Stochastic Access Scheme for Delay Sensitive Applications in Wireless Ad Hoc Networks

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ABSTRACT

To improve the transmission throughput, this paper investigates the problem of the optimization of stochastic access probability for delay-sensitive applications in wireless ad hoc networks. Specifically, the transmission throughput is first defined and adopted as the performance metric to evaluate the network performance. The closed expression of the successful transmission probability is derived based on stochastic geometry. Then, the queueing delay including the waiting and transmission delay is also achieved through modeling the queueing process as M/M/1 model. After that, the problem of maximizing the network transmission throughput is formulated into an optimization problem under the delay constraints. To solve it, the closed-form expression of the optimal stochastic access probability is derived. Numerical results demonstrate the proposed optimal stochastic access scheme can improve the transmission throughput performance through comparison with two existing schemes.

CCS CONCEPTS

•Networks →Mobile ad hoc networks;

KEYWORDS

stochatic access probability, transmission throughput, stochastic geometric, queueing theory

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1 INTRODUCTION

Along with the diversification of wireless data traffics, lots of applications have more and more strict delay quality of service (QoS) requirement such as the real-time video streaming or interactive multimedia [4, 9]. With the flexibility of an ad hoc network, mobile nodes could spontaneously form a network without relying on any infrastructures or centralized management. However, there are also many challenges for such ad hoc networks to support the high throughput requirement especially for the delay-sensitive applications. For ad hoc networks, throughput is still an important performance metric for measuring how much traffic can be delivered by the network [15]. The network throughput could be affected by the network topology, the medium access control (MAC) protocol, the link interference as well as the delay constraint. Accordingly, in order to improve the network throughput especially for the delay-sensitive applications, all the above factors should be taken into consideration in wireless ad hoc networks.

Aloha-typed MAC protocol plays a important role in a spectrum sharing interference-limited network. Due to its ease of implementation and their random nature, it is widely utilized and studied in many network scenarios such as cellular and ad hoc networks [1, 2, 11]. For an ad-hoc network with aloha random access scheme, the stochastic access probability is an important design parameter which will determine how much opportunity for the users to access the shared channel. The value of stochastic access probability will impact the network throughput. On the one hand, large stochastic access probability implies that it allows as many simultaneous transmission as possible over different areas of the network. But the large access probability will also incur sever interference which could decrease the probability of successful transmission and then further decrease the network throughput. On the other hand, the small stochastic access probability indicates the less transmission opportunity which could incur long queue delay. Therefore, it is critical to design an optimal stochastic access probability for aloha access scheme to improve the network throughput especially under QoS constrained.

Several efforts have been done to investigate the stochastic access scheme in random access networks. For example, the optimization of the transmission probability have been investigated in [11] for wireless peer discovery to maximize the average number of successfully discovered peers. The authors in [2] focused on optimizing the medium access probability with an aloha-type access scheme with the objective of maximizing the average number of successful transmitters. However, these prior work did not focus on studying the impact of stochastic probability on the network performance with delay-sensitive applications. To characterize the interference in the interference-limited access networks, stochastic geometry has became an useful tool to analyze the performance of networks [6, 13, 16, 18, 19]. Based on the stochastic geometry theory, a transmission capacity framework has been proposed as the metric of quantification of the achievable rate in [18], where the transmission capacity is defined as the maximum number of successful transmission users in unit area under an predefined outage probability constraint. Then, based on the concept of transmission capacity, the authors investigated the achievable rate in the DF cooperation overlaid wireless networks. Similarly, the authors in [13] proposed a concept of transmission throughput by taking the node density, transmission rate and outage probability into account. However, few of the aforementioned work has considered the QoS requirement of delay-sensitive traffic when investigating the stochastic random access scheme. Differing from the existing work, we focus on investigating the optimal stochastic access probability with the objective of maximize the network transmission throughput by jointly considering the network topology, queue state as well as the delay QoS constraint.

The rest of this paper is organized as follows. The network model considered in this paper is introduced in Section 2. The definition of the transmission throughput is also included in this section. In Section 3, the analysis of network transmission throughput is presented. Section 4 presents the problem formulation. The optimal solution is also included in this section. Section 5 shows the numerical results to evaluate the performance of the proposed optimal stochastic access probability scheme. Section 6 concludes the whole paper finally.

2 NETWORK MODEL AND SYSTEM SETUP

In this paper, we consider an ad-hoc network, where all the users (transmitter-receiver pair) are with the delay-sensitive traffics such as video streaming. The locations of all transmitters are distributed following a homogeneous Poisson point process (PPP) with density ω on a two-dimensional plane. Let $\Pi = \{X_i, i \in \mathbb{Z}\}$ denote the set of all transmitters and $X_i \in \mathbb{R}^2$ is the position of the transmit node i. Each transmitter has been assigned an itended receiver in a distance d m away to communicate through single-hop route. An illustration of described network topology is shown in Fig. 1. All the users share the same spectrum resource and access to the frequency channel with a tractable Aloha MAC protocol with the stochastic access probability $p \in [0, 1]$. Based on the

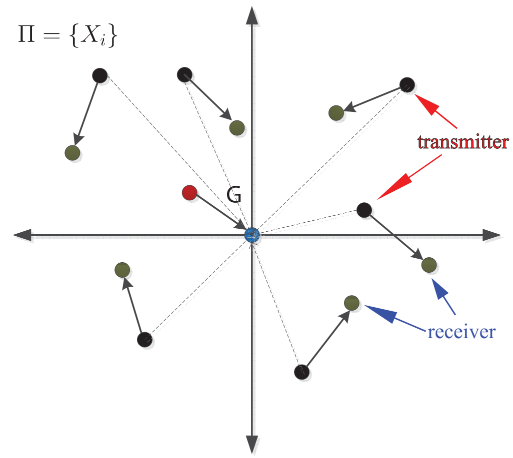

Figure 1: One example of the network topology. The transmitters locations (black circles) form a Poisson process, Π; each transmitter has a fixed receiver (green receivers). The reference communication link has a reference receiver located at the origin (blue) and a reference transmitter departed d (red). The dashed lines indicate the interference generated by each black transmitter.

stochastic geometric theory[3, 8], the set of nodes simultaneously transmitting also forms a homogeneous PPP $\bar{\Pi}$ with the new density $p\omega$. Furthermore, the statistic performance of the PPP is not affected by the addition of a referenced transmitter-receiver pair according to the Slivnyak's theorem [8]. The referenced transmitter-receiver pair can also characterize the average performance of the whole network. Therefore, without loss of generality, we consider and investigate the performance of a reference receiver located at the original [18].

To avoid the concept confusion, we first redefine the transmission throughput to characterize the average network throughput satisfying the users' delay QoS requirements. The definition of transmission throughput is given below.

Definition 2.1. Transmission throughput R of a random PPP deployed in wireless network is defined as the product among the stochastic access probability p, the network node density ω, the packet arrival rate λ and the packet success transmission probability P_{suc} over a wireless link. Hence, the transmission throughput is expressed as

$$R(p) = p\omega\lambda P_{suc}. \tag{1}$$

It is worth noting that the transmission throughput defined above indicates the number of successful transmission packets per second per unit area.

3 TRANSMISSION THROUGHPUT

In this section, in order to derive and analyze the transmission throughput defined in Section 2, we first introduce the the wireless channel model, and then derive the probability of successful transmission based on the SINR interference model. After that, the queueing delay model is also presented.

3.1 channel model

In order to analyze the probability of successful transmission for a packet, the channel model employed should be first settled. The large scale path loss and small scale Rayleigh block fading are considered to model the channel between any pair of transmitter and receiver. The power gain $G(y)$ between a transmitter and a receiver, located at x and y, can be expressed as

$$G_(y) = P_t(x)H_{xy}\|x-y\|^{-\alpha}. \tag{2}$$

where $P_t(x)$ is the transmission power at $x \in \mathbb{R}^2$. In this paper, we assume each transmitter transmits packets with the same power. H_{xy} represents the random channel fading gain with exponentially distributed with unit mean, and it is independent across different links. $\|\cdot\|$ is the Euclidean norm, α is the path-loss exponent (where $\alpha > 2$). $\|x-y\|^{-\alpha}$ denotes the large-scale behavior of the channel.

3.2 Probability of successful transmission

Based on the channel model, the typical SINR interference model in [19] is utilized to derive the probability of packet successful transmission. The SINR for the receiver located at $y \in \mathbb{R}^2$ can be calculated as follows,

$$SINR(y) = \frac{P_t(x_0)H_{x_0 y}\|x_0-y\|^{-\alpha}}{N_0 + \sum_{x\in\mathcal{I}} P_t(x)H_{xy}\|x-y\|^{-\alpha}}. \tag{3}$$

where x_0 is the location of the desired transmitter. $\mathcal{I}$ denotes the set of the interfering users, and N_0 is the noise power. Similar to [13, 18], a typical user whose receiver node locates at origin is considered as the reference node in this paper. Additionally, the noise power can be omitted due to the interference-limited scenarios. Hence, the SINR is rewritten as,

$$SIR = \frac{H_{X_0}d^{-\alpha}}{\sum_{X_i\in\bar{\Pi}/\{X_0\}} H_{X_i}\|X_i\|^{-\alpha}} = \frac{H_{X_0}d^{-\alpha}}{\mathcal{I}_{\text{agg}}}. \tag{4}$$

where the index 0 of the referenced receiver at origin is omitted. The interference term $\mathcal{I}_{\text{agg}}$ is

$$\mathcal{I}_{\text{agg}} = \sum_{X_i\in\bar{\Pi}/\{X_0\}} H_{X_i}\|X_i\|^{-\alpha}. \tag{5}$$

Definition 3.1. The probability of successful transmission for a packet over wireless channel is defined as the probability that the value of its SIR is no less than a given threshold β.

According to the definition 3.1 and the stochastic geometry theory [3], the probability of packet success transmission over wireless link, denoted by P_{suc}, is expressed as

$$\begin{aligned} P_{\text{suc}} &= \mathbb{P}\{SIR \geq \beta\} && (6)\\ &= \mathbb{P}\{\frac{H_{X_0}d^{-\alpha}}{\mathcal{I}_{\text{agg}}} \geq \beta\} && (7)\\ &= \mathbb{P}\{H_{X_0} \geq \beta\mathcal{I}_{\text{agg}}d^{\alpha}\} && (8)\\ &= \mathbb{E}[\exp(-\beta\mathcal{I}_{\text{agg}}d^{\alpha})] && (9)\\ &= \mathcal{L}_{\mathcal{I}_{\text{agg}}}(s)|_{s=\beta d^{\alpha}} && (10)\\ &= \exp\left(-p\omega\pi\beta^{\frac{2}{\alpha}}d^2\frac{2\pi/\alpha}{\sin(2\pi/\alpha)}\right). && (11) \end{aligned}$$

where $\mathcal{L}_{\mathcal{I}_{\text{agg}}}(s)$ represents the Laplace transform of the aggregate interference and its detailed derivation can be referred to [8].

3.3 Queueing delay model

For the delay-sensitive application, the delay constraint of users should be satisfied. The queue delay should be firstly considered. Let m denote the number of time slots taken by a node to transmit one packet. Let τ denote the duration of a time slot. The probability mass function of the service time S for transmitting one packet is given as

$$\text{Prob}(S = m\tau) = (1-p)^{m-1}p. \tag{12}$$

Then, the expection of the service time S can be given as

$$\mathbb{E}[S] = \sum_{m=1}^{+\infty} m\tau(1-p)^{m-1}p = \frac{\tau}{p}, \tag{13}$$

where $\mathbb{E}[\cdot]$ denotes expectation operator. Let $\upsilon = 1/\mathbb{E}[S] = \psi(\beta)$. For simplicity, the pdf in (12) can be approximated by an exponential distribution function with the parameter υ as in [17]. Thus we have

$$\text{Prob}(S = m\tau) \approx \upsilon\exp(-\upsilon m). \tag{14}$$

The approximation accuracy of the exponential distribution function is verified in Fig. 2, where we can observe that (14) fits well with the original probability mass function in (12).

Consequently, the average service rate for the video packets, μ, is given by

$$\mu = \frac{1}{\mathbb{E}\{S\}} = \frac{p}{\tau}. \tag{15}$$

Hence, the load factor ρ for the queue can be obtained as follows,

$$\rho = \frac{\lambda}{\mu} = \frac{\lambda\tau}{p}. \tag{16}$$

where $\rho \leq 1$ is required to keep the stability of the queue. Therefore, we have the lower bound on the stochastic access probability p as follows,

$$p \geq \lambda\tau. \tag{17}$$

Similar to [12, 14] , the arrival process of data packets is assumed to follow Poisson distribution with the parameter λ (packets/s).The arrival packets are stored in a queue at the buffer of transmitter and served in a first in first out fashion. Based on the approximation in (14), the queue of user can be modeled as an M/M/1 queue [5, 7]. According to the

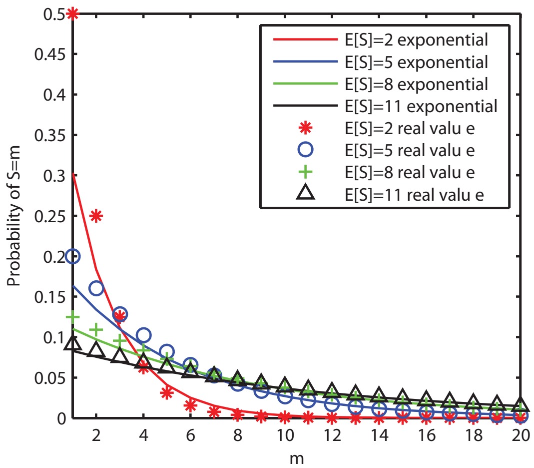

Figure 2: The approximation of the probability density function of S

queueing theory [10], the average queue delay including the average waiting time and the average transmission time in a queue, denoted by $\bar{W}$, can be expressed as follows,

$$\overline{W} = \frac{1}{\mu - \lambda} = \frac{\tau}{p - \lambda\tau}. \tag{18}$$

where $p \geq \lambda\tau$.

In this work, the delay constraint for all the users is specified using a delay upper bound D, i.e.,

$$\overline{W} \leq D. \tag{19}$$

Substituting (18) into (19), the average delay constraint of user is equivalently expressed as

$$p \geq \frac{\tau}{D} + \lambda\tau. \tag{20}$$

where the another lower bound of stochastic access probability is formed. To satisfy the delay requirement, the constraints both (17) and (20) are satisfied simultaneously. It can be easily prove that only if (20) is satisfied and the constraint in (17) is also satisfied.

4 PROBLEM FORMULATION AND SOLUTION

4.1 Problem formulation

Base on the analysis in Section 2 and Section 3, the average transmission throughput on unit area can be formulated as follows,

$$\begin{aligned} R(p) &= p\omega\lambda P_{\text{suc}} \\ &= p\omega\lambda \exp\left(-p\omega\pi\beta^{\frac{2}{\alpha}} d^2 \frac{2\pi/\alpha}{\sin(2\pi/\alpha)}\right). \end{aligned} \tag{21}$$

Then, the problem of maximizing the average transmission throughput under the delay QoS constraint can be formulated into an optimization problem as below

$$\begin{aligned} \text{Given}:&\quad \lambda, \tau, D, \omega, \beta, d, \alpha, && (22)\\ \underset{p}{\text{Maximize}}:&\quad R(p) && (23)\\ \text{Subject to}:&\quad p \leq 1; && (24)\\ &\quad p \geq \frac{\tau}{D} + \lambda\tau. && (25) \end{aligned}$$

where (25) denotes the average delay constraint for delay-sensitive traffic.

4.2 Optimal stochastic access probability

Based on the formulated optimization problem shown in (22)-(25), the optimal stochastic access probability is obtained and shown as follows,

$$p_{\text{opt}} = \begin{cases} 1, & if\ \frac{1}{\omega Q} \geq 1 \\ \frac{1}{\omega Q}, & if\ \eta < \frac{1}{\omega Q} < 1 \\ \eta, & if\ \frac{1}{\omega Q} \leq \eta \end{cases} \tag{26}$$

where $Q = \pi\beta^{\frac{2}{\alpha}} d^2 \frac{2\pi/\alpha}{\sin(2\pi/\alpha)}$ and $\eta = \frac{\tau}{D} + \lambda\tau$).

The proof of (26) is presented in details as below,

Proof. Given the network parameter $\tau, D, \beta, d, \alpha$, the optimal stochastic access probability is variable along with the node density ω and traffic load λ. In order to obtain the solution of optimal stochastic access probability, we need to check the characteristics of monotone and convexity-and-concavity. To this end, the first derivation of $R(p)$ shown in (21) with respect to p is derived firstly,

$$\frac{\mathrm{d}R(p)}{\mathrm{d}p} = \omega\lambda \exp(-p\omega Q)(1 - p\omega Q), \tag{27}$$

Then, the second derivative of $R(p)$ with respect to p is obtained as follows,

$$\frac{\mathrm{d}^2 R(p)}{\mathrm{d}^2 p} = \omega^2 \lambda Q \exp(-p\omega Q)(p\omega Q - 2). \tag{28}$$

Due to the delay constraint on the stochastic access probability, i.e., $p \in [\eta, 1]$, if $\frac{\mathrm{d}^2 R(p)}{\mathrm{d}^2 p} < 0$ holds, i.e., $p < \frac{2}{\omega Q}$, the optimization problem is concave and thus there exists a optimal solution to maximize the network transmission throughput. Setting the first derivative shown in (27) to be zero, we get $p = \frac{1}{\omega Q}$. If $\frac{1}{\omega Q} \in [\eta, 1]$ holds, $\frac{1}{\omega Q}$ is the optimal stochastic access probability which also satisfies the delay QoS constraint. If $\frac{1}{\omega Q} > 1$ holds, $p < \frac{1}{\omega Q}$ holds because of $p \leq 1$. And thus there is $\frac{dR(p)}{dp} > 0$, which implies that the objective function (21) is a monotone increasing function with respect to p in the interval $[\eta, 1]$. In such a case, the optimal solution of the optimization problem is $p = 1$. Otherwise, when $\frac{1}{\omega Q} < \eta$ holds, $p > \frac{1}{\omega Q}$ holds because of $p \geq \eta$. Therefore, there is $\frac{\mathrm{d}R(p)}{\mathrm{d}p} < 0$, which implies that the objective function (21) is a monotone decreasing function with respect to p in the interval $[\eta, 1]$. In such a case, the optimal solution of the optimization problem is $p = \eta$. □

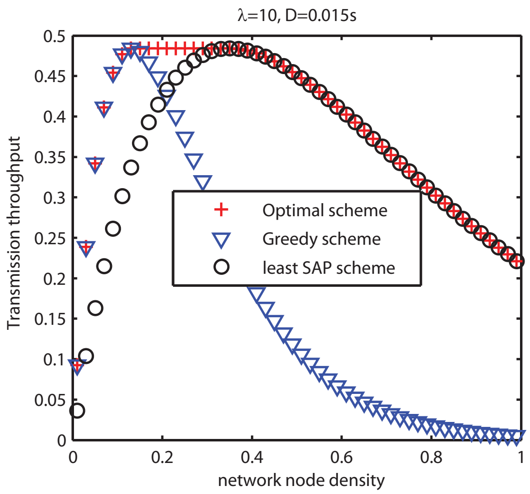

Figure 3: Comparison of the average transmission throughput of the three schemes with different node density when $\lambda = 10$ packets/s and $D = 0.015s$.

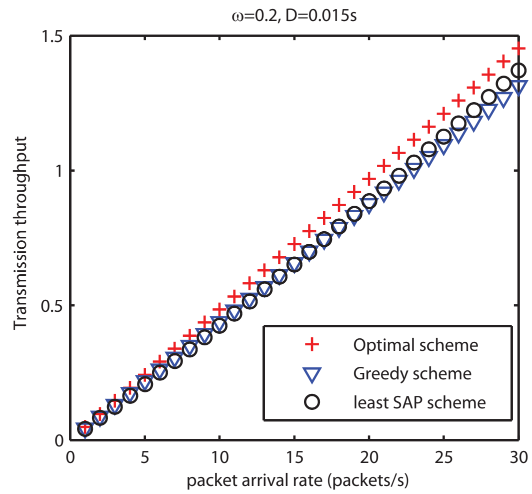

Figure 4: Comparison of the average transmission throughput of the three schemes with different packet arrival rate when $\omega = 0.2$ and $D = 0.015s$.

5 NUMERICAL RESULTS

In order to evaluate the performance of the proposed stochastic access scheme, numerical results are provided in this section. The impacts of the network parameters on the average transmission throughput are also investigated. To evaluate fairly, the performance of the proposed scheme is also compared with those of the other two existing schemes, i.e., greedy scheme and least SAP scheme. For the greedy scheme, all the user access the frequency channel with the probability 1. For the least SAP scheme, the users access the channel with the least probability on the premise of satisfying the users' delay QoS requirements.

The results are obtained under the following system setup. All the users transmit packets with the same transmission power. The duration of a slot is set to be 5 ms and the distance between the transmitter and receiver is set to be 10 m. The path loss factor is set to be 3. In addition, the SIR threshold is also set to be a typical value of 10.

Fig. 3 shows the transmission throughput of the three schemes with respect to the network node density ω under the given packet arrival rate $\lambda = 10$ packets/s and the delay deadline $D = 0.015$ s. From the Fig. 3, we can observe that the proposed optimal scheme always obtains the optimal performance compared with the other two schemes in terms of transmission throughput. Especially when the node density lies in the interval $[0.15, 0.38]$, the optimal stochastic access probability scheme outperforms both the greedy and least stochastic access probability schemes. This is because the optimal scheme can be adaptive to the network conditions such as the node density and traffic load. In addition, it can be observed that the performance of the optimal scheme is almost same as that of the greedy scheme when the network node density is below 0.15. This is because the lower node density, the less number of users and thus causes a lower

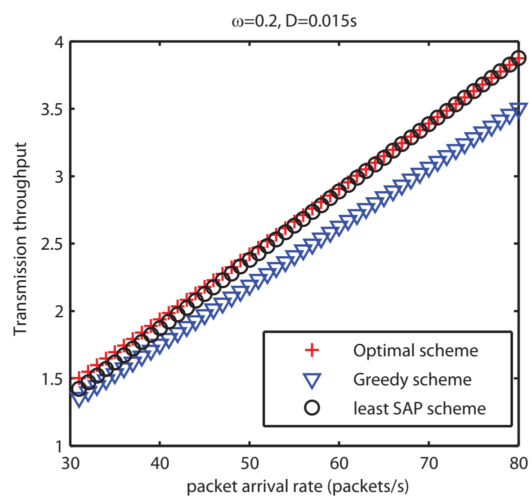

Figure 5: Comparison of the average transmission throughput of the three schemes with different packet arrival rate when $\omega = 0.2$ and $D = 0.015s$.

interference. Therefore, all the users could simultaneously transmit with probability 1. In a similar way, the higher node density, the larger number of users. In this case, if all users transmit with a higher probability, it may cause server interference and thus decrease the transmission throughput. Hence, the optimal selection for the users is to choose the least stochastic access probability to transmit on the premise of satisfying the delay QoS requirement.

Fig. 4 and 5 show the average transmission throughput of the three schemes with respect to different packet arrival rate with the given the network node density $\omega = 0.2$ and the given delay deadline $D = 0.015$s. From the above two figures, it can

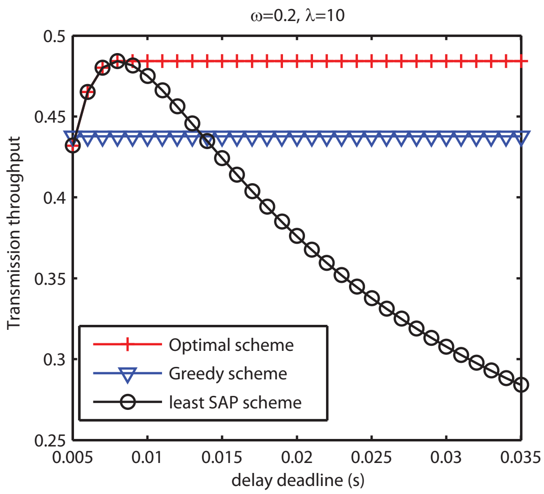

Figure 6: Comparison of the average transmission throughput of the three schemes with different delay deadline when $\omega = 0.2$ and $\lambda = 10$ packets/s.

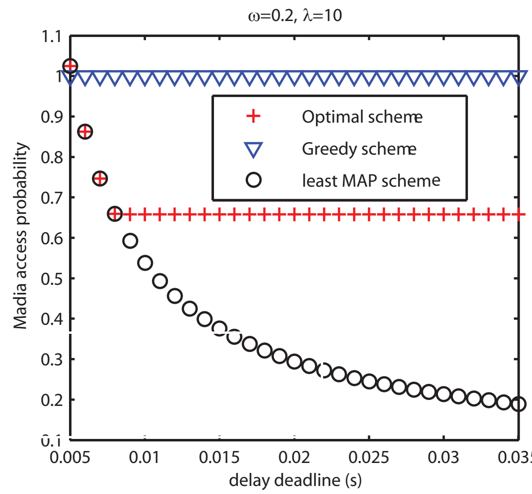

Figure 7: Comparison of the stochastic access probability of the three schemes with different delay deadline when $\omega = 0.2$ and $\lambda = 10$ packets/s.

been observed that the transmission throughput of the three schemes increases with the increase of λ. In addition, from Fig. 4, the performance of the proposed optimal scheme also outperforms than those of the other two schemes when the packet arrival rate λ is below 30 packets/s. In Fig. 5, it can be observed that the performance of the proposed optimal scheme is almost the same as that of the least stochastic access probability scheme, and the greedy scheme achieves the worst transmission throughput performance when the packet arrival rate λ is above 30 packets/s. The reason is that when the traffic load is too heavy, all the users tend to choose the least stochastic access probability to transmit packets in order to decrease interference level.

Furthermore, the effect of delay deadline D on the transmission throughput and on the stochastic access probability of the three schemes are also investigated. During the simulation, we take $\omega = 0.2$ and $\lambda = 10$ as an example. To be thorough, the queue delay deadline is assumed to vary from 5 ms to 35 ms with a step of 5 ms in the simulation and the results are illustrated in Fig. 6 and 7. It can be seen that the performance of the proposed optimal scheme first increases and then remains unchanged along with the increase of the delay deadline. This is because the users are more sensitive to delay when the delay bound is blow 10 ms, which also indicates the delay requirement becomes more stringent. In addition, the performance of the greedy scheme is almost invariable with the increase of the delay deadline. This is because all the users access the channel with probability 1 without considering the impact of delay. Moreover, results also show the performance of the least SAP scheme decreases with the increase of delay bound when the delay deadline is above 9 ms. This also indicates that the least SAP probability is not the optimal stochastic access probability for the users when the delay requirement relaxes. Fig. 7 presents the stochastic access probability of three schemes, where the curves also validate the above analysis.

6 CONCLUSIONS

In this paper, we proposed an optimal stochastic access scheme to improve the network transmission throughput for wireless ad-hoc networks with the delay-sensitive applications. According to the proposed access scheme, we derived the probability of successful transmission for a packet utilizing the typical SINR interference model based on the stochastic geometry theory. After that, the lower bound of stochastic access probability was obtained through deriving the queueing delay based on the M/M/1 queueing model. Then, the problem of maximizing the average network throughput has been formulated as an optimization problem. The closed-form expression of the optimal access probability was also obtained. Numerical results shows that the proposed optimal stochastic access probability scheme could adapt to differnt network conditions (e.g., different densities and different delay requirents). Moreover, the numerical results shows the superiority of the proposed optimal scheme through comparing with the other two existing schemes.

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