Tags-to-WiFi Transmission Analysis in Node-Assisted WiFi Backscatter Network with Stochastic Geometry

Yulei Wang[1], Qinglin Zhao[1], Shumin Yao[1], Mengchu Zhou[2], Hong Liang[1]
[1] School of Computer Science and Engineering, Macau University of Science and Technology, Avenida Wai Long, Taipa, Macau
[2] Department of Electrical and Computer Engineering, New Jersey Institute of Technology, Newark, NJ 07102 USA
Email:wylpaper@126.com, qlzhao@must.edu.mo, zhysm@outlook.com, zhou@njit.edu, coolboom@126.com

***Abstract*—Node-assisted WiFi backscatter (NWB) is a promising scheme that significantly extends the communication range of traditional WiFi backscatter. In an NWB network, it consists of one access point (AP) and multiple WiFi nodes, where the coverage area of each WiFi node contains a number of tags. The NWB network protocol comprises two-level contentions (i.e., tag contention and WiFi contention) as follows. First, when detecting a transmitting WiFi excitation signal, tags contend to transmit their information to their respective WiFi nodes by reflecting the excitation signal. Second, these WiFi nodes later contend to relay their received tags' information to the AP. In this paper, we mainly investigate the first-stage transmission from tags to WiFi nodes (i.e., tags-to-WiFi), the performance matrix of which is the successful transmission probability of tags in tags-to-WiFi transmission. The great challenge is to capture the impact of the two-level contentions and the geometric distributions of tags and WiFi nodes on the successful transmission probability. As far as we know, we are the first to utilize a stochastic geometry (SG) approach to characterize the contention randomness of randomly deployed tags and WiFi nodes and exclude non-interfering tags for each tag-to-WiFi transmission. Then, we formulize the mathematical expression of the successful transmission probability of tags with NWB parameters, including the intensities of tags and WiFi nodes. Finally, we also run extensive simulation to validate the accuracy of our SG-based theoretical model. The simulation results manifest that our theoretical model is exactly accurate.**

***Index Terms*—WiFi backscatter, stochastic geometry, analysis**

I. Introduction

Node-assisted WiFi backscatter (NWB) [1] is a promising scheme that significantly extends the communication range of traditional WiFi backscatter (WB). An NWB network consists of one access point (AP), multiple WiFi nodes and numerous backscatter tags, where the coverage area of each WiFi node contains a number of tags. The NWB network protocol comprises two-level contentions (i.e., tag contention and WiFi contention) as follows. First, when detecting a transmitting ambient WiFi excitation signal, tags *contend* to transmit their information to their respective WiFi nodes by reflecting the excitation signal from other coverage areas. Second, these WiFi nodes later *contend* with each other to relay their received tags' information to the AP. With WiFi nodes assisted, the NWB network realizes the low-cost and long-range transmission from tags to the AP (i.e., tags-to-AP). In this paper, we mainly investigate the first-stage transmission from tags to WiFi nodes (i.e., tags-to-WiFi), the performance matrix of which is the successful transmission probability of tags in tags-to-WiFi transmission.

When a WiFi node receives a signal (i.e., target signal) reflected by a tag (i.e., target tag) in its coverage area, the WiFi node might also receive signals (i.e., interfering signals) reflected by another transmitting tags (i.e., interfering tags) in other coverage areas. At the WiFi node, the power of target signal and that of interfering signals, which together determine successful transmission probability of tags and hence the system performance, depend on the locations and numbers of the transmitting tags. In practice, the tags and WiFi nodes in an NWB network are randomly deployed in the space. Hence, the locations of tags and WiFi nodes are *random*. In addition, the aforementioned two-level contentions lead to at most one randomly located winner tag in the coverage area of each WiFi node excluding the WiFi node that is transmitting excitation signal. Hence, for each tag-to-WiFi transmission, the number of interfering tags is also *random* in the two-level contentions. In this paper, we need to capture the impact of the two-level contentions and the geometric distributions of tags and WiFi nodes on the successful transmission probability. The great challenge lies in how to characterize the contention *randomness* of randomly deployed tags and WiFi nodes and how to exclude *non-interfering* tags (e.g., tags whose respective WiFi nodes are transmitting excitation signals), which is worthy to be investigated.

Fortunately, stochastic geometry (SG) has been regarded as a powerful tool to model the geometric distribution of wireless devices in the space and describe the interferences for the data transmission in wireless networks [2]–[5]. We have known that two-level contentions and the geometric distributions of tags and WiFi nodes govern the successful transmission probability of each tag-to-WiFi transmission, and further affect the system performance of NWB networks, which has not been investigated so far. This motivates us to utilize an SG approach to capture the impact of two-level contentions and

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the geometric distributions of tags and WiFi nodes to analyze the successful transmission probability of tags in tags-to-WiFi transmission.

The contribution of this paper is the first to consider the two-level contentions and the geometric distributions of tags and WiFi nodes, and utilize an SG approach to analyze the successful transmission probability of tags in an NWB network. Specifically, 1). We propose an SG-based theoretical model to capture the impact of two-level contentions and the geometric distributions of tags and WiFi nodes. For each tag-to-WiFi transmission, we effectively derive the geometric distributions and intensity of the interfering tags in the two-level contentions. 2). We formulize the mathematical expression of the successful transmission probability of tags with NWB parameters, including the intensities of tags and WiFi nodes. 3). We also conduct extensive simulations to verify that our theoretical model is very accurate.

The paper is organized as follows. Section II briefly introduces the SG approach. Section III presents an NWB network. Section IV models the NWB network with an SG approach. Section V theoretically analyzes the successful transmission probability of tags with our theoretical model. Section VI evaluates the accuracy of our theoretical model via extensive simulations. Section VII finally concludes the paper.

II. Stochastic geometry approach

SG approach has been regarded as a powerful tool to model the geometric distribution of wireless devices and describe the interferences in wireless networks. In addition, Poission point process (PPP) is the most basic model in SG and commonly used to describe the geometric distribution of wireless devices in the space. Without loss of generality, we assume that the WiFi nodes and tags follow two independent homogeneous PPPs in this paper. Here, we briefly introduce the definitions and properties of PPP in SG. Besides, a detailed account of the underlying theory can be found in [6], [7].

A spatial point process $\Phi = \{x_i, i \in \mathbb{N}^+\} \subset \mathbb{R}^d$ is a PPP if and only if the number of points inside any bounded Borel set $B \subset \mathbb{R}^d$ is a Poisson random variable, and the numbers of points in disjoint bounded sets are independent.

According to the definition, PPP can be characterized by two fundamental properties:

- *Poisson distribution of point counts*: The number of points of PPP Φ in a given bounded set $B \subset \mathbb{R}^d$ has a Poisson distribution of mean $\Lambda(B)$;
- *Completely random*: The numbers of points of PPP Φ in n disjoint Borel sets form n independent random variables, for arbitrary n.

The probability that there are k points in the given set B can be expressed as

$$P\left[\Phi(B) = k\right] = e^{-\Lambda(B)} \frac{\Lambda(B)^k}{k!} \tag{1}$$

where $\Lambda(B)$ is intensity measure of Φ and represents the average number of points falling in the given set B. For a homogeneous PPP, $\Lambda(B) = \lambda|B|$, where λ is the intensity of Φ and represents the average number of points falling in per unit area or volume, $|B|$ is the Lebesgue measure of B in Euclidean space.

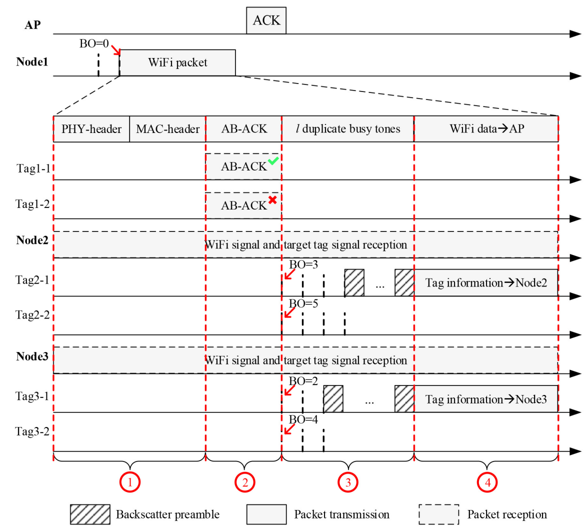

Fig. 1. An example of transmission process in MAC protocol.

III. Node-assisted WiFi backscatter network

In this section, we briefly describe an uplink NWB network in terms of media access control (MAC) layer protocol [1]. An NWB network consists of one AP, multiple WiFi nodes and numerous backscatter tags, where the coverage area of AP which is called a *cell* contains all the WiFi nodes, the coverage area of each WiFi node which is called a *subcell* contains a number of tags. Further, we describe the MAC layer protocol of an NWB network with an example shown in Fig. 1. The AP serves all the WiFi nodes (Node*k*, *k* = 1,2,3) in its cell. Each WiFi node (Node*k*) serves two tags (Tag*k*-*m*, *m* = 1,2) in its respective subcell (subcell*k*).

In the uplink data transmission process, the MAC procotol includes two-level contentions (i.e., WiFi contention and tag contention) as follows. First, WiFi nodes (i.e., Node1, Node2 and Node3) perform 802.11 carrier sense multiple access/collision avoidance (CSMA/CA) mechanism and binary exponential backoff (BO) algorithm to contend for their transmissions to AP. We assume that the BO counter of Node1 first reaches 0, which means that Node1 wins the contention among three WiFi nodes. Then, Node1 starts its data transmission to the AP, Node2 and Node3 keep in idle state or receive tags' signals from its served tags if needed. Meanwhile, the WiFi siginal of Node1 is detected by the tags, which can be divided into the following four steps as shown in Fig. 1.

- Step 1: energy harvest. In this step, Node1 broadcasts a WiFi physical (PHY) header and a MAC header. All tags in each subcell of WiFi node harvest energy from the ambient WiFi excitation signal of Node1.
- Step 2: asynchronous block ACK (AB-ACK) reception. In this step, Node1 broadcasts an AB-ACK. The AB-ACK indicates the successful data transmission of its

served tags (i.e., Tag1-1 and Tag1-2 in subcell1) between its last transmission and current transmission, and also indicates the beginning of contention instant for the tags (i.e., Tag2-1 and Tag2-2 in subcell2, Tag3-1 and Tag3-2 in subcell3). All the tags receive and detect the AB-ACK. Tag1-1 detects its successful transmission index in the AB-ACK, but Tag1-2 fails. Tags in subcell2 and subcell3 continue harvesting energy until the end of the AB-ACK. For more details can refer to [1].

- Step 3: tags' contention. In this step, Node1 broadcasts l duplicated busy tones with length of 1 micro-slot. Since the WiFi devices are half-duplex, when Node1 is transmitting, it can not perform reception simultaneously. The tags in subcell1 cannot send their information to Node1 and will harvest energy. However, Node2 and Node3 are not transmitting, they can perform reception, so the tags in subcell2 and subcell3 will *contend* to transmit their information to their respective WiFi nodes by reflecting the excitation signal of Node1, respectively. We assume that the BO counters of Tag2-1 and Tag3-1 first reach 0, which means that Tag2-1 and Tag3-1 win the contention in its subcell, respectively. Then, the winner tag broadcasts backscatter preamble repeatedly until the l-th micro-slot in its subcell. Meanwhile, the loser tag (i.e., Tag2-2, Tag3-2) stops its BO counter when it detects the backscatter preamble in its subcell.
- Step 4: tags' transmission. In this step, Node1 follows the WiFi standard to send its WiFi data and the buffered tag's (i.e., Tag1-1's) information to the AP. Besides, the winner tag (i.e., Tag2-1, Tag3-1) sends its information to its respective WiFi node (i.e., Node2, Node3), respectively. The WiFi node buffers its received tag's information and records the tag's address, and then contends to relay the received tag's information to the AP in its next transmission.

IV. System model

In this section, we model the NWB network with an SG approach.

A. Network Deployment

We consider an uplink NWB network and then illustrate the network deployment using the example shown in Fig. 1. We assume that the WiFi nodes and tags are spatially distributed following two independent homogeneous PPPs Φ_w and Φ_t with intensities λ_w and $\lambda_t (\lambda_t \gg \lambda_w)$, respectively. Let $\Phi_w = \{x_{wi},\ i \in \mathbb{N}^+\} \subset \mathbb{R}^2$ and $\Phi_t = \{x_{ti},\ i \in \mathbb{N}^+\} \subset \mathbb{R}^2$, where x_{wi} and x_{ti} represent a WiFi node and tag, respectively. We denote the AP cell by $S_{AP} \subset \mathbb{R}^2$ with radius of d_w, and denote the subcell of each WiFi node by $S_w \subset \mathbb{R}^2$ with radius of d_t ($d_w \gg d_t$). We assume the subcell of each WiFi node is disjoint in the space. We consider the uplink noise with average power σ^2 and a Rayleigh fading with the channel power gain h assumed to be exponentially distributed with unit mean, i.e., $h \sim exp(1)$. All channel gains are assumed to be independent and identically distributed (i.i.d.).

B. Interference Description

Here, we also take the example in Fig. 1 to describe the interference for a tag-to-WiFi transmission. We focus on the *typical tag-to-WiFi transmission link* from the target Tag2-1 to target WiFi node Node2. While Node2 is receiving the target signal from Tag2-1, it also receives the interference signal from Tag3-1 for the tag-to-WiFi transmission from Tag3-1 to Node3 in subcell3. In order to accurately analyze the successful transmission probability of tags, we need to evaluate the multiple sources of interferences for each tag-to-WiFi transmission. Hence, we need to exclude non-interfering tags, and derive the geometric distribution and intensity of interfering tags. We note that the non-interfering tags are these 1). whose respective WiFi node is transmitting excitation signal; 2). which fail the tags' contention in their subcells.

Let Φ'_w denote the set of the non-transmiting WiFi nodes except the target WiFi node (i.e., Node2), which can be expressed as

$$\Phi'_w = \{\Phi_w \backslash \{x_{w1}, x_{w2}\}\} \tag{2}$$

where Φ'_w is equivalent to Φ_w excluding the transmitting WiFi node x_{w1} (i.e., Node1) and the target WiFi node x_{w2} (i.e., Node2).

Each successful data transmission of WiFi node (i.e., Node1) can provide a transmission opportunity (TXOP) for all winner tags in other $n-1$ subcells (except the subcell of current WiFi transmitter). The simulations verify that occurrence probability of contention collision among the tags in a subcell is very small, which has a negligible impact on each tag-to-WiFi transmission. Hence, we assume there only one tag that wins the contention in the subcell of each non-transmiting WiFi node. Therefore, for a *typical tag-to-WiFi transmission link* from the target tag to the target WiFi node, the intensity of interfering tags (denoted by λ'_t) is equal to the intensity of the other non-transmiting WiFi nodes (denoted by λ'_w) of Φ'_w, that is,

$$\lambda'_t = \lambda'_w \tag{3}$$

In the given area S_{AP}, λ'_w can be given as

$$\begin{aligned} \lambda'_w &= \frac{E\left(\Phi'_w\left(|S_{AP}|\right)\right)}{|S_{AP}|} = \frac{E\left(\Phi_w\left(|S_{AP}|\right)\right) - 2}{|S_{AP}|} \\ &= \frac{\lambda_w \cdot |S_{AP}| - 2}{|S_{AP}|} = \lambda_w - \frac{2}{|S_{AP}|} \end{aligned} \tag{4}$$

where $\Phi'_w\left(|S_{AP}|\right)$ represents the average number of WiFi nodes Φ'_w and Φ_w in the given area S_{AP}, respectively. $|S_{AP}| = \pi {d_w}^2$ is the 2-demensional Lebesgue measure (i.e., area [6], [7]) of S_{AP}.

C. Communication Link Model

We assume that the power of each reflecting signal is same for all the tags, which is denoted by P_0. Due to path loss [8], the power of received signal at the WiFi node from any tag is $P_r = P_0 h r^{-\alpha}$, where $h \sim exp\left(1\right)$ models Rayleigh fading, r is the transmission distance between the tag transmitter and the WiFi node receiver, and α is the path-loss exponent. Therefore, the signal-to-interference-plus-noise ratio (SINR) [9] received at the target WiFi node can be written as

$$SINR\left(r_i\right) = \frac{P_0 h_i {r_i}^{-\alpha}}{I_0 + \sigma^2} \tag{5}$$

where h_i is the channel power gain of the typical data transmission link from the target tag to the target WiFi node, r_i is the transmission distance between the target tag and the target WiFi node, and σ^2 is the average noise power in the uplink. I_0 are the aggregate interferences received at the target WiFi node and given as

$$I_0 = \sum_{j \in \Phi_t'} P_0 h_j {r_j}^{-\alpha} \tag{6}$$

where Φ_t' is the set of interfering tags for the typical data transmission link from the target tag to the target WiFi node, h_j and r_j are the channel power gain and transmission distance between the interfering tags and the target WiFi node, respectively.

V. Successful Transmission Probability Analysis

In this section, we theoretically analyzes successful transmission probability of tags in the NWB network with our proposed SG-based theoretical model.

When detecting a transmitting ambient WiFi excitation signal, tags *contend* to send their information to their respective WiFi nodes by reflecting the excitation signal from other subcells. Therefore, each successful transmission of a tag is determined by two independent events: successful '*contention*' event and successful '*transmission*' event. First, a tag need win the contention among multiple (i.e., m) tags in its subcell. We define the average occurrence probability of the successful 'contention' event as P_m^c. Second, the winner tag (i.e., target tag) sends its information to its target WiFi node by reflecting the WiFi excitation signal. The target signal received at the WiFi node can be successfully extracted tag's information, only when the received SINR measured at the target WiFi node exceeds a certain threshold θ (that is, SINR $> \theta$) [9]. We define the occurrence probability of the successful 'transmission' event as P_{th}. Only when both of the two independent events happen, the tag-to-WiFi transmission can be successful. Let P_s denote the successful transmission probability of tags, which can be formulated as the product of occurrence probabilities of the two independent events, and given as

$$P_s = \sum_{m=1}^{\infty} P_m^c \cdot P_{th} \tag{7}$$

A. Expression of P_m^c.

First, the average occurrence probability of the successful 'contention' event P_m^c can be expressed as

$$P_m^c = P_m \cdot P_c \tag{8}$$

where P_m denotes the probability that there are m tags in the subcell of WiFi node, P_c denotes the probability that only one tag wins the contention among m tags in the subcell.

1) Expression of P_m: According to the properties of PPP, the number of tags in a given area satisfies Poisson distribution with mean Λ_t. Therefore, the probability P_m that there are m tags in a subcell can be expressed as

$$P_m = exp(-\Lambda_t)\frac{{\Lambda_t}^m}{m!} \tag{9}$$

where $\Lambda_t = \lambda_t \left|S_w\right|$ denotes the intensity measure of Φ_t in a given subcell of WiFi node, $\left|S_w\right| = \pi {d_t}^2$ is the 2-demensional Lebesgue measure (i.e., area [6], [7]) of each subcell.

2) Expression of P_c: The probability P_c that only one tag wins the contention among m tags [1] can be expressed as

$$P_c = \frac{\sum_{i=0}^{l-2} C_m^1 \left(C_{l-i-1}^1\right)^{m-1}}{\left(C_l^1\right)^m} \tag{10}$$

where the denominator represents the number of all possible contention results among m tags, while the numerator represents the number of all possible successful contention results that only one tag wins the contention.

B. Expression of P_{th}.

The average occurrence probability of the successful 'transmission' event P_{th} can be formulated as the mean of probability $P(SINR(r_i) > \theta)$ in terms of two independent variables: the aggregate interferences I_0 and distance r_i between the target tag and the target WiFi node, which is expressed as

$$\begin{aligned} P_{th} &= E_{I_0} E_{r_i}\left[P(SINR(r_i) > \theta)\right] \\ &= E_{I_0}\left[\int_0^{d_t} P(SINR(r_i) > \theta) \cdot f(r_i) dr_i\right] \\ &= \int_0^{d_t} E_{I_0}\left[P(SINR(r_i) > \theta)\right] \cdot f(r_i) dr_i \end{aligned} \tag{11}$$

where $E_{I_0}\left[P(SINR(r_i) > \theta)\right]$ (abbreviated as $E_{I_0}\left[*\right]$) is the mean value of probability $P(SINR(r_i) > \theta)$ in terms of I_0 for a given r_i, $f\left(r_i\right)$ is the probability density function (PDF) of r_i. According to the conditional property of PPP, given that there are m tags in a subcell, r_i follows independent and identical uniform distribution [10], [11], and $f(r_i)$ can be expressed as

$$f(r_i) = \begin{cases} \frac{2r_i}{{d_t}^2} & 0 < r_i \leq d_t; \\ 0 & Otherwise; \end{cases} \tag{12}$$

where d_t is the radius of each subcell.

Further, $E_{I_0}\left[*\right]$ can be expressed as

$$\begin{aligned} E_{I_0}\left[*\right] &= E_{I_0}\left[P\left(\frac{P_0 h_i {r_i}^{-\alpha}}{I_0 + \sigma^2} > \theta\right)\right] \\ &= E_{I_0}\left[P\left(h_i > \frac{\theta\left(I_0 + \sigma^2\right) {r_i}^{\alpha}}{P_0}\right)\right] \\ &= E_{I_0}\left[exp\left(-\frac{\theta {r_i}^{\alpha}}{P_0}\left(I_0 + \sigma^2\right)\right)\right] \\ (a) &= exp\left(-\frac{\theta {r_i}^{\alpha}}{P_0}\sigma^2\right) E_{I_0}\left[exp\left(-\frac{\theta {r_i}^{\alpha}}{P_0} I_0\right)\right] \\ (b) &= exp\left(-\frac{\theta {r_i}^{\alpha}}{P_0}\sigma^2\right) \cdot \mathcal{L}_{I_0}\left(s\right) \end{aligned} \tag{13}$$

where (a) follows from the fact that $h \sim exp(1)$, and (b) follows from the definition of Laplace transform (LT) [12] of I_0 evaluated at $s = \frac{\theta {r_i}^{\alpha}}{P_0}$, that is, $E\left[exp(-sI_0)\right] = \mathcal{L}_{I_0}(s)$. Furthermore, the LT of I_0 received at the target WiFi node is given as

$$\begin{aligned}\mathcal{L}_{I_0}(s) &= E_{r_j}\left[exp\left(-\frac{\theta {r_i}^{\alpha}}{P_0}\sum_{j\in\Phi_t'} P_0 h_j {r_j}^{-\alpha}\right)\right]\\ (a) &= E_{r_j}\left[\prod_{j\in\Phi_t'} E_{h_j}\left(exp\left(-\theta {r_i}^{\alpha}{r_j}^{-\alpha}h_j\right)\right)\right]\\ (b) &= E_{r_j}\left[\prod_{j\in\Phi_t'}\left(\frac{1}{1+\theta {r_i}^{\alpha}{r_j}^{-\alpha}}\right)\right]\\ (c) &= exp\left(-2\pi{\lambda_t}'\int_{d_t}^{d_w}\left(1-\frac{1}{1+\theta {r_i}^{\alpha}y^{-\alpha}}\right)ydy\right)\end{aligned} \tag{14}$$

where $E_x[\cdot]$ is the expectation with respect to x, λ_t' is given in Eq. 3. (a) follows that the channel coefficients are i.i.d., (b) follows from $h \sim exp(1)$. (c) follows from the probability generation functional (PGFL) of PPP, i.e., $E\left[\prod_{x\in\Phi} f(x)\right] = exp\left(-\lambda\int_{\mathbb{R}^2}\left(1-f(x)\right)\right)dx$.

Substituting Eq. 13 and Eq. 14 into Eq. 11, we can obtain the expression of P_{th}, then substituting Eq. 8 and Eq. 11 into Eq. 7, we can obtain the expression of successful transmission probability P_s of tags.

VI. Performance Evaluation

In this section, we conduct extensive simulations to verify our theoretical model on the successful transmission probability of tags P_s (which is calculated by Eq. 7). In our simulation, we consider a saturated NWB network, where the WiFi nodes and tags always have data to transmit. Besides, we set the default system parameters according to IEEE 802.11ah [13]. Without loss of generality, the AP is deployed in the origin of the cell, WiFi nodes and tags are deployed in the AP cell following two independent PPPs Φ_w and Φ_t, respectively. Here, the radius d_w of the AP cell is 20 m, and the radius d_t of the subcell of each WiFi node is 0.9 m. In all figures, the labels '*Ana.*' and '*Sim.*' denote the theoretical and simulation results, respectively.

A. Successful Transmission Probability VS. SINR Threshold

In Fig. 2, we plot the successful transmission probability of tags P_s as the SINR threshold θ varies from 0 dB to 50 dB, when considering the impact of the SINR threshold or not. Here, λ_w = 0.005 WiFi nodes/m^2, λ_t = 1.0 tags/m^2, P_0 = 1 dBm, σ^2 = -100 dB, α = 3. From this figure, we have the following observations.

- The theoretical curves closely match the simulation curves. This manifests that our theoretical model is very accurate.
- As θ increases, P_s decreases when considering the impact of θ (i.e., $0 <= P_{th} < 1$), as the '*black solid*' line shows. It is because as θ increase, P_{th} decreases. Besides, λ_t keeps unchanged, P_m^c also keeps unchanged. According to Eq. 7, P_s decreases.
- As θ increases, P_s keeps unchanged when not considering the impact of θ (i.e., P_{th} = 1), as the '*black dash*' line shows. Here, P_s is determined by Eq. 8, λ_t keeps unchanged, so P_s keeps unchanged.

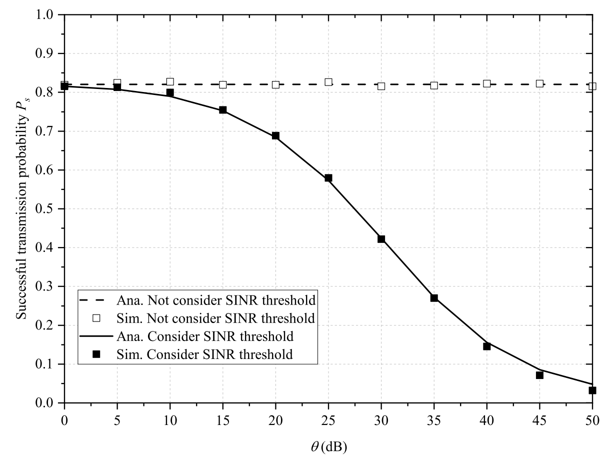

Fig. 2. Successful transmission probability P_s vs. SINR threshold θ.

B. Successful Transmission Probability VS. Intensity of WiFi Nodes

In Fig. 3, we plot the successful transmission probability of tags P_s as the intensity of WiFi nodes λ_w varies from 0.005 to 0.03 WiFi nodes/m^2, when considering the impact of the SINR threshold or not. Here, λ_t = 1.0 tags/m^2, P_0 = 1 dBm, σ^2 = -100 dBm, θ = 10 dB, α = 3. From this figure, we have the following observations.

- The theoretical curves closely match the simulation curves. This manifests that our theoretical model is very accurate.
- As λ_w increases, P_s decreases when considering the impact of θ (i.e., $0 <= P_{th} < 1$), as the '*black solid*' line shows. It is because that as λ_w increases, the total number of winner tags increases as well, which yields to larger I_0 for a target signal reception at the WiFi node, P_{th} decreases. Besides, λ_t keeps unchanged, P_m^c also keeps unchanged. According to Eq. 7, P_s decreases.
- As λ_w increases, P_s keeps unchanged when not considering the impact of θ (i.e., P_{th} = 1), as the '*black solid*' line shows. Here, the P_s is determined by Eq. 8, λ_t keeps unchanged, so P_s keeps unchanged.

C. Successful Transmission Probability VS. Intensity of Tags

In Fig. 4, we plot the successful transmission probability of tags P_s as the intensity of tags λ_t varies from 0.5 to 3.0 tags/m^2, when considering the impact of the SINR threshold or not. Here, λ_w = 0.005 WiFi nodes/m^2, θ = 10 dB, P_0 = 1 dBm, σ^2 = -100 dBm, α = 3. From this figure, we have the following observations.

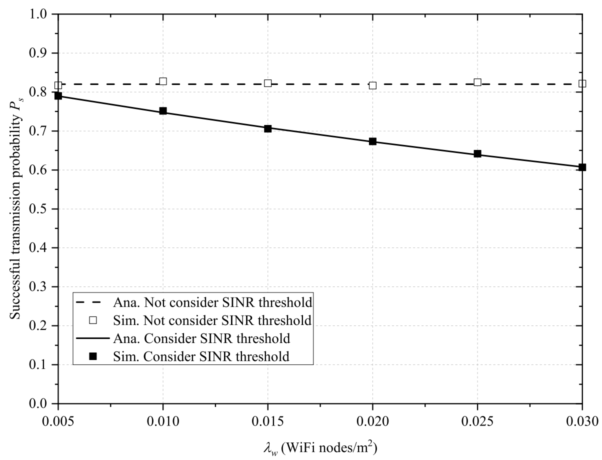

Fig. 3. Successful transmission probability P_s vs. intensity of WiFi nodes λ_w.

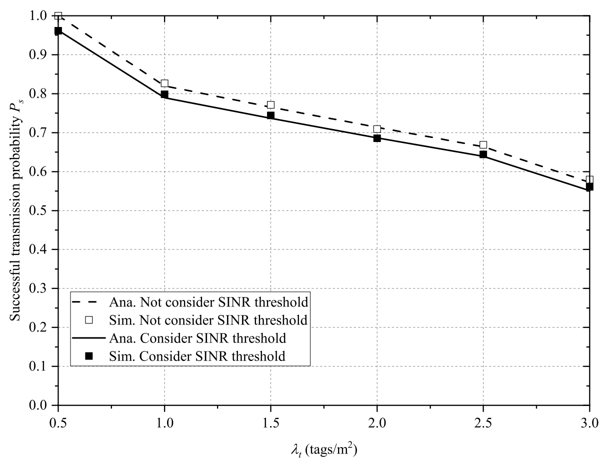

Fig. 4. Successful transmission probability P_s vs. intensity of tags λ_t.

- The theoretical curves closely match the simulation curves. This manifests that our theoretical model is very accurate.
- As λ_t increases, P_s decreases when considering the impact of θ (i.e., $0 <= P_{th} < 1$), as the '*black solid*' line shows. It is because that as λ_t increases, the number of tags m in a subcell increases, the contention among tags also increases, P_m^c decreases. Besides, θ keeps unchanged, P_{th} also keeps unchanged. According to Eq. 7, P_s decreases.
- As λ_t increases, P_s decreases when not considering the impact of θ (i.e., P_{th} = 1), as the '*black dash*' line shows. Here, the P_s is determined by Eq. 8, λ_t increases, P_m^c decreases, so P_s decreases. For a given λ_t, P_s is larger than that when considering the impact of θ.

VII. Conclusion

In this paper, we mainly investigate the first-stage tags-to-WiFi transmissions in an NWB network. As far as we know, we are the first to consider the impact of the two-level contentions and the geometric distributions of tags and WiFi nodes on the successful transmission probability. We propose an SG-based theoretical model to characterize the contention randomness of randomly deployed tags and WiFi nodes and exclude non-interfering tags for each tag-to-WiFi transmission. With our model, we theoretically analyze the successful transmission probability of tags in the NWB network. We also conduct extensive simulations to verify that our theoretical model is very accurate. In future research, we will explore more impacts of different influential factors (i.e., path-loss exponent, average noise power and reflecting power of tags) on successful transmission probability of tags, and also analyze more performance matrixes (i.e., system throughput) in NWB networks. Particularly, it is significant to develop a universal framework to provide theoretically guided parameter settings for NWB networks, and hence improve the system performance.

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