, r)$. To remove the conditioning upon fading, we remind that all the power fading coefficients are

TABLE I: Parameters to evaluate numerical results

Parameter	Description	Value
P_{tI}	LTE transmit power	18 dBm; 24 dBm
P_{ts}	Wi-Fi transmit power	20 dBm
R	Radius of the area A	40 m
r_s	CCA range	$0 \leq r_s \leq R$
α	Path-loss exponent	4 (for indoors)
λ_s	density of LTE aggregate interference	0.0014
R_{bI}	LTE transmit rate(16 QAM & 20MHz)	57 Mbit/s
R_{bs}	Wi-Fi preamble rate	6 Mbit/s
$f_s^{(lte)}$	LTE sampling frequency	30.72 MHz
$f_s^{(wifi)}$	Wi-Fi sampling frequency	20 MHz
n_b	Number of bits per LTE symbol	4
n_s	Number of samples per LTE symbol	2208 [16]

i.i.d. exponentially distributed r.vs. and the CF is computed in $\frac{jv}{1-j2v}\frac{\varepsilon_0}{N_0 r^{-\alpha}}$ for the useful signal, and in $\frac{jv}{1-j2v}\frac{c\times\varepsilon_I}{N_0 r^{-\alpha}}$ for the interference. Removing all the conditionings and using the result in Lemma 2, the CF of the d.v. under the statistical hypothesis $\mathcal{H}_1$ can be written as follows

$$\Psi_1(v) = \frac{1}{(1-j2v)^Q} \times \frac{1}{1-\frac{jv\varepsilon_s}{1-j2vN_0}} \times \exp\left(-\lambda_s\left(\frac{jvc\varepsilon_I}{(-1+j2v)N_0}\right)^{2/\alpha} \times \frac{2\pi^2}{\alpha}\csc\left(\frac{2\pi}{\alpha}\right)\right). \quad (19)$$

V. Numerical Results

We recall that the unlicensed frequency under study is the 5 GHz band. For numerical Wi-Fi parameters, we rely on the IEEE 802.11n standard for the typical 20 MHz channel, 20 dBm transmit power and $N = 52$ OFDM sub-carriers. The CCA indication of busy channel with a probability $P_{\mathrm{d}} > 0.9$ has to be done within 4 μs. The CCA preamble sequence uses $N_{\mathrm{s}} = 5$ legacy short training field with each symbol that lasts t_{s}=0.8 μs. The LTE system bandwidth is assumed W=20 MHz, which is the maximum value without carrier aggregation. In LTE we have $M = 12$ sub-carriers per resource block and we assumed that a 16-QAM modulation is used for down-link data transmission.

Relying on the numerical values shown in Table I, we perform a link budget analysis based on the work in [17] to compute the signal-to-noise-ratio (SNR) per bit, i.e. ε/N_0, for both Wi-Fi and LTE transmissions, where the transmitted energy per bit is generally computed as $\varepsilon = P_{\mathrm{t}}/R_{\mathrm{b}}$, at a rate of R_{b} bits/s. The path-loss exponent was assumed to $\alpha = 4$, as the value to model the signal propagation in indoor environments. Further, the re-sampling factor c is calculated as $c = f_{\mathrm{s}}^{(\mathrm{lte})}/f_{\mathrm{s}}^{(\mathrm{wifi})}$ due to LTE signal oversampling in the Wi-Fi receiver; n_{b} is the number of bits in an LTE symbol and n_{s} the number of samples per symbol. During the 4 μs CCA duration, the received Wi-Fi energy $\varepsilon_{\mathrm{rs}}^{(\mathrm{CCA})}$ and the interference energy $\varepsilon_{\mathrm{rI}}^{(\mathrm{CCA})}$ can be expressed as

$$\varepsilon_{\mathrm{rs}}^{(\mathrm{CCA})} = \left(\frac{P_{\mathrm{ts}}/R_{\mathrm{bs}}}{L}\right) \times N_{\mathrm{s}}$$
$$\varepsilon_{\mathrm{rI}}^{(\mathrm{CCA})} = \left(n_{\mathrm{b}} \times \frac{P_{\mathrm{tI}}/R_{\mathrm{bI}}}{L_0}\right) \times \frac{c \times N_{\mathrm{s}} \times W \times t_s}{n_{\mathrm{s}}}, \quad (20)$$

where L is the path-loss at distance r_{s} and L_0 is the path-loss at one meter. Both expressions are used in the link budget to compute the average SNR per bit also assuming the noise figure equal to 15 dBm. The reason for calculating the energy of the interfering signal at the transmitter side can be found in Eqs. (15) and (18), where it was shown that the effect of interference is already averaged over all possible distances within the area of radius R.

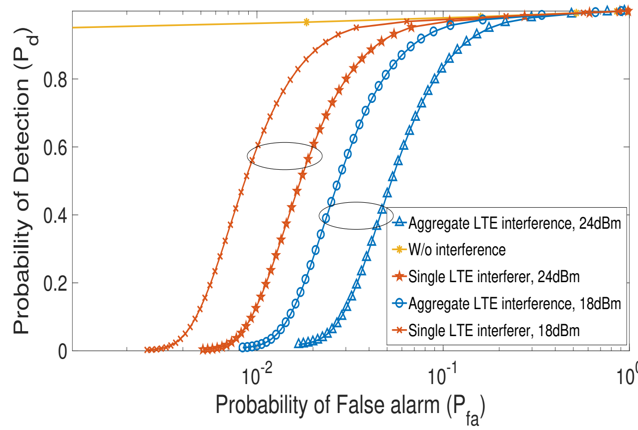


Fig. 3: P_{d} vs. P_{fa} for different interference configurations

Fig. 3 shows P_{d} versus P_{fa} comparing the different interference cases, assuming CCA range $r_{\mathrm{s}} = 10$ m. The result highlights that even a single LTE transmission from a hidden terminal degrades the CCA performance compared to the case without in which only path-loss and fading affect the preamble signal reception (solid yellow line). As expected, the degenerate case of an aggregate LTE interference affects most severely and the transmit power plays an important role in all cases. We may observe that to target a high detection probability (e.g. ≥ 0.9) the false alarm would range from 0.023 in the single interference case and 18 dBm of LTE transmit power (leftmost curve) to 0.13 in aggregate interference case and LTE transmit power of 24 dBm (rightmost curve). In any case, the degradation with respect to the situation without interference is remarkable. Fig. 4 shows P_{d} versus the CCA range r_{s} when selecting target $P_{\mathrm{fa}} = 5 \times 10^{-2}$. Looking at the results, we may notice that with aggregate interference and LTE transmit power 24 dBm, the CCA range for which the detection probability does not fall below 0.9 is at most 7 m, whereas without interference the Wi-Fi station attains the same detection probability up to 15 m. This also allows us to conclude that interference cause a loss in range around 50% in order to not compromise the detection. We also point out that our results are in line with [18], where it is generally stated that the detection carried out with an ED receiver affected by interference is always less effective than in the case without.

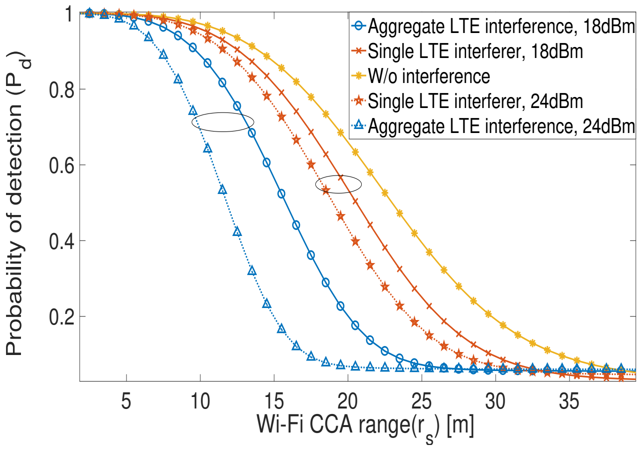


Fig. 4: Comparison of detection probabilities

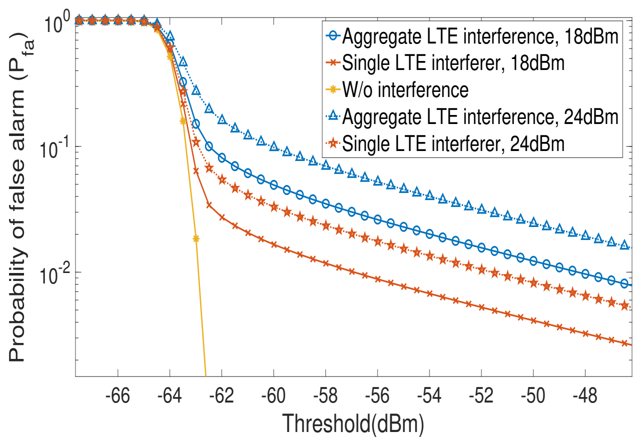


Fig. 5: Comparison of false alarms probabilities

Fig. 5 shows P_{fa} versus the energy detection threshold λ. Without interference the threshold to target $P_{\text{fa}} = 5 \times 10^{-2}$ is approximately -63 dBm, whereas with this value the false alarm probability would raise to 0.2 in case of aggregate LTE interference (the figure shows also that we cannot target any lower value in this case). Therefore, to achieve the same P_{fa} target in the presence of aggregate LTE interference, we would need to increase the ED threshold to -55 dBm. On the other hand, with single LTE interfering transmitter and 24 dBm transmit power, a threshold of approximately -61.5 dBm is sufficient to achieve the target false alarm.

The results obtained in this work allows us to conclude that co-existence between LTE and Wi-Fi networks in the 5 GHz unlicensed band is not straightforward since interference may degrade significantly CCA performance. We need to bear in mind that CCA is a crucial operation to enable the Medium Access Control layer (MAC) to perform properly. Therefore, the possibility of intelligently re-configuring the ED threshold based on interference conditions can constitute a viable approach. Comparing to the situation without interference, in case of single LTE interferer, increasing the Wi-Fi ED threshold of approximately 2 dBm allows to limit the degradation of the false alarm probability. In case of aggregate interference instead an 8 dBm increase of the ED threshold is required to keep the same target false alarm. Anyway, the increased energy threshold would lead to a lower probability of preamble detection during CCA. In equivalent terms, as already anticipated above, the coverage area within which the Wi-Fi performance are not compromised shows to be smaller than in the case without interference. In this regard, we may also conclude that adjusting the ED threshold alone cannot preserve the Wi-Fi network performance unless a more intelligent decision-making process is enabled, which may allow to control LTE transmission parameters as well as the number of active LTE transmitters in the unlicensed band.

Future work will develop in two main directions. On the one hand, the current analysis will be extended in order to evaluate the impact of LTE transmissions on the Wi-Fi throughput when the CCA operation is affected by interference. On the other hand, we shall develop a prototype aiming to demonstrate that LTE and Wi-Fi transmissions can be coordinated. In this regard, since we believe crucial to preserve the performance of Wi-Fi, the authors will pursue an approach based on Software-Defined Radio Access Network (SD-RAN) controller. This is an extension to the wireless access of the well-known Software-Defined Networking (SDN) concept in fixed networks. The role of an SD-RAN controller is to enable dynamic (re)configuration of parameters in heterogeneous access networks. For example, convergence between LTE and Wi-Fi was already looked at by means of approaches such as LTE-WLAN Aggregation (LWA) in 3GPP Release 13, and this topic has been considered also in the Release 15 to provide inter-working with non-3GPP untrusted technologies. Anyway, the approach based on SD-RAN control has the merit to render possible controlling both Wi-Fi and LTE transmissions in unlicensed bands through a central point that can take effect on both systems. For example, the ED threshold of Wi-Fi as well as the permission for LTE to commence a transmission and/or LTE transmission parameters such as the transmit power can be adapted in a dynamic manner depending on channel condition and performance reports.

VI. Conclusions

In this work, we evaluated the probabilities of false alarm and detection that characterize the performance of the CCA operation, the crucial mechanism to grant a Wi-Fi station channel access when affected by the interference caused by LTE down-link transmissions over the 5 GHz unlicensed band. To achieve this result, we developed closed form expressions of the characteristic function of the energy detector decision variable in different interference configurations, which were numerically evaluated to obtain the probabilities mentioned above. While this method proved to be very powerful, at the same time it allowed us to obtain the general design guidelines for tuning the energy detection threshold. Comparing to the case without interference, the threshold has to be increased while seeking a trade-off between the degradation of false alarm and detection probabilities.

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Appendix A
Derivation of Lemma 2

First of all, by some manipulation, we can write the left hand side of eq. (17) as follow:

$$\frac{2s}{R^2}\int_0^\infty \frac{r}{s+r^\alpha}dr \; . \tag{21}$$

Using [19, Eq. 3.241/4], we can see

$$\int_0^\infty \frac{x^{u-1}}{(p+qx^\nu)^{k+1}}dx = \frac{1}{\nu p^{k+1}}\left(\frac{p}{q}\right)^{u/\nu}\frac{\Gamma(u/\nu)\Gamma(1+k-u/\nu)}{\Gamma(1+k)}$$

Replacing $u=2$, $\nu=\alpha$, $p=s$, $q=1$, $k=0$ and $x=r$ we are able to solve the integral in eq. (21).

$$\int_0^\infty \frac{r}{(s+r^\alpha)}dr = \frac{1}{\alpha s}s^{(2/\alpha)}\left(\frac{\Gamma(\frac{2}{\alpha})\Gamma(1-\frac{2}{\alpha})}{\Gamma(1)}\right) \; . \tag{22}$$

By means of the Euler's reflection formula, $\Gamma(\frac{2}{\alpha})\Gamma(1-\frac{2}{\alpha}) = \pi\csc(\pi\frac{2}{\alpha})$, eq. (22) can be rewritten as

$$\int_0^\infty \frac{r}{(s+r^\alpha)}dr = \frac{1}{\alpha s}s^{(\frac{2}{\alpha})}\pi\csc(\frac{2\pi}{\alpha}) \; .$$

Replacing the result of the integral in eq. (21), the proof of Lemma 2 is complete.

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