Throughput–Delay Tradeoff for Wireless Multichannel Multi-Interface Random Networks Le compromis entre délais et débits dans les réseaux aléatoires multi-interfaces et multicanaux sans fil

Xiaolin Ma, Fangmin Li, Jian Liu, and Xinhua Liu

***Abstract*— Capturing throughput–delay tradeoff in wireless networks has drawn considerable attention, as it could bring better usage experience by considering different requirements of throughput/delay demands. Traditional works consider only typical single-channel single-interface networks, whereas multichannel multi-interface (MCMI) networks will become mainstream since they provide concurrent transmissions in different channels, which in turn helps each node to obtain better performance. Unlike previous works, this paper investigates the throughput–delay tradeoff for MCMI random networks. Two queuing systems, i.e., the M/M/m queuing system and the *m* M/M/1 queuing system, are established for MCMI nodes, and a parameter in routing implementation named routing deviation is also considered in the analytical model. This paper studies concurrent transmission capacity (CTC) using the physical interference model and also explores the impact on CTC of different physical parameters. Moreover, the relations between throughput and delay are achieved using two queuing systems in MCMI random networks respectively. The deterministic results obtained with a group of real network configuration parameters demonstrate that the proposed tradeoff model could be applied to the real network scenarios.**

***Résumé*— Le compromis délais/débits dans les réseaux sans fil attire, de plus en plus, une attention particulière car il pourrait apporter une meilleure utilisation en tenant compte de différentes exigences des délais/débits. Les recherches traditionnelles ne considèrent que les réseaux typiques à canal et à interface uniques, alors que les réseaux multi-interfaces et multicanaux (MIMC) deviendront dominants puisqu'ils fournissent des transmissions simultanées dans différents canaux, ce qui permet à chaque nœud d'obtenir de meilleures performances. Contrairement aux recherches précédentes, cet article analyse le compromis délais/débits pour les réseaux aléatoires MIMC. Deux systèmes de file d'attente, c'est-à-dire, le système M/M/m et le système M/M/1 de file d'attente, sont établis pour les nœuds MIMC. De plus, un paramètre de routage, nommé écart de routage, est également pris en compte dans le modèle analytique. Cet article porte sur la capacité de transmission simultanée (CTS) en utilisant le modèle d'interférence physique et explore également l'impact de différents paramètres physiques sur la CTS. En outre, les relations entre débit et délai sont obtenues en utilisant deux systèmes de files d'attente dans les réseaux aléatoires MIMC. Les résultats obtenus avec un groupe de paramètres de configuration de réseaux réels démontrent que le modèle de compromis proposé pourrait être appliqué aux scénarios réels du réseau.**

***Index Terms*— Multichannel multi-interface (MCMI), queuing system, random networks, routing deviation (RD), throughput–delay tradeoff.**

I. INTRODUCTION

TRADITIONAL multihop wireless networks are often built based on single common channel used by all nodes to ensure network connectivity. In such networks, the network bandwidth utilization rate may become very low due to collision occurring when two nodes attempt to transmit simultaneously. This drawback can be tackled by adopting multichannel multi-interface (MCMI) technology, with which nodes are equipped with multiple interfaces and leverage multiple channels to carry data, and thus have the potential to provide concurrent transmissions without collisions in different channels through different interfaces. In addition, with the rapid growth in IEEE 802.11 technology [1], which is widely used in wireless networks and offers multiple available channels (e.g., IEEE 802.11b offers three nonoverlapping channels, while IEEE 802.11a offers 12 nonoverlapping channels), the price of the node constructed with MCMI technology has reduced sharply. The MCMI-enabled networks, therefore, have recently received considerable attention and will become mainstream.

Manuscript received September 8, 2014; revised December 21, 2014; accepted February 20, 2015. Date of current version June 10, 2015. This work was supported by the National Natural Science Foundation of China under Grant 60970019 and Grant 61373042.

X. Ma, F. Li, and X. Liu are with the Key Laboratory of Fiber Optical Sensing Technology and Information Processing, School of Information Engineering, Ministry of Education, Wuhan University of Technology, Wuhan 430070, China (e-mail: maxiaolin0615@whut.edu.cn; lifangmin@whut.edu.cn; liuxinhua@whut.edu.cn).

J. Liu is with the Department of Electrical and Computer Engineering, Stevens Institute of Technology, Hoboken, NJ 07030 USA (e-mail: jliu28@stevens.edu).

Associate Editor managing this paper's review: Waleed Ejaz.

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/CJECE.2015.2414091

As in traditional single-channel single-interface multihop wireless networks, the network capacity issue is also a key research problem in MCMI networks. The milestone research on network capacity in [2] establishes two network models, i.e., an arbitrary network model and a random network model, for studying throughput scaling in static wireless networks. Here, the arbitrary network model refers to the type of networks where the node locations, destinations of sources, and traffic demands are all arbitrary, while the random network model means the type of networks where the nodes and their destinations are randomly chosen. We obtain the capacity scale as $\Theta(W\sqrt{n})$ bit-m/s in an arbitrary network model and the network capacity scale as $\Theta(W(n/\log n)^{1/2})$ bits/s in a random network model, where n is the number of nodes in the network. We also proved that the capacity of a network with one single channel and one interface per node is equal to the capacity of a network with c channels and $m = c$ interfaces per node. However, the work does not capture the impact of using fewer than c interfaces per node on the capacity. Kyasanur and Vaidya [3] explore the capacity of MCMI networks under two such network models, especially when $c \leq m$. The results show that the capacity is dependent on the ratio of c/m, not on the exact value of either c or m. These works concern only the network structure itself and aim to provide theoretic upper capacity performance limits. However, from the perspective of network users or applications, only capacity performance is inadequate to support applications with diverse quality of service (QoS) requirements.

Once the features of applications are considered in the network design, throughput and end-to-end delay become two of the most important metrics [4] to evaluate network performance. In addition, in a wide range of wireless applications, different applications require different levels of throughput and delay demands. For instance, a voice over IP application requires only a sufficiently low delay; a high-volume downloading application requires only a throughput as high as possible; while the Internet online games need both high throughput and low delay to enhance players' experiences. In addition, applications with different QoS also require different throughput/delay demands depending on the traffic flow requirements. Thus, it is significant and pressing to pursue a deep understanding of the fundamental throughput–delay tradeoff that governs the performance balance so as to provide flexible QoS guarantees that can support diverse QoS requirements.

Motivated by the MCMI technology and the diverse QoS requirements derived from various applications, we take the MCMI multihop wireless networks as the considered network scenario, and focus on theoretic analysis of throughput–delay tradeoff, which is not intended to be closely tied up with any specific wireless networks. The aim of this paper is trying to provide a guidance in terms of designing throughput–delay tradeoff schemes to satisfy various applications with different QoS requirements. In particular, the major contributions of this paper can be summarized as follows.

1) We investigate the concurrent transmission capacity (CTC) in each channel for MCMI random networks, i.e., the maximum number of simultaneously transmitting nodes that can successfully send the packets to their receivers in the same time slot and in the same channel.
2) We obtain CTC using the physical interference model, which considers several factors in a physical layer [e.g., channel fading parameter and the minimum signal-to-interference ratio (SIR)] so as to analyze their impact on the CTC. Here, we use the physical interference model instead of a simple protocol interference model, since it is more practical and more related to the real physical layer considerations [2].
3) Two kinds of queuing systems, i.e., M/M/m queuing system and m M/M/1 queuing system, are established for MCMI node constructions. We obtain the throughput–delay tradeoff for MCMI random networks under such two different queuing systems based on the defined routing deviation (RD).
4) By providing the detailed network parameters, we present the deterministic analytical results of throughput–delay tradeoff and then investigate the possible practical applications. Note that, the theoretic analysis in this paper is not closely tied up with any specific wireless networks. However, as its specific applicable scenarios, multihop wireless networks composed of multi-interface IEEE 802.11-based nodes are typical applicable networks. Other multihop wireless networks, such as wireless mesh network or mobile ad hoc networks (MANETs), can also be the potential applicable networks, provided that MCMI technology is adopted and nodes are constructed complying with m M/M/1 queuing system or M/M/m queuing system.

The remainder of this paper is organized as follows. We survey the related work in Section II. Section III provides the network model, definitions, and hypotheses. In Section IV, we investigate the relation between CTC and several physical parameters, which have a great impact on the throughput–delay tradeoff analysis. We then establish two queuing systems for MCMI nodes and capture their throughput–delay tradeoff in Section V. In Section VI, we evaluate the deterministic analytical results by providing a group of detailed network environment parameters. Finally, the conclusion is given in Section VII.

II. Related Work

Throughput and delay are two key performance metrics in most network scenarios. In addition, the deep understanding of throughput–delay tradeoff is important to achieve QoS requirements for most applications. Much research has been done to study the delay-constrained throughput or the tradeoff between throughput and delay.

In [5], a random network with both mobile and static nodes is considered. We propose a routing algorithm, which exploits the patterns in the mobility of nodes, to achieve near optimum in terms of throughput while keeping the delay low. The throughput achieved by this algorithm is only a polylogarithmic factor off the optimal. In [6], exact expressions for network capacity are derived, and a fundamental rate–delay curve is established, which represents performance bounds on throughput and end-to-end delay for any conceivable routing and scheduling policy. El Gamal *et al.* [7]–[9] conducted a fundamental work on throughput–delay tradeoff. In [7], throughput and delay scaling for static and mobile networks is investigated, and the optimal throughput–delay tradeoff is established. El Gamal *et al.* [8] provide the results on throughput–delay tradeoff for mobile networks under a random-walk (RW) model instead of the less realistic hierarchical Brownian motion model assumed in [7]. For more realistic scenario, El Gamal *et al.* [9] study the throughput–delay tradeoff when the packet size remains constant, and find that it does not scale down with the number of nodes n in the network. This finding is valuable, since packet sizes normally do not change with the changes of n in practical networks.

Moreover, mobility models [4] have significant impact on the tradeoffs between throughput and delay. Ying *et al.* [10] consider four node mobility models, i.e., 2-D independent and identically distributed (i.i.d.) mobility, 2-D hybrid RW, 1-D i.i.d. mobility, and 1-D hybrid RW. We propose joint coding-scheduling approaches to improve capacity-delay tradeoff. In [11], the throughput–delay tradeoff is also studied by employing coding techniques, and a scheme to achieve the optimal improvement under RW mobility model is proposed. Li *et al.* [12] consider a restricted mobility model, in which a network of unit area has n nodes. The network is evenly divided into many cells, each of which is further divided into many identical squares, and all nodes can only move inside the cell. They show that the restriction on mobility range decreases capacity, and find that smooth tradeoff between throughput and delay can be achieved by controlling node mobility pattern. Jacquet *et al.* [13] propose a georouting strategy for relaying packets toward their destinations to maximize the capacity of mobile networks while keeping the delay bounded with increasing number of nodes. Furthermore, Liu *et al.* [14] study the throughput–delay tradeoff in large-scale MANETs, and propose a generalized i.i.d. mobility model; under which, constructive bounds for throughput and delay in MANETs are developed.

To the best of our knowledge, among the related works on throughput–delay tradeoff, works considering multichannel are relatively insufficient. For multichannel communications, Ghosh *et al.* [15] consider the routing tree construction problem on random geometric graphs and study the impact of routing trees on both maximizing the aggregated sink throughput and minimizing the maximum delay. For MCMI cognitive radio networks, Qin *et al.* [16] achieve different tradeoffs between throughput and delay of the secondary network by adjusting the number of backlogs in scheduling and channel allocation schemes.

Overall, the defects of the existing single-channel wireless networks can be summarized as: 1) many works capture the throughput–delay tradeoff constrained by specific node mobility model, the results of which are difficult to generalize; 2) most of the previous works study the asymptotic character in large networks; 3) the queuing characters are not paid enough attention, which are closely related to node constructions of networks; and 4) few works point out how to apply their results in practical scenarios. In addition, when extending to MCMI wireless networks, the throughput–delay tradeoff issue becomes more complex because: 1) it involves more factors, such as subchannels; 2) interference analysis and representation are more difficult due to concurrent transmission in multiple subchannels; and 3) queuing features cannot be ignored anymore. In this paper, we first establish two kinds of queuing systems, i.e., M/M/m queuing system and m M/M/1 queuing system, for MCMI node constructions, and analyze the queuing delay at each node of the routing path. Then, we investigate the throughput–delay tradeoff representations under the two queuing systems for MCMI wireless networks, which facilitates the practical design. Thus, the results of this paper avoid most problems in the existing works and are easier to apply to practical network scenarios.

III. Network Model and Definitions

A. Network Model

This paper considers a network setting on a planar disk of unit area. We assume there are c nonoverlapping channels available and each node is equipped with m interfaces satisfying $1 \leq m \leq c$. We call such network (m, c) network. We also assume that there are n nodes that are fixed and uniformly distributed in the disk. We adopt the random network model [2], [3], [17]. Furthermore, each node has the same transmitting power P and the same receiving range, and has one traffic flow to a randomly chosen destination in each channel. The packet length is fixed to a constant value, denoted as L_p.

We use physical interference model in this paper to analyze its impact on network performance with several physical parameters. Under the aforementioned assumptions, the physical interference model for (m, c) random networks can be given as follows.

Supposing node X_i transmits packets to node X_j over a channel, packets can be successfully received by the node X_j only if

$$\frac{\frac{P}{|X_i - X_j|^{\alpha}}}{N_0 + \sum_{\substack{k \in K \\ k \neq i}} \frac{P}{|X_k - X_j|^{\alpha}}} \geq \beta \tag{1}$$

where X_k represents any other node that simultaneously transmits packets to its destination (other than X_j) over the same channel. In addition, in (1), K is the transmitting node set. In this model, the minimum SIR, β, is a threshold for successful receptions, and N_0 is the ambient noise power. Channel fading represents by the model of signal power decaying with distance (i.e., $1/r^{\alpha}$ if distance is r).

B. Definitions

In this paper, concurrent transmission performance and transmission routing are analyzed to investigate throughput–delay tradeoff for (m, c) random networks. We first provide several necessary definitions to facilitate presentation in the remaining sections of this paper.

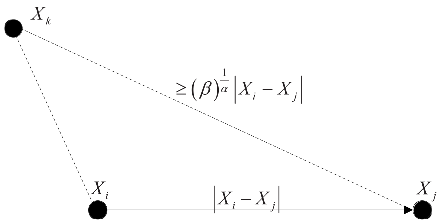


Fig. 1. X_i transmits packets to X_j, while X_k transmits packets to other node in the same channel (which may create interference to X_i and/or X_j).

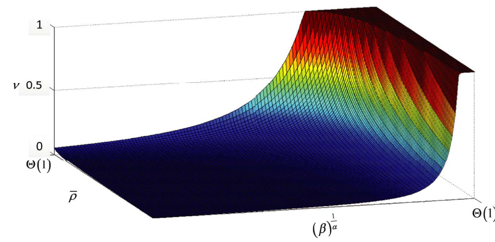


Fig. 2. Ideal CTR value with different network parameters.

1) Concurrent Transmission Capacity: When utilizing an ideal schedule policy, a subset of nodes can simultaneously transmit packets in the same channel. CTC is defined as the maximum number of simultaneously transmitting nodes that can successfully send packets to their receivers in the same channel. We use G denoting CTC.

2) Concurrent Transmission Ratio: We define the fraction of CTC over the number of total nodes in the network, n, as concurrent transmission ratio (CTR), denoted by ν, i.e., $\nu = G/n$.

3) Routing Deviation: We can depict a straight line [source–destination (S-D)] joining the source and the destination node in the network. In the (m, c) random network, each node has one traffic flow to a randomly chosen destination in each channel. Each node and its destination establish an S-D pair, and there are many relay nodes helping the S-D pair for forwarding packets. Define the maximum distance between the S-D pair and the corresponding relay nodes as RD, denoted by $\max(h)$.

4) Routing Length: When packets are transmitted from a source node to its destination, the number of hops along the transmitting path is called routing length (RL).

5) Pass Route Number: In MCMI random networks, each node is a traffic source and it randomly selects a node as its destination. Meanwhile, each node may be a relay node for other traffic flows to forward packets. The number of traffic flows that pass the node is defined as pass route number (PRN).

IV. Concurrent Transmission Analysis

In this paper, since CTC and CTR are very crucial for further studying on the throughput–delay tradeoff, we first analyze their features and representations under physical interference model.

As shown in Fig. 1, we assume that node X_i transmits packets to node X_j in a fixed channel, while a node set $\{X_k; k \in K, k \neq i\}$ simultaneously transmits packets to other nodes (i.e., their destinations) in the same channel. We consider one node X_k of such node set, and it satisfies

$$\frac{\frac{P}{|X_i - X_j|^\alpha}}{\frac{P}{|X_k - X_j|^\alpha}} \geq \frac{\frac{P}{|X_i - X_j|^\alpha}}{N_0 + \frac{P}{|X_k - X_j|^\alpha}} \geq \frac{\frac{P}{|X_i - X_j|^\alpha}}{N_0 + \sum_{\substack{k \in K \\ k \neq i}} \frac{P}{|X_k - X_j|^\alpha}} \geq \beta. \tag{2}$$

Equation (2) can be rewritten by

$$|X_k - X_j| \geq (\beta)^{\frac{1}{\alpha}} |X_i - X_j|. \tag{3}$$

As shown in Fig. 1, due to (3) and the triangle inequality principle, we have

$$|X_k - X_i| \geq \left((\beta)^{\frac{1}{\alpha}} - 1\right) |X_i - X_j|. \tag{4}$$

We use d_i to denote the distance between node X_i and its next hop receiver X_j, $|X_i - X_j|$. Therefore, node X_i and the node set $\{X_k; k \in K, k \neq i\}$ can successfully transmit packets to their receivers only if any two concurrent transmitting nodes, X_i and X_k, satisfy

$$|X_i - X_k| \geq \left((\beta)^{\frac{1}{\alpha}} - 1\right) \max(d_i, d_k). \tag{5}$$

In the defined MCMI random network, we suppose the mean distance of each hop is $\bar{d}$. In the ideal network topology, the number of concurrent transmitting nodes in each channel can be maximized only if the distance of each hop is identical to $\bar{d}$. Then, disks of radius $(((\beta)^{1/\alpha} - 1)\bar{d}/2)$ centered at each transmitter in one fixed channel are disjoint. Therefore, we have the CTC as

$$G \leq \frac{4}{\pi \left((\beta)^{\frac{1}{\alpha}} - 1\right)^2 \bar{d}^2}. \tag{6}$$

According to CTC, we obtain Theorem 1 as follows.

Theorem 1: In a random network, suppose $\bar{d}$ is the mean distance of each hop, and n is the number of total nodes. In addition, α and β are the channel fading parameter and the minimum SIR threshold, respectively. Then, CTR can be obtained by

$$\nu = \frac{4}{\pi \left((\beta)^{\frac{1}{\alpha}} - 1\right)^2 \bar{d}^2 n}.$$

For comparative analysis, we suppose $\rho_i = \pi {d_i}^2 n$ being the number of nodes within the disk of radius d_i centered at X_i, and have $\bar{\rho} = \pi \bar{d}^2 n$. Due to quadratic function being convex, we obtain the following:

$$\frac{\sum_{i=1}^{G} \rho_i}{G} \geq \bar{\rho} \tag{7}$$

where $\bar{\rho}$ represents node density in the network.

Then, substituting $\bar{\rho}$ in Theorem 1 gives

$$\nu = \frac{4}{\left((\beta)^{\frac{1}{\alpha}} - 1\right)^2 \bar{\rho}}. \tag{8}$$

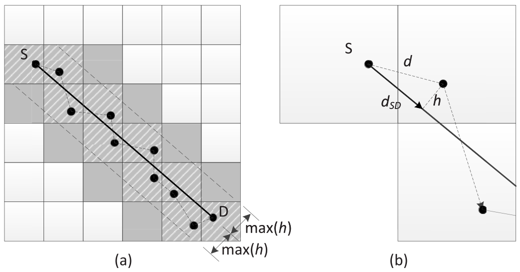


Fig. 3. Routing scheme with RD $\max(h)$: (a) Divided network domain with square cells. (b) Part of a traffic link.

The CTR is shown in Fig. 2 to clearly study the impact on CTR with different $\bar{\rho}$, α, and β. From Fig. 2, we can draw the following conclusions.

1) CTR increases with the decrease of node density (note: the premise is guaranteeing connectivity) of the network. In other words, the smaller the node density is, the bigger the fraction of CTC G over the number of total nodes n.
2) CTR increases with the decrease of parameter $(\beta)^{1/\alpha}$ (i.e., increasing α or decreasing β). It implies that we should decrease the minimum SIR threshold and increase the channel fading parameter if possible in the real network environment to enhance CTR.

From Fig. 2, we have $\nu = 1$ when $\bar{\rho} = \Theta(1)$ and $(\beta)^{1/\alpha} = O(\sqrt{c})$. When $\bar{\rho}$ is relatively small, the requirement of $(\beta)^{1/\alpha}$ can be loosened so as to achieve a high CTR. However, the value of α is determined by ambient environment (e.g., temperature, humidity, and obstacles) and the value of β, which is determined by antenna gain, is also uncontrollable. Therefore, we have two ways to increase CTR: 1) decreasing $\bar{\rho}$ on the premise of ensuring connectivity and 2) upgrading the wireless node with improved the antenna to decrease β.

V. Throughput–Delay Tradeoff

In this section, we first establish a routing scheme to analyze the relation between routing path and end-to-end delay, and then two queuing systems are established for MCMI nodes. Finally, we obtain the throughput–delay tradeoff in the network scenarios where nodes are constructed with these two different queues severally.

A. RD, RL, and PRN

The network domain is divided into square cells [as shown in Fig. 3(a)] similar to the cell construction used in [7]. Packets are routed through the cells that lie along the solid straight line S-D pair, as shown in Fig. 3. Recalling that the defined RD $\max(h)$ in Section III-B, the source node should select several relay nodes, which satisfy RD requirement to forward packets. Hence, the RD $\max(h)$ determines the departure level of the actual route to the S-D pair.

Since all nodes are located uniformly in the network region, according to [18] and [19], we can obtain the average distance between two points uniformly and independently chosen in the s-dimensional Euclidean space network as follows:

$$E[L] = \frac{s}{2s+1}\beta_s m(L) \tag{9}$$

where

$$\beta_s = \begin{cases} \dfrac{2^{3s+1}((s/2)!)^2 s!}{(s+1)(2s)!\pi}, & \text{for even } s \\ \dfrac{2^{s+1}(s!)^3}{(s+1)(((s-1)/2)!)^2(2s)!}, & \text{for odd } s. \end{cases}$$

Moreover, if the domain is a disc in 2-D with the diameter $m(L)$ (i.e., $s = 2$), we have $E[L] = 64m(L)/45\pi = 0.45271\ldots m(L)$. Here, due to $m(L) = 2\sqrt{1/\pi}$, we then have

$$E[L] = \frac{128}{45\pi}\sqrt{\frac{1}{\pi}} \approx 0.51083\ldots \tag{10}$$

Furthermore, we assume that the number of nodes in a specific area of the considered networks has a Poisson distribution with parameter λ, and the probability when this area has k nodes is

$$p(x = k) = \frac{\lambda^k e^{-\lambda}}{k!} \tag{11}$$

where λ is the mean number of nodes located in a specific area, and k is the actual number of nodes located in the area.

Fig. 3(b) shows a part of a traffic link. Here, in the figure, d represents the hop length, d_{SD} is the projection of d on the S-D pair link, h is the distance between a relay node and the S-D pair, and $\max(h)$ is RD. Due to the aforementioned requirements, the relay node has to lie in the rectangle with length d_{SD} and width $2\max(h)$. Since the positions of nodes are uniformly and independently distributed, the probability of a node located in this area is $p = 2\max(h)d_{\mathrm{SD}}$. The number of nodes in this area has a Poisson distribution with parameter $\lambda = np = 2n\max(h)d_{\mathrm{SD}}$, and then the probability when there is no node in this rectangle area is $P(D_{\mathrm{SD}} \geq d_{\mathrm{SD}}) = e^{-2n\max(h)d_{\mathrm{SD}}}$. Then, we have the cumulative distribution function of D_{SD} as

$$\begin{aligned} F_{D_{\mathrm{SD}}}(d_{\mathrm{SD}}) &= P(D_{\mathrm{SD}} < d_{\mathrm{SD}}) \\ &= 1 - e^{-2n\max(h)d_{\mathrm{SD}}}. \end{aligned} \tag{12}$$

Now, we have the corresponding probability density function as

$$f_{D_{\mathrm{SD}}} = 2n\max(h)e^{-2n\max(h)d_{\mathrm{SD}}}. \tag{13}$$

In addition, the mean value of D_{SD} can be obtained, which is

$$\begin{aligned} E[D_{\mathrm{SD}}] &= \int_0^\infty d_{\mathrm{SD}} f_{D_{\mathrm{SD}}}(d_{\mathrm{SD}})d(d_{\mathrm{SD}}) \\ &= \frac{1}{2n\max(h)}. \end{aligned} \tag{14}$$

According to (10) and (14), we obtain Theorem 2 as follows.

Theorem 2: The mean value of RL in the considered network can be obtained as

$$\bar{o} = \frac{E[L]}{E[D_{\mathrm{SD}}]} = \frac{256n\max(h)}{45\pi}\sqrt{\frac{1}{\pi}}.$$

In (m, c) random networks, each node randomly selects another node as its destination and the source node transmits packets over c channels separately, and so there are cn S-D pairs in the network. If the mean value of RL is $\bar{o}$, the

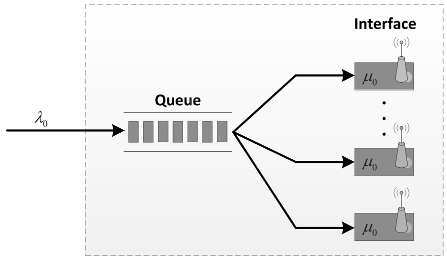


Fig. 4. M/M/m queuing system.

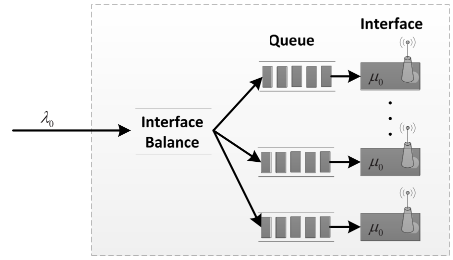


Fig. 5. m M/M/1 queuing system.

mean number of relay nodes in an S-D pair is $\bar{o}-1$. Therefore, we can obtain the mean value of PRN shown in Theorem 3.

Theorem 3: The mean value of PRN in the considered network can be obtained as

$$\bar{s} = \frac{cn(\bar{o}-1)}{n} = c(\bar{o}-1).$$

B. Throughput–Delay Tradeoff for Two Queuing Systems

As mentioned in the system model in Section II, each node in the (m, c) random network is equipped with m interfaces. We first establish two queuing systems, i.e., M/M/m and m M/M/1, according to the hardware design of nodes.

1) M/M/m Queuing System: We first study an S-D traffic flow to obtain the delay model. As shown in Fig. 4, packets transmitting through an S-D pair can be regarded as a tandem M/M/m queuing system, since each node has one queue and m interfaces to buffer/transmit packets.

In the M/M/m queuing system [20], the arrival of customers is a Poisson process with the arrival rate of λ_0, and the service time satisfies exponential distribution with mean service time $1/\mu_0$. Therefore, the mean stay time of a customer, including waiting time and service time, can be obtained as

$$\begin{aligned} t_s &= \frac{1}{\lambda_0}(L_q + m\rho) \\ &= \frac{1}{\lambda}\left(\frac{(m\rho)^m\rho}{m!(1-\rho)^2}P_0 + m\rho\right), \quad \rho < 1 \end{aligned} \tag{15}$$

where

$$P_0 = \left(\sum_{i=0}^{m-1}\frac{1}{i!}(m\rho)^i + \frac{1}{m!}\frac{1}{1-\rho}(m\rho)^m\right)^{-1}$$
$$\rho = \frac{\lambda_0}{m\mu_0}.$$

In the MCMI random network, the arrival of packets at each node is Poisson process with parameter $\bar{s}\lambda$ when this node is considered as a relay node according to Theorem 3. When the node is considered as a destination, the arrival of packets at each node is a Poisson process with parameter $c\lambda$, since the source transmits packets to the destination over different c channels simultaneously. Synthesizing each kind of node roles, the arrival of packets at each node is a Poisson process with parameter $\bar{s}\lambda + c\lambda = c\bar{o}\lambda$. In addition, recalled that CTR $\nu = G/n$, all nodes can be divided into $1/\nu$ groups and each group is assigned to a time slot to guarantee concurrent transmission. Therefore, the service time satisfies exponential distribution and the mean service time is $1/\mu\nu$ for each node transmitting once every ν time slots. Substituting the values in (15), we obtain the delay per hop as follows:

$$\overline{\text{Delay}}_{\text{hop}} = \frac{1}{c\bar{o}\lambda}\left(\frac{(m\rho)^m\rho}{m!(1-\rho)^2}P_0 + m\rho\right), \quad \rho < 1 \tag{16}$$

where

$$P_0 = \left(\sum_{i=0}^{m-1}\frac{1}{i!}(m\rho)^i + \frac{1}{m!}\frac{1}{1-\rho}(m\rho)^m\right)^{-1}$$
$$\rho = \frac{c\bar{o}\lambda}{m\mu\nu}.$$

Because the mean number of hops in each S-D traffic flow is $\bar{O}$, we have the end-to-end delay

$$\begin{aligned} \overline{\text{Delay}_{S-D}} &= \bar{o}\cdot\overline{\text{Delay}_{\text{hop}}} \\ &= \frac{1}{c\lambda}\left(\frac{(m\rho)^m\rho}{m!(1-\rho)^2}P_0 + m\rho\right), \quad \rho < 1 \end{aligned} \tag{17}$$

where

$$P_0 = \left(\sum_{i=0}^{m-1}\frac{1}{i!}(m\rho)^i + \frac{1}{m!}\frac{1}{1-\rho}(m\rho)^m\right)^{-1}$$
$$\rho = \frac{256c\lambda n\max(h)}{45\pi m\mu\nu}\sqrt{\frac{1}{\pi}}.$$

The throughput $\overline{T_{S-D}}$ is the product of the traffic rate λ and the packet length L_p. Then, we obtain Theorem 4 as follows.

Theorem 4: In the MCMI random network, if the MCMI nodes are designed based on the M/M/m queuing system, we have the relation between throughput $\overline{T_{S-D}}$ and end-to-end delay $\overline{\text{Delay}_{S-D}}$ as

$$\overline{\text{Delay}_{S-D}} = \frac{L_p}{c\overline{T_{S-D}}}\left(\frac{(m\rho)^m\rho}{m!(1-\rho)^2}P_0 + m\rho\right), \quad \rho < 1$$

where

$$P_0 = \left(\sum_{i=0}^{m-1}\frac{1}{i!}(m\rho)^i + \frac{1}{m!}\frac{1}{1-\rho}(m\rho)^m\right)^{-1}$$
$$\rho = \frac{256cn\max(h)\overline{T_{S-D}}}{45\pi m\mu\nu L_p}\sqrt{\frac{1}{\pi}}.$$

2) m M/M/1 Queuing System: As shown in Fig. 5, in an m M/M/1 queuing system, each node has m queues and m interfaces to buffer/transmit packets. Similar with the M/M/m queuing system, in the M/M/1 queuing system, the arrival of customers is a Poisson process with arrival rate of λ_0, and the service time obeys exponential distribution with mean service time $1/\mu_0$. Therefore, the mean stay time of a customer, including waiting time and service time, can be obtained as

$$t_s = \frac{1}{\mu_0 - \lambda_0}, \quad \rho < 1 \tag{18}$$

where

$$\rho = \frac{\lambda_0}{\mu_0}.$$

In the designed m M/M/1 queuing system, an interface balance mechanism is used to make the interface utilization balanced. The arrival rate of packets is λ_0/m at each interface if the arrival rate of packets at each node is λ_0. In addition, we also divide all nodes into $1/\mu$ groups, and we then have

$$\overline{\text{Delay}}_{\text{hop}} = \frac{m}{\mu m \nu - c\bar{o}\lambda}, \quad \rho < 1 \tag{19}$$

where

$$\rho = \frac{c\bar{o}\lambda}{m\mu\nu}.$$

On average, there are $\bar{o}$ hops in each S-D traffic flow; then, we have the end-to-end delay as

$$\begin{aligned}\overline{\text{Delay}}_{S-D} &= \bar{o} \cdot \overline{\text{Delay}}_{\text{hop}} \\ &= \frac{m\bar{o}}{\mu m \nu - c\bar{o}\lambda}, \quad \rho < 1\end{aligned} \tag{20}$$

where

$$\rho = \frac{c\bar{o}\lambda}{m\mu\nu}.$$

The throughput $\overline{T_{S-D}}$ is the product of the traffic rate λ and the packet length L_p. Then, we obtain Theorem 5 as follows.

Theorem 5: In the MCMI random network, if the MCMI nodes are designed based on the m M/M/1 queuing system, we have the relation between throughput $\overline{T_{S-D}}$ and end-to-end delay $\overline{\text{Delay}}_{S-D}$

$$\overline{\text{Delay}}_{S-D} = \frac{256n\max(h)mL_p\sqrt{\frac{1}{\pi}}}{45\pi\,\mu m\nu L_p - 256nc\max(h)\sqrt{\frac{1}{\pi}}\overline{T_{S-D}}}, \quad \rho < 1$$

where

$$\rho = \frac{256n\max h\overline{T_{S-D}}}{45\pi m\mu\nu L_p}\sqrt{\frac{1}{\pi}}.$$

VI. Deterministic Analytical Results

From Theorems 4 and 5, we can obtain the theoretical relation between link throughput and its end-to-end delay under the two queuing system considered in Section V. In real networks, a deterministic result can be captured using practical network parameters, and it can be leveraged to improve the network performance for different application demands. To this end, we first provide a group of network parameters: 1) the number of total nodes is $n = 1000$; 2) $m = 3$ interfaces are equipped in each node; 3) $c = 5$ nonoverlapping channels are available in the network; 4) packet length is $L_p = 1000$ bits; and 5) the transmitting rate of each interface is 10 packets/s. Moreover, we set the value range of $\max(h)$ is $0 \sim 3 \times 10^{-3}$ m, since the network domain is a 2-D disc whose radius is $\sqrt{1/\pi}$ m. Note that, the value of $\max(h)$ should be scaled by $\sqrt{A}$ if the area of the network domain is A square meters. We set $\gamma = \partial(\overline{\text{Delay}_{S-D}})/\partial(\overline{T_{S-D}})$ to denote the corresponding change rate of delay with the change of throughput.

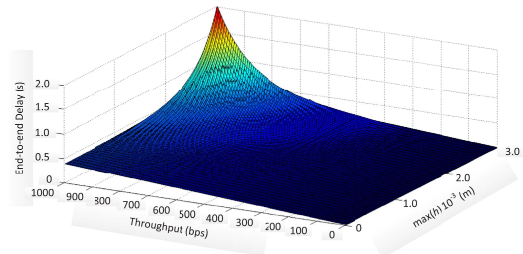


Fig. 6. Deterministic result for the M/M/m queuing system.

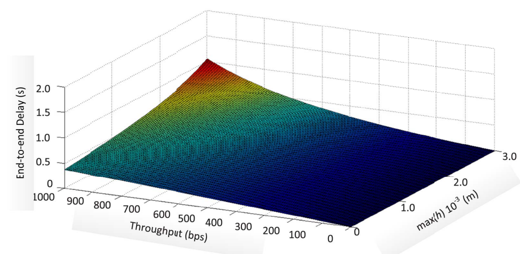


Fig. 7. Deterministic result for m M/M/1 queuing system.

Fig. 6 shows the deterministic result with the proposed practical parameters for the M/M/m queuing system. In the network with the provided parameters above, we see that γ changes slowly, and we have $\gamma \approx 4 \times 10^{-4}$ when $\max(h)$ is between 0 and 2×10^{-3} m. Specially, the delay will increase 0.4 s once the throughput increases 1000 bit/s. Therefore, throughput–delay can be easily selected in this case. However, when $\max(h)$ is between 2×10^{-3} and 3×10^{-3} m, γ changes dramatically; thus, it is hard to improve the entire network performance.

Fig. 7 shows the deterministic result with the proposed practical parameters for the m M/M/1 queuing system. In this queuing system, we can observe that the value of throughput-constrained delay also increases with a constant $\max(h)$ and increasing the value of throughput. In addition, γ would increase slowly if $\max(h)$ increases within the provided $\max(h)$ range. Hence, such queuing system is better for obtaining through-delay tradeoff with a very small influence of RD $\max(h)$.

It is well known that we need perfect network environment, appropriate node locations and even more routing layer messages in order to minimize $\max(h)$. Thus, unlike previous M/M/m queuing system, we can loose up $\max(h)$ strict constraint in the m M/M/1 queuing system.

In practical wireless applications, we can consider more factors in physical and routing layers on protocol design to satisfy different applications with different QoS demands. By leveraging detailed network configurations for different practical networks, we can capture corresponding throughput–delay tradeoff according to Theorems 4 and 5. Finally, we can make throughput–delay balanced or improve the performance on any one of them according to practical demands (e.g., only high throughput, only low delay or relatively good performance of the both).

VII. Conclusion

In this paper, we investigate the CTC in each channel for MCMI random networks using the physical interference model. Routing scheme is also studied and the RD is considered in the analysis of throughput–delay tradeoff. For the design of MCMI nodes, two queuing systems, i.e., M/M/m queuing system and *m* M/M/1 queuing system, are established. Then, we capture the relations between throughput and delay in the two queuing systems considered individually. By providing a group of practical network configuration parameters, we also study the deterministic results of throughput–delay tradeoff, which is close to its possible practical use in real scenarios.

References

[1] *IEEE Standard for Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, IEEE Standard P802.11, Nov. 1997.

[2] P. Gupta and P. R. Kumar, "The capacity of wireless networks," *IEEE Trans. Inf. Theory*, vol. 46, no. 2, pp. 388–404, Mar. 2002.

[3] P. Kyasanur and N. H. Vaidya, "Capacity of multi-channel wireless networks: Impact of number of channels and interfaces," in *Proc. ACM MobiCom*, Cologne, Germany, Aug. 2005, pp. 43–57.

[4] N. Lu and X. Shen, "Scaling laws for throughput capacity and delay in wireless networks—A survey," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 2, pp. 642–657, May 2014.

[5] N. Bansal and Z. Liu, "Capacity, delay and mobility in wireless ad-hoc networks," in *Proc. IEEE INFOCOM*, San Francisco, CA, USA, Mar./Apr. 2003, pp. 1553–1563.

[6] M. J. Neely and E. Modiano, "Capacity and delay tradeoffs for ad hoc mobile networks," *IEEE Trans. Inf. Theory*, vol. 51, no. 6, pp. 1917–1937, Jun. 2005.

[7] A. El Gamal, J. Mammen, B. Prabhakar, and D. Shah, "Throughput-delay trade-off in wireless networks," in *Proc. IEEE INFOCOM*, Hong Kong, Mar. 2004, pp. 464–475.

[8] A. El Gamal, J. Mammen, B. Prabhakar, and D. Shah, "Optimal throughput-delay scaling in wireless networks—Part I: The fluid model," *IEEE Trans. Inf. Theory*, vol. 52, no. 6, pp. 2568–2592, Jun. 2006.

[9] A. El Gamal, J. Mammen, B. Prabhakar, and D. Shah, "Optimal throughput-delay scaling in wireless networks—Part II: Constant-size packets," *IEEE Trans. Inf. Theory*, vol. 52, no. 11, pp. 5111–5116, Nov. 2006.

[10] L. Ying, S. Yang, and R. Srikant, "Optimal delay–throughput tradeoffs in mobile ad hoc networks," *IEEE Trans. Inf. Theory*, vol. 54, no. 9, pp. 4119–4143, Sep. 2008.

[11] Z. Kong, E. M. Yeh, and E. Soljanin, "Coding improves the throughput-delay tradeoff in mobile wireless networks," *IEEE Trans. Inf. Theory*, vol. 58, no. 11, pp. 6894–6906, Nov. 2012.

[12] P. Li, Y. Fang, and J. Li, "Throughput, delay, and mobility in wireless ad hoc networks," in *Proc. IEEE INFOCOM*, San Diego, CA, USA, Mar. 2010, pp. 1–9.

[13] P. Jacquet, S. Malik, B. Mans, and A. Silva, "On the throughput-delay trade-off in georouting networks," in *Proc. IEEE INFOCOM*, Orlando, FL, USA, Mar. 2012, pp. 765–773.

[14] W. Liu *et al.*, "On the throughput-delay trade-off in large-scale MANETs with a generalized i.i.d. mobility model," in *Proc. IEEE INFOCOM*, Turin, Italy, Apr. 2013, pp. 1321–1329.

[15] A. Ghosh, O. D. Incel, V. S. A. Kumar, and B. Krishnamachari, "Multichannel scheduling and spanning trees: Throughput–delay tradeoff for fast data collection in sensor networks," *IEEE/ACM Trans. Netw.*, vol. 19, no. 6, pp. 1731–1744, Dec. 2011.

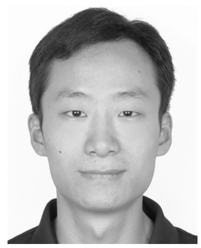
[16] Y. Qin *et al.*, "Opportunistic scheduling and channel allocation in MC-MR cognitive radio networks," *IEEE Trans. Veh. Technol.*, vol. 63, no. 7, pp. 3351–3368, Sep. 2014.

[17] J. Liu, F. Li, X. Liu, and H. Wang, "The capacity of multi-channel multi-interface wireless networks with multi-packet reception and directional antenna," *Wireless Commun. Mobile Comput.*, vol. 14, no. 8, pp. 803–817, Jun. 2014.

[18] S. R. Dunbar, "The average distance between points in geometric figures," *College Math. J.*, vol. 28, no. 3, pp. 187–197, May 1997.

[19] L. A. Santalo, "Integral geometry and geometric probability," in *Encyclopedia of Mathematics and Its Applications*, vol. 1. Reading, MA, USA: Addison-Wesley, 1976.

[20] L. Kleinrock, *Queueing Systems: Theory*, vol. 1, 1st ed. Hoboken, NJ, USA: Wiley, Jan. 1975.



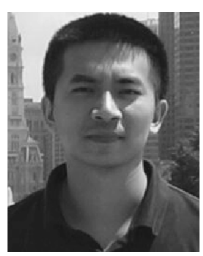
Xiaolin Ma received the B.Sc. degree in electrical and information engineering, and the M.Sc. and Ph.D. degrees in information and communications engineering from the Wuhan University of Technology, Wuhan, China, in 2008, 2011, and 2014, respectively.

He is currently a Lecturer with the Department of Information Engineering and a member with the Key Laboratory of Fiber Optical Sensing Technology and Information Processing, School of Information Engineering, Ministry of Education, Wuhan University of Technology. His current research interests include wireless communications and networks, radio resource optimization, and wireless sensing systems.

Fangmin Li received the B.Sc. degree from the Huazhong University of Science and Technology, Wuhan, China, in 1990, the M.Sc. degree from the National University of Defense Technology, Changsha, China, in 1997, and the Ph.D. degree from Zhejiang University, Hangzhou, China, in 2001, all in computer science.

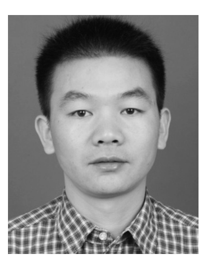
He is currently a Professor with the Department of Communications Engineering and a Senior Member with the Key Laboratory of Fiber Optical Sensing Technology and Information Processing, School of Information Engineering, Ministry of Education, Wuhan University of Technology, Wuhan. He has authored several books on embedded systems and over 30 academic papers in wireless networks, and also holds ten Chinese patents. His current research interests include wireless communications and networks, computer systems and architectures, and embedded systems.

Dr. Li is a Senior Member of China Computer Federation (CCF), and a Committee Member of the Technical Committee on Sensor Network, CCF.



Jian Liu received the B.E. and M.S. degrees from the Department of Information Engineering, Wuhan University of Technology, Wuhan, China, in 2011 and 2014, respectively. He is currently pursuing the Ph.D. degree with the Department of Electrical and Computer Engineering, Stevens Institute of Technology, Hoboken, NJ, USA.

His current research interests include information security and privacy, mobile computing, and sensing.



Xinhua Liu received the B.Sc. degree in computer science from the University of South China, Hengyang, China, in 1997, and the M.Sc. and Ph.D. degrees in information and communications engineering from the Wuhan University of Technology, Wuhan, China, in 2006 and 2010, respectively.

He is currently a Professor with the Department of Communications Engineering and a member with the Key Laboratory of Fiber Optical Sensing Technology and Information Processing, School of Information Engineering, Ministry of Education, Wuhan University of Technology. He has authored ten academic papers in wireless communications and networks. His current research interests include wireless communications and networks, and wireless sensor and actuator networks.