Impact of Aggregate Interference on Meteorological Radar from Secondary Users

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***Abstract*—In this paper, we investigate the impact of aggregate interference in a secondary spectrum access system. Particularly, meteorological radar operating in 5.6 GHz band is considered to be a primary user. Secondary users are WLAN devices spreading in a large area which induce aggregate interference to the radar. We develop a mathematical model to derive the probability distribution function (PDF) of the aggregate interference. The derivation considers dynamic frequency selection (DFS) mechanism for the protection of the radar such that the transmission of each WLAN is regulated by an interference threshold. Numerical experiments are performed with various propagation environments and densities of WLAN devices. It is observed that the effect of aggregate interference is severe in a rural environment. The interference threshold for individual WLAN should be much lower than the maximum tolerable interference at the radar. Thus, only a limited number of WLANs can transmit at the same time. On the other hand, adverse effect of the aggregate interference is not shown in an urban environment, where up to 10 WLANs per square kilometer can use the radar spectrum without considering the aggregate interference. The framework discussed in this paper can readily be adapted to assess the aggregate interference for other types of radars.**

Index Terms - Aggregate interference, secondary spectrum access, meteorological radar

I. INTRODUCTION

Increasing use of existing communication technologies as well as emerging innovations in this field is creating a constantly growing demand for radio spectrum. The traditional way to manage spectrum has been assigning exclusive frequency bands to different systems for long periods of time. The problem that has emerged under the fixed spectrum allocation is that there is not enough spectrum available for the increasing demand of wireless services. On the other hand, measurement results indicate that the allocated spectrum is being under-utilized [1]. A possible solution to use the allocated spectrum more efficiently is secondary spectrum access which is envisioned by cognitive radio [2]. This allows secondary users to access the spectrum that has already been assigned to primary users. The basic idea is that the secondary users should be capable of detecting opportunities for using the allocated spectrum without causing harmful interference to the primary user.

A practical example of the secondary access can be found in 5 GHz frequency band (5150-5350 MHz and 5470-5725 MHz) where WLAN[1] devices can have access to the spectrum primarily assigned for radio detection and ranging systems (radars). The decision was made by the international telecommunication union (ITU) at the world radio conference 2003 (WRC2003) [3]. ETSI standard [4] specifies the thresholds and requirements for WLANs as secondary devices. The major concern of the secondary access in 5 GHz spectrum is the protection of radars from the adverse interference by WLANs. IEEE 802.11h standard specifies dynamic frequency selection (DFS) as an interference protection mechanism [5]. DFS is a distributed algorithm by which each WLAN decides if it can transmit or not depending on the result of the spectrum sensing. WLAN device monitors the presence of radar before and while using a channel, and it has to leave the channel if a radar signal is detected above a given detection threshold.

The authors of [6], [7] collected data from field experiments, showing the degradation on the radar imagery caused from the interference by WLAN. They concluded an enough protection can be provided by using the DFS for the case of the meteorological radar in 5.6 GHz. However, the measurements did not consider multiple interferers spreading in a large area. In such a case, WLANs operating simultaneously in a large area may not be aware of each other because the distance from each other is far beyond their transmission range. Thus, it is possible that they induce harmful interference to the radar in total even with the perfect interference protection in the individual level. To our best knowledge, the impact of aggregate interference to the radar has not been investigated.

Accurate modeling of the aggregate interference is of crucial importance in addressing the impact of multiple interfering WLANs. Mathematical model for the aggregate interference in secondary access has recently been investigated in [8]–[11], where an exclusion region of a circle with a fixed radius offers the protection to the primary user from detrimental interference. However, the existing models are not adequate to the radar application as suggested in [12]. This is because the DFS mechanism is not properly described by a circular exclusion region in the presence of fading.

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[1] This is also termed as radio local area network (RLAN) and wireless access system (WAS) in the literature.

In this paper we investigate the impact of interference coming from multiple WLANs on the meteorological radar operating in 5.6 GHz band. The main objective of this work is to address the following questions:

- *What is the impact of propagation environment and the density of WLANs on the aggregate interference?*
- *How much margin is needed for the interference protection threshold of individual WLAN in order to allow for the multiple secondary interferers?*

We develop a mathematical model based on our previous work [12]. Probability distribution function (PDF) of the aggregate interference is derived considering the horizonal antenna beam width of radar and the DFS mechanism. The derived PDF is compared with Monte Carlo simulation. Then, the aggregate interference is examined under the various propagation enviroments and WLAN deployment densities.

The rest of the paper is organized as follows. In Section II we introduce the basic characteristics of radars and the DFS mechanism. Section III details the system model, the assumptions, and presents the analytic model for the aggregate interference. Section IV shows the numerical results obtained from mathematical analysis and simulation. Finally, we close with the conclusion in section V.

II. SECONDARY ACCESS IN RADAR SPECTRUM

A. *Radar as a primary system*

The main function of radars is to determine range information by measuring the time difference between a transmitted signal and the returned echo. The radar signal is generated by a high power transmitter with pulse width in the order of a few microseconds and received by a highly sensitive receiver, which in general is the same antenna. This characteristic is an advantage to secondary access systems because this enables each secondary device to estimate the interference that it will induce to the radar by measuring the signal strength received from the radar. Thus, it is available to protect the radar based on the spectrum sensing at the individual WLAN device provided that a proper protection threshold is applied to the WLAN devices.

The performance of radar is affected by interference to noise ratio (INR). It has been reported that INR of -6 dB to -9 dB is required to prevent the performance degradation of radar depending on the type of the radar [13]. It should be noted that the various types of radars have diverse range of operational characteristics and protection requirements. Extensive review of different radar types and protection requirements can be found in [13].

We consider a ground-based meteorological radar which operates between 5600 and 5650 MHz band. It is equipped with an antenna that scans through 360° and has an azimuthal beam width of about 2°. The INR requirement of -9 dB is considered in this study. This corresponds to the maximum tolerable interference power of -109 dBm according to the parameters shown in table I. Detailed specifications of the ground meteorological radars are introduced in [14].

B. *DFS standard*

DFS is an interference avoidance mechanism described in the standards and ITU recommendation [4], [5], [15]. WLAN devices accessing the 5GHz radar spectrum are mandated to implement the DFS algorithm to provide the protection to radars. The DFS is based on the detection of radar signals. WLAN avoids the use of a channel identified as being occupied by the radar. The detection threshold requirements to identify the transmission of a radar depend on the radiation power of WLAN. When a WLAN radiated power is 200 mW or less, the detection threshold of radar signals is -62 dBm. For higher radiated power the detection threshold value is -64 dBm.

Fig. 1 shows the procedure of the DFS mechanism. When a WLAN network desires to use a channel, it has to check if the channel is free of primary transmitter with a channel availability check (CAC) command. If a radar signal above the detection threshold is detected, the WLAN devices assume that a primary user is active. Then, it has to vacate the channel and find a new channel to continue transmission. During the channel moving time (CMT) a broadcasting of commands to cease transmission has to be repeated so that by the time that CMT is over all WLAN devices in the network have left the channel.

The maximum tolerable interference power of -109 dBm at the radar is equivalent to the detection threshold of -41 dBm at the WLAN device according to the parameters shown in Table 1. This means the detection threshold specified by DFS

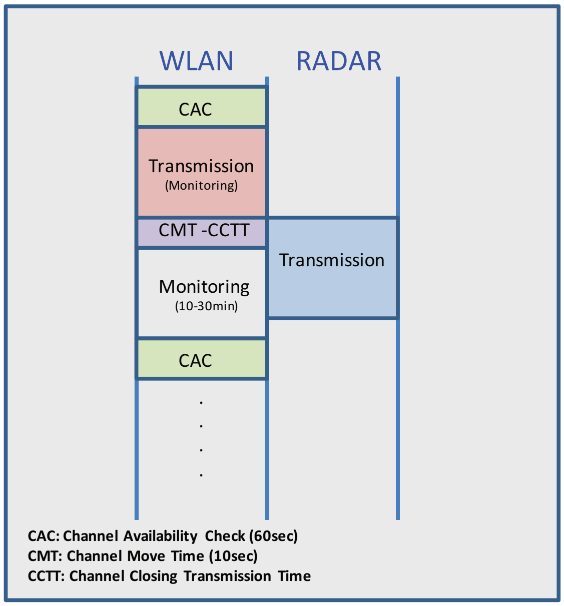

Fig. 1. DFS algorithm implementation.

standard (-62 dBm) will provide an enough margin for the protection of the radar for the case of single WLAN interferer. The impact of different detection thresholds with multiple WLAN interferers is discussed in the next section.

III. PROBABILITY DISTRIBUTION OF AGGREGATE INTERFERENCE

A. System Model

We consider N active WLAN devices uniformly distributed within a circle of radius R. The radar is located at the origin of the circle. Fig.2 gives an illustration of this scenario. We assume that the mobility of WLAN devices are limited, i.e. nomadic or stationary. Then, it is reasonable to assume the detection of the radar and the estimation of propagation loss are accurate at each WLAN device.

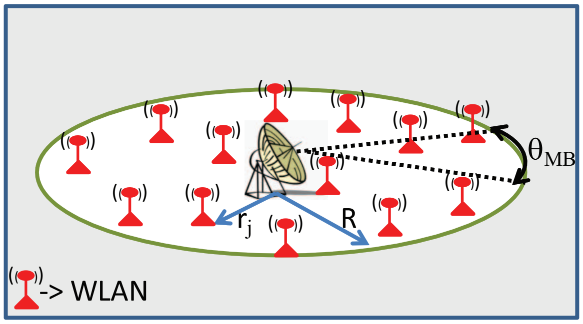

Fig. 2. Representation of the scenario.

We define A_{thr} as the maximum aggregate interference power that the radar can tolerate. This is fixed as -109 dBm in this study. We also define I_{thr} as the interference threshold applied to each individual WLAN. Let I_a be the aggregate interference that the radar receives from all the WLANs. Note that I_a depends on the individual interference threshold I_{thr} and the number of active WLAN devices N. Aggregate interference greater than the defined threshold A_{thr} causes a degradation on the radar and should be avoided. Therefore, a maximum permissible probability of interference β is defined as a regulatory constraint, which is expressed as:

$$\Pr[I_a > A_{thr}] \leq \beta. \tag{1}$$

The value of β is a crucial decision that should be taken by the regulator on behalf of the radar operators. In this study, we consider β=0.05.

The mathematical model in this section is based on our previous work [12]. Let us consider an arbitrary WLAN j whose distance from the radar is denoted by a random variable (RV) r_j with the following PDF:

$$f_{r_j}(y) = \frac{2y}{R^2}, \; 0 < y \leq R. \tag{2}$$

Let $L(r_j)$ denote the distance based propagation loss including WLAN's antenna gain and radar's maximum antenna gain, G_w and G_r respectively. Then, $L(r_j)$ is given by

$$L(r_j) = G_r G_w C {r_j}^{-\alpha}, \tag{3}$$

where C and α are the path loss constant and exponent, respectively. The shadow fading on the path between WLAN j and the radar is denoted by X_j. Let $\sigma_{X_j}^{dB}$ be the standard deviation of the shadow fading in dB scale. Then, X_j follows a log-normal distribution with the parameter $\sigma_{X_j} = \sigma_{X_j}^{dB} \ln(10)/10$.

We consider that all WLAN devices transmit with a fixed power P_w^t. The radar is affected by a fraction of P_w^t because the bandwidth of radar B_r is narrower than that of WLAN B_w. Thus, the effective transmission power of WLAN affecting the radar is shown as:

$$P_{eff}^t = P_w^t \frac{B_r}{B_w}. \tag{4}$$

Let ξ_j be the interference that the radar will receive from WLAN j if it transmits. Since the transmission of j is regulated by the DFS mechanism, the actual interference from WLAN j, namely I_j, is given by:

$$I_j = \begin{cases} \xi_j, & \text{if } \xi_j \leq I_{thr}, \\ 0, & \text{otherwise.} \end{cases} \tag{5}$$

B. Interference from the arbitrary WLAN j

We begin with probability distribution of ξ_j in order to obtain the PDF of I_a. From the above notations, ξ_j is given by:

$$\xi_j = P_{eff}^t L(r_j) X_j. \tag{6}$$

Note that ξ_j is a function of the RVs r_j and X_j. It is shown in [12] that the PDF of ξ_j can be expressed by using the Gaussian error function:

$$f_{\xi_j}(z) = \Omega z^{\frac{-2}{\alpha}-1} \left[1 + \operatorname{erf}\left(\frac{\ln\left(\frac{z}{P_{eff}^t L(r_j)}\right) - 2\sigma_{X_j}^2/\alpha}{\sqrt{2\sigma_{X_j}^2}} \right) \right], \tag{7}$$

where the constant Ω is given by:

$$\Omega = \frac{1}{R^2\alpha} \left(\frac{1}{P_{eff}^t G_r G_w C} \right)^{\frac{-2}{\alpha}} \exp\left(2\sigma_{X_j}^2/\alpha^2\right). \tag{8}$$

WLAN j stops transmission if ξ_j exceeds I_{thr} due to the DFS mechanism. This means a portion of secondary users have *zero* transmission power. That portion of users is given as $1 - F_{\xi_j}(I_{thr})$, where $F_{\xi_j}(.)$ denote de cumulative distribution function (CDF) of ξ_j. Thus, the PDF of I_j is as follows:

$$f_{I_j}(z) = \begin{cases} 1 - F_{\xi_j}(I_{thr}), & \text{if } z = 0 \\ f_{\xi_j}(z), & 0 < z \leq I_{thr} \\ 0, & \text{otherwise.} \end{cases} \tag{9}$$

The derivation of I_j is based on the assumption that the WLAN j faces the main beam of the radar. In practice, the antenna pattern of the radar should be considered in the calculation of I_j because the radar antenna is rotating with a narrow beam width. Note that, however, the DFS decision is taken by considering the instance of the maximum interference. Once the WLAN j estimates that ξ_j will exceed I_{thr} while facing the main beam of the radar, it cannot transmit even if $\xi_j < I_{thr}$ during the rotation of the radar.

Notice that in this work we do not consider the co-channel interference that secondary users may cause to each other. In practice, the transmission of the secondary users can be restricted by the medium access control (MAC) protocol. Thus, if the assessed number of WLANs that can transmit without interfering the radar is greater than the number that the MAC protocol allows, we can conclude that the radar will not experience harmful experience from the secondary users.

TABLE I
SIMULATION PARAMETER VALUE

PARAMETERS		VALUES
RADAR	Radius [R in km]	150
	Frequency band [MHz]	5600
	Antenna height [meter]	30
	Noise figure [dB]	8
	Transmission power [kW]	250
	Antenna gain [G_r in dBi]	40
	Bandwidth [B_r in MHz]	4
WLAN	Antenna height [meter]	1.5
	Transmission power [P_w^t in W]	0.2
	Antenna gain [G_w in dBi]	0
	Bandwidth [B_w in MHz]	20
Standard deviation of shadow fading [$\sigma_{X_j}^{dB}$ in dB]		8
Interference to noise ratio threshold [INR in dB]		-9
Aggregate interference threshold [A_{thr} in dBm]		-109

C. Aggregate Interference

Now we express the aggregate interference I_a from N WLAN devices to the radar as follows:

$$I_a = \sum_{j=1}^{N} I_j \psi(\theta_j), \tag{10}$$

where $\psi(\cdot)$ is the antenna gain function of the radar and θ_j denotes the angle between WLAN j and the main beam of the radar antenna. We employ a simple antenna pattern model of the radar. The maximum antenna gain of the radar G_r is applied to WLANs that are located within the main beam width denoted by θ_{MB}. The gain of zero dBi is applied to WLANs that are not inside θ_{MB}. In spite of its simplicity, our antenna pattern model gives similar results to the one suggested by ITU recommendation M.1652 [15]. We formally define the used antenna pattern as:

$$\psi(\theta_j) = \begin{cases} 1, & \text{if } \theta_j < \theta_{MB} \\ \frac{1}{G_r}, & \text{otherwise.} \end{cases} \tag{11}$$

The value of θ_{MB} is approximated using the expression $\theta_{MB} = 50[0.25G_r + 7]^{0.5}/10^{[G_r/20]}$. The antenna elevation beam width is not used for simplicity, which will influence to get conservative results.

A cumulant-based approach is employed to approximate the PDF of I_a. Note that a cumulant of the sum of independent RVs is equal to the sum of the individual cumulants. Also, the first and second cumulants of a RV correspond to the mean and variance. Let $k_{I_j}(i)$ and $k_{I_a}(i)$ denote the i^{th} cumulant of I_j and I_a, respectively. Then, from (10) the following relationship is established for the first two cumulants:

$$k_{I_a}(1) = \psi(\theta_j) k_{I_j}(1), \tag{12}$$

$$k_{I_a}(2) = \psi(\theta_j)^2 k_{I_j}(2). \tag{13}$$

We employ a log-normal approximation so that the PDF of I_a can be described by the mean and the variance of I_j which can be easily calculated from (7).The PDF of I_a is approximated by the following log-normal distribution:

$$f_{I_a}(z) = \frac{1}{z\sqrt{2\pi\sigma_{I_a}^2}} \exp\left(\frac{\ln(z) - \mu_{I_a}}{2\sigma_{I_a}^2}\right). \tag{14}$$

The parameters μ_{I_a} and $\sigma_{I_a}^2$ of the PDF can be obtained from the first and second cumulant computation as:

$$k_{I_a}(1) = E[I_a] = \exp[\mu_{I_a} + \sigma_{I_a}^2/2], \tag{15}$$

$$k_{I_a}(2) = Var[I_a] = (\exp[\sigma_{I_a}^2] - 1)\exp[2\mu_{I_a} + \sigma_{I_a}^2]. \tag{16}$$

IV. NUMERICAL RESULTS

In this section we present the results of the numerical experiments. The system is modeled with the parameters values indicated in Table I. The basic propagation loss model used in this study is the WINNER D1 model for rural macro-cell which is proposed for 5GHz band by WINNER project in [16]. Using the parameters in Table I, the WINNER D1 model reduces to the following formula in dB scale:

$$L(d) = 57.7483 + 24.45\log_{10}(d[\text{meter}]). \tag{17}$$

Various path loss exponents are applied to (17) to represent different propagation environments.

The CDF of ξ_j and I_j are presented in Fig.3. The figure shows how the distribution of ξ_j is truncated for different interference threshold requirements I_{thr}. Higher I_{thr} prevents more users from transmitting, e.g. when $I_{thr} = -120$ dBm about 36% of the users are not allowed to transmit.

As explained in section III, the aggregated interference I_a on the radar is approximated using a log-normal distribution. Fig.4 shows the CDF of I_a compared with the Monte Carlo simulation when WLANs density is 1 per km^2. The log-normal approximation for I_a presents a good match with the simulation, especially in the tail region of the CDF. Note that the accuracy in the tail region is important when interference is modeled, given that the probability of creating harmful interference to the primary user is one of the main concerns in the secondary access. The simplicity of the log-normal approximation has the advantage of faster computation compared with simulations.

The characterization of the propagation environment plays an important role on the received I_a at the radar depending on whether it is rural ($\alpha \approx 2.5$) or urban ($\alpha \approx 3.5$) environment. From Fig.5, it is observed that if the radar is located in a rural area, WLANs density has to be much lower than 1 per km^2 or a margin for the individual interference threshold I_{thr} has to put in place in order to keep I_a below the threshold A_{thr}. The margin is over 15 dB when the density is 1 per km^2, and even goes up to 30 dB if the density is high. On the contrary, in the case where the propagation environment resembles an urban area, more WLANs are able to get a chance to transmits without crossing the aggregate interference threshold until the density reaches 10 per km^2.

Fig.6 shows the effect of density on the aggregate interference when $\alpha = 2.5$. Two cases are observed: Fig.6(a) shows the case when each WLAN only fulfils the condition that $\xi_j \leq A_{thr}$ without being aware of the total aggregate interference, i.e. $I_{thr} = A_{thr}$. Under this condition I_a to the radar becomes harmful even for lower WLANs density values. The second case is presented in Fig.6(b), where each WLAN adjusts its I_{thr} value to satisfy the condition $I_a \leq A_{thr}$ for a given WLAN density. This means that the aggregate interference requirement can be met by putting more stringent requirement to WLAN devices depending on the propagation environment and the user density.

A WLAN device cannot use the radar spectrum if it will generate interference higher than I_{thr}. Thus, the adjustment of I_{thr} affects the portion of WLAN devices that can transmit. Fig.7 shows the probability of transmission as a function of the distance from the radar. In a rural environment, less than 40% of WLANs have access to the radar band when the distance from the radar is 50km even with the density of 0.1 per km^2. For the case of the urban environment, the separation of 5km from the radar is enough to prevent harmful interference even for 10 WLAN per km^2.

It should be noted that the numerical result hugely depends on not only the propagation environment but also on the type of radar. The provided results are based on the parameters in Table 1, which describes a single type of radar. However, the framework discussed in this paper can readily be adapted to assess the aggregate interference for various types of radars.

V. CONCLUSION

We assessed the impact of aggregate interference on ground-based meteorological radar operating in 5.6 GHz. Secondary users are WLAN devices employing DFS mechanism for the protection of the radar. We derived the PDF of aggregate interference considering the narrow beam width of radar and the operation of the DFS. The analytic PDF shows a good agreement with Monte Carlo simulation, which suggests that our model has an advantage of avoiding complicated and time-consuming simulation.

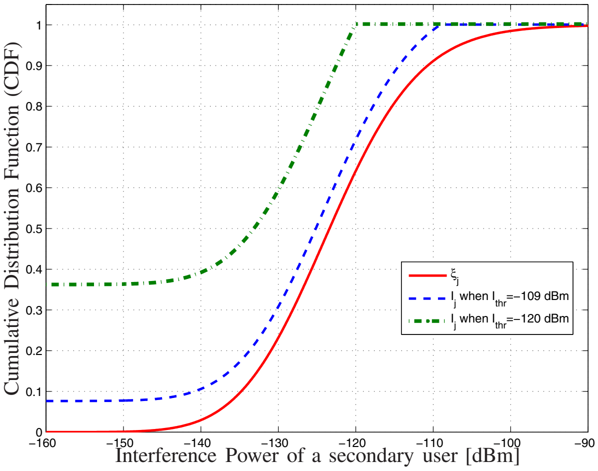

Fig. 3. CDF of ξ_j and I_j for different I_{thr}.

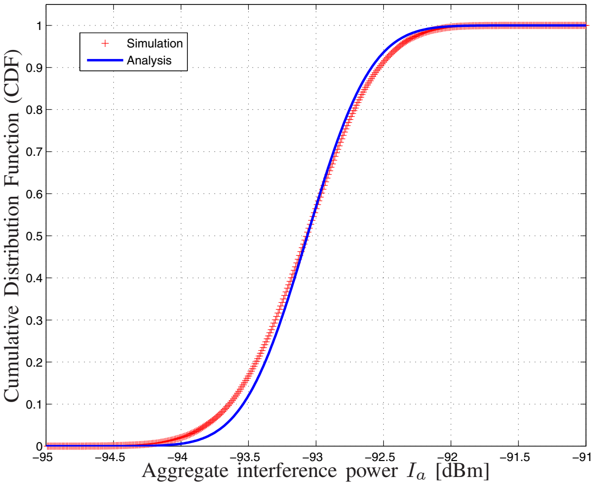

Fig. 4. PDF and CDF of aggregate interference when density is 1 per km^2 and $I_{thr} = -109$ dBm

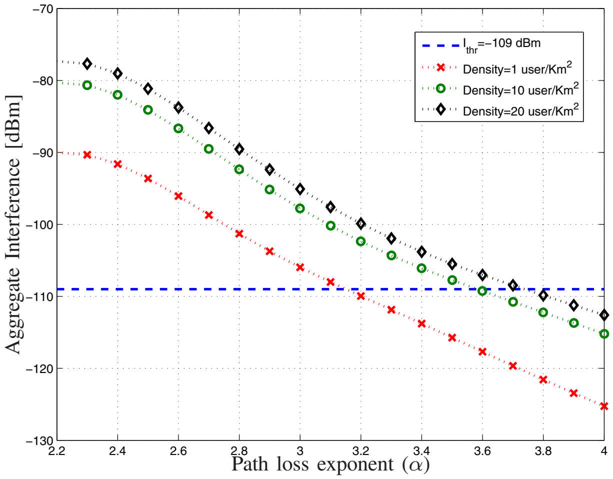

Fig. 5. Effect of path loss exponent on the aggregate interference.

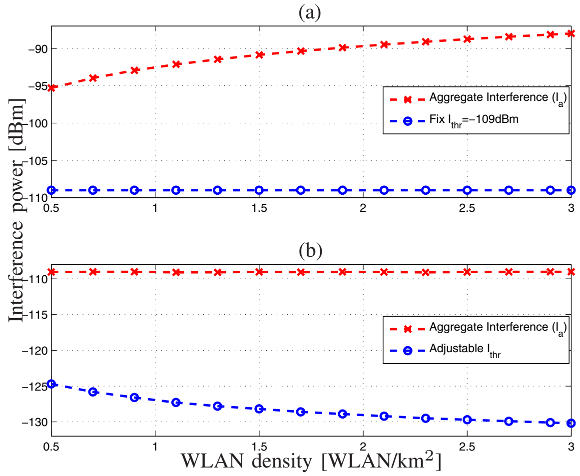

Fig. 6. (a) I_a when I_{thr} is fixed. (b) I_a when I_{thr} is adjusted according to the WLAN density.

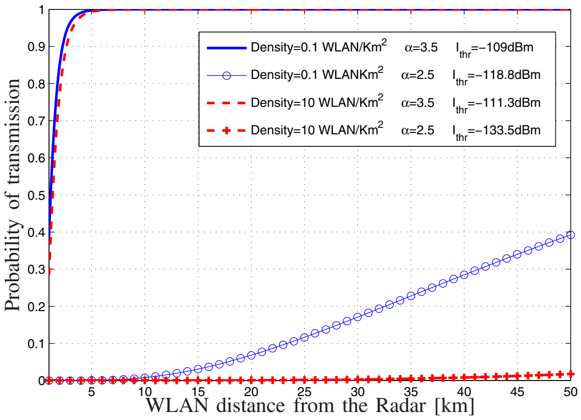

Fig. 7. Probability of transmission depending on the distance from the radar.

Our findings from the numerical experiments are as follows: the aggregate interference hugely depends on the propagation environment. The aggregating impact of multiple interferers is severe in rural area (path loss exponent of 2.5), whereas an adverse impact of aggregate interference does not appear in urban environment (path loss exponent of 3.5) until the density of simultaneously transmitting WLANs reaches 10 WLANs per km^2. This implies the accurate estimation of propagation loss is crucial in determining the interference threshold for individual WLAN. Also, this value should be adjusted according to the environment. For the case of rural environment, a margin of up to 30 dB needs to be put in place for the interference threshold of each WLAN device when the density of WLANs is 20 per km^2.

This work considered uniformly distributed WLANs and homogeneous propagation environment in a large area. Thus, the consideration of non-uniform WLAN deployment and heterogeneous propagation environments remain as interesting areas of further research.

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