Throughput-Delay Tradeoff in Mobile Ad Hoc Networks with Correlated Mobility

Jiajia Liu*§, Hiroki Nishiyama*, Nei Kato*, Jian-feng Ma†, and Xiaohong Jiang‡
*Graduate School of Information Sciences, Tohoku University, Japan
†Department of Computer Sciences, Xidian University, China
‡School of Systems Information Science, Future University Hakodate, Japan
§Email: liu-jia@it.ecei.tohoku.ac.jp

***Abstract*—Reference Point Group Mobility (RPGM) has been a practical mobility model used to efficiently capture the potential correlation among mobile nodes in many important applications. In this paper, we explore the throughput-delay tradeoff in a mobile ad hoc network (MANET) operating under the RPGM model and also a general setting of node moving speed. In particular, we consider a MANET with unit area and n nodes being divided evenly into $\Theta(n^\alpha)$ groups, $\alpha \in [0, 1]$, where the center of each group moves according to a random direction model with speed no more than $v \in [0, 1]$. We determine the regions of per node throughput, average delay and their tradeoffs that can be achieved (in order sense) in such a network. For the regime of $v = 0$, we first prove that the per node throughput capacity is $\Theta(n^{-\alpha/2})$, and then develop a routing scheme to achieve this capacity, resulting an average delay of $\Theta(\max\{n^{1/2}, n^{1-\alpha}\})$ for any $\alpha \in [0, 1]$. Regarding the regime of $v > 0$, we prove that the per node throughput capacity there can be improved to $\Theta(1)$, which is achievable by adopting a new routing scheme with an average delay of $\Theta(\max\{n^{1-\alpha}, n^{\alpha/2}/v\})$ for $v = o(1)$ and $\Theta(n)$ for $v = \Theta(1)$. The results in this paper help us to have a deep understanding on the fundamental performance scaling laws and also enable an efficient throughput-delay tradeoff to be achieved in MANETs with correlated mobility.**

I. INTRODUCTION

Mobile ad hoc networks (MANETs) are highly promising to provide communication support in many important applications like disaster relief, military troop communication, last-mile internet service, etc. The capacity theory for MANETs, a theory defining the maximum rates achievable between all node pairs, is of fundamental importance and serves as the instruction guideline for the design, development and commercialization of such networks [1], [2].

The available studies on capacity and related delay performance in MANETs mainly focus on network scenarios where mobile nodes are independent from each other and they can visit all network area in an uniform way (please refer to Related Works in the later part of this section). It is notable, however, that in many important scenarios like soldier movement in battlefield, large scale disaster recovery, movement of attendee groups in exhibitions, etc., nodes there not only exhibit strong correlation but also move only in some restricted areas. Reference Point Group Mobility (RPGM) has been a practical mobility model proposed for efficiently capturing the potential correlation among mobile nodes in lots of important scenarios [3]. Thus, a thorough study on MANET capacity and related delay performance under the RPGM model is critical for the applications of MANETs in scenarios with correlated node mobility.

In this paper, we explore the throughput capacity, in particular the throughput-delay tradeoff, in MANETs with correlated node mobility defined by RPGM and also a general setting of node moving speed. Specifically, we consider a MANET with unit area and n nodes being evenly divided into $\Theta(n^\alpha)$ groups, $\alpha \in [0, 1]$. At any time slot, all nodes belonging to a group are constrained to reside concurrently within a disk area of radius R associated with the group. Each group center (i.e., the central point of the disk area associated with the group) moves according to a random direction mobility model [4] with speed no more than $v \in [0, 1]$.

The main results of this paper are summarized as follows.

1) In the regime of $v = 0$, all group centers are static and the disk area associated with each group remains unchanged over the time. Nodes belonging to a group can only move within a limited region of the network. Therefore, the regime of $v = 0$ represents a special mobile network where node movements are not only correlated but also restricted. For this regime, we first prove that the per node throughput is upper bounded by $O\big(n^{-\frac{\alpha+1}{2}}/r\big)$ for any transmission range $r = \Omega(1/\sqrt{n})$ and $r = O(n^{-\alpha/2})$. We further propose a new routing scheme for this regime and then use it to derive an achievable throughput lower bound $\Omega\big(n^{-\frac{\alpha+2}{2}}/r^2\big)$, which comes with an average delay of $\Theta\big(\max\big\{\frac{1}{r}, \frac{n^{-\alpha}}{r^2}\big\}\big)$. Based on these results, we finally show that the per node throughput capacity in this regime is determined as $\Theta(n^{-\alpha/2})$ for any $\alpha \in [0, 1]$, and more importantly, our new routing scheme can actually achieve this throughput capacity at the cost of introducing a $\Theta(\max\{n^{1/2}, n^{1-\alpha}\})$ average delay.

2) In the regime of $v > 0$, each group center moves across the network at a speed uniformly selected from $[0, v]$ in each time slot. We first prove that the per node throughput of this regime is upper bounded by $O\big(n^{-1/2}/r\big)$ for any $r = \Omega(1/\sqrt{n})$ and $r = O(n^{-\alpha/2})$. Another new routing scheme is then proposed to derive an achievable throughput lower bound $\Omega\big(n^{-1}/r^2\big)$ for this regime, resulting an average delay $\Theta\big(\max\big\{\frac{n^{-\alpha}}{r^2}, \frac{n^{\alpha/2}}{v}\big\}\big)$ for $v = o(1)$ and $\Theta\big(\frac{1}{r^2}\big)$ for $v = \Theta(1)$. Finally, we prove that the per node throughput capacity for this regime is $\Theta(1)$, and our second routing scheme can achieve

this capacity with an average delay $\Theta(\max\{n^{1-\alpha}, n^{\alpha/2}/v\})$ for $v = o(1)$ and $\Theta(n)$ for $v = \Theta(1)$.

Related Works: Since the seminal work of Grossglauser and Tse [5], a significant amount of works have been done to understand the fundamental capacity in mobile ad hoc networks. The authors in [5] showed that by introducing i.i.d. mobility to the network, the per node throughput can be significantly improved to $\Theta(1)$, as compared with the $\Theta(\frac{1}{\sqrt{n \log n}})$ throughput reported in [6]. Following this line, it was further proved that $\Theta(1)$ per node throughput can also be achieved under other mobility models, like random walk model [7], Brownian motion model [8] and uniform mobility model [9].

In addition to the basic capacity study, the throughput-delay tradeoff issue in MANETs has also been extensively explored recently. Gamal *et al.* showed that to achieve a $\Theta(1)$ throughput, the average delay will be $\Theta(n \log n)$ under random walk model [7] and will be $O(\sqrt{n}/v(n))$ under Brownian motion with $v(n)$ node velocity [8]. Neely *et al.* [10] proved that we always have $delay/capacity \geq O(n)$ under i.i.d. model. All above studies mainly focus on MANETs with independent and uniform mobility process, where nodes are independent from each other and they visit network area in an uniform way. Some works have already considered the restricted node mobility [11]–[13]. However, the node mobility process there was still assumed to be independent from each other, and thus they can not reflect the correlation among nodes.

To the best of our knowledge, the work most related to ours is [14], [15]. Li *et al.* [14] considered a network which is evenly divided into $n^{2\alpha}$ cells and each cell is further evenly divided into squares of area $n^{-2\beta}$, where a node moves according to random walk model only within the cell it was initially distributed in. The authors showed the possible tradeoffs between throughput and delay by controlling the mobility pattern (α, β). Ciullo *et al.* [15] considered a network where nodes are divided into groups. All nodes of a group have to reside in the cluster-region associated with the group, and each group center moves according to i.i.d. model in the network area. These two works actually represent two extreme cases in real-world networks, where the moving speed of each group center is either 0 [14] or infinite [15]. We have a gap here, i.e., *what is the throughput-delay tradeoff under correlated mobility with a general setting of node moving speed?* It is also noticed that only the maximum throughput and the minimum delivery delay were reported in [15], while in [14] the throughput-delay tradeoff was presented without exploring the important throughput capacity.

The rest of this paper is organized as follows. Section II introduces system models and definitions, and Section III introduces the scheduling scheme and some related results. We analyze the throughput-delay tradeoffs for the $v = 0$ regime and the $v > 0$ regime in Sections IV and V, respectively. Finally, we conclude this paper in Section VI.

II. System Models and Definitions

A. Network Model

We consider a unit torus network with n mobile nodes, which are evenly divided into $m = \Theta(n^\alpha)$ groups, $\alpha \in [0, 1]$. Time is divided into slots of equal duration for packetized transmission. We assume in any time slot all nodes of one group are constrained to stay within the same portion of network area, i.e., a *group region*, which is defined as a disk area with radius R. In the following we refer to "the central point of a group region" as "group center". For a node i, we use $\mathcal{G}(i)$ to denote the group that i belongs to, i.e., $i \in \mathcal{G}(i)$.

To exclusively explore and thus clearly illustrate the impact of correlated mobility on throughput and delay performance, we maintain an average node density n in each group region. As each group contains $\Theta(n/n^\alpha) = \Theta(n^{1-\alpha})$ nodes, then we have $R = \Theta(\sqrt{n^{1-\alpha} \cdot n^{-1}}) = \Theta(n^{-\alpha/2})$.

B. Correlated Mobility Model

The Reference Point Group Mobility (RPGM) model introduced in [3] is adopted here to model the correlated mobility of nodes in a group. We assume that the group center follows the random direction mobility model [4], where each group center moves across the network with a speed and a direction uniformly selected from $[0, v]$ and $[0, 2\pi)$, respectively. All group centers are initially uniformly distributed, and there exists no correlation among the movements of different group centers.

During each time slot, once the position of a group center is determined, all nodes belonging to the group will concurrently move into the disk area centered at the group center. Notice that under most settings (except for the case $\alpha = 0$), all nodes belonging to a group have to reside in a diminishing disk area of $\Theta(n^{-\alpha})$ during each time slot. Thus, we assume that each node moves within its group region according to the i.i.d. mobility model [10].

C. Interference Model

We employ the Protocol Model introduced in [6], [8] as the interference model. Suppose that node i is transmitting to node j at a time slot. To ensure successful data reception at j, for any other simultaneous transmitting node k, we should have $d(i, j) \leq r$ and $d(k, j) \geq (1 + \Delta) d(i, j)$. Here $d(i, j)$ denotes the distance between i and j, r is the transmission range adopted by each node, and $\Delta > 0$ is a protocol specified guard factor. We consider a single channel with limited capacity W bits per time slot, and we do not consider the techniques of multi-user reception or network coding.

D. Traffic Model

We assume that there are n distinct unicast flows. Without loss of generality, the source-destination pairs of these n flows are defined as $1 \to 2$, $2 \to 3$, ..., $(n-1) \to n$, $n \to 1$; so that node i generates traffic destined for node $i + 1$ for $i = 1, \ldots, n-1$ and node n generates traffic destined for node 1. The traffic generated at each source node is assumed to have an average input rate $\lambda(n)$ bits per time slot. We assume the traffic generation process at each node is independent of the mobility process. Besides, there is no lifetime limit on each packet or buffer limit in each node. Therefore, a node could carry a packet for a long time, until it delivers the packet to the destination or to another node.

E. Definitions and Notations

Throughput Capacity: We say throughput $\lambda(n)$ is *feasible* if there exists a spatial and temporal scheduling scheme, such that the source can send data to the destination at an average rate of $\lambda(n)$ packets per time slot, without causing the queue length to grow to infinity as the time goes to infinity. The per node throughput capacity is then defined as the maximum feasible input rate $\lambda(n)$.

Average Delay: Similar to [16], the *delay* of a packet is defined as the time it takes for the packet to reach its destination after it leaves its source, which depends heavily on node mobility. The average delay $D(n)$ is then obtained by averaging over all packets received by the network as time goes to infinity.

Notations: Given two functions $f(n) \geq 0$ and $g(n) \geq 0$, i) $f(n) = O(g(n))$ means that there exist a positive constant c and an integer N such that $f(n) \leq cg(n)$ for all $n > N$; ii) $f(n) = o(g(n))$ means that $\lim_{n\to\infty} f(n)/g(n) = 0$; iii) $f(n) = \Omega(g(n))$ means that $g(n) = O(f(n))$; iv) $f(n) = \omega(g(n))$ means that $g(n) = o(f(n))$; v) $f(n) = \Theta(g(n))$ means that $f(n) = O(g(n))$ and also $f(n) = \Omega(g(n))$.

III. TDMA Scheduling and Some Basic Results

This section introduces a cell partition based time division multiple access (TDMA) scheme [7], [14] and some related basic results, which will help us to derive the throughput lower bounds and also average delay in Sections IV and V.

As illustrated in Fig. 1 that based on the TDMA scheme, the unit torus is evenly divided into square cells with side length a each. We assume a node in a cell can only transmit to nodes in the same cell or eight adjacent cells, then the transmission range can be accordingly determined as $r = \sqrt{8}a$.

For a node group $\mathcal{G}$, we denote by $\mathcal{C}_g$ the set of cells that are fully or partially covered by the group region associated with $\mathcal{G}$. After analyzing the geometry of cells in the group region, we can actually divide all cells of $\mathcal{C}_g$ into the following groups:

- *Border Cell:* A cell in $\mathcal{C}_g$ is called a border cell if a node (belonging to group $\mathcal{G}$) in this cell can transmit to nodes belonging to other groups.
- *Inner Cell:* Otherwise, if a node in this cell can only transmit to nodes belonging to the same group, i.e., group $\mathcal{G}$, the cell is called inner cell.

Now we present some basic results regarding the distribution of nodes in the cell partitioned torus.

Lemma 1: If we denote by P_E the probability that a cell has at least one node, then as $n \to \infty$, we have $P_E \to 1$ with $a = \omega(\frac{1}{\sqrt{n}})$, and $P_E \to 1 - e^{-c_0^2}$ with $a = \frac{c_0}{\sqrt{n}}$ (c_0 is a positive constant).

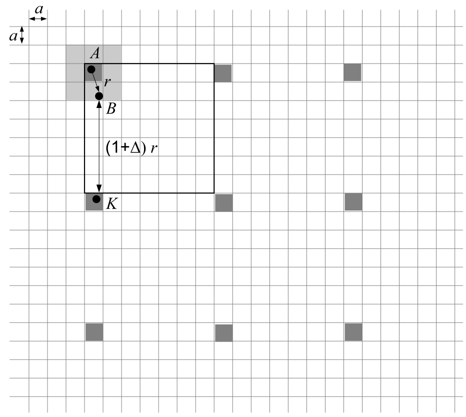


Fig. 1. Illustration of the cell partition based TDMA scheme. The unit torus is equally divided into square cells with side length a and nodes in all shaded cells can transmit simultaneously without interfering with each other.

Lemma 2: If a transmitter-receiver pair can always be found for a cell, then each cell can transmit W bits at most every $(2 + \lceil(1 + \Delta)\sqrt{8}\rceil)^2$ time slots.

Lemma 3: If we denote by P_I the probability that a transmitter in an active inner cell can transmit to a node belonging to the same group, then as $n \to \infty$, we have $P_I \geq 1 - e^{-9}$ for any $a = \Omega(\frac{1}{\sqrt{n}})$ and $a = O(R)$.

Lemma 4: If we denote by P_B the probability that a transmitter in an active border cell can transmit to a node belonging to another group, then as $n \to \infty$, we have $P_B \geq 1 - e^{-9}$ for any $a = \Omega(\frac{1}{\sqrt{n}})$ and $a = O(R)$.

Please refer to [17] for proofs of above lemmas. Based on the results of Lemmas 1, 3 and 4 and also notice that $r = \sqrt{8}a$, we set $r = \Omega(\frac{1}{\sqrt{n}})$ and $r = O(R)$ in the following analysis.

IV. Regime of $v = 0$

With the setting $v = 0$, all group centers are static and the group region associated with each group remains unchanged over the time. Therefore, a node can only move within its group region during all time slots. Analysis under this scenario is important, because it helps us understand the throughput and delay performance for situations where nodes' mobility is not only correlated but also restricted within a limited area.

A. Throughput Region and Throughput Capacity

We first provide an upper bound on throughput, and then propose a routing scheme and use it to derive a lower bound on throughput, such that the throughout region and throughput capacity can be determined.

Consider a large enough time interval $[0, T]$, and the total number of data bits that can be transmitted end-to-end in this interval is then $n\lambda(n)T$. Let $h(b)$ be the number of hops taken by bit b, $1 \leq b \leq n\lambda(n)T$, let $l(b, h)$ be the travel distance of bit b in hop h, and let $\bar{L}$ be the accumulated per bit travel distance averaged over all end-to-end transmitted data bits. Then we have

$$\sum_{b=1}^{n\lambda(n)T} \sum_{h=1}^{h(b)} l(b, h) = n\lambda(n)T\bar{L} \tag{1}$$

Note that for a source-destination pair, a bit will take the shortest travel distance if it is transmitted just along the line directly connecting the centers of these two groups where the source-destination pair reside. As each transmission takes a travel distance $c_1 a$ ($1 \le c_1 \le \sqrt{8}$), then we have

$$\bar{L} \ge \frac{c_2}{2R} \cdot c_1 a \tag{2}$$

where $c_2 = \Theta(1)$ is the sample mean of the line connecting the centers of these two groups where a source-destination pair reside. Substituting (2) into (1),

$$\sum_{b=1}^{n\lambda(n)T} \sum_{h=1}^{h(b)} l(b,h) \ge n\lambda(n)T \cdot \frac{c_1 c_2 a}{2R} \tag{3}$$

Suppose nodes i and k are transmitting to nodes j and l, respectively. According to the Protocol interference model, the following inequalities must hold so as to guarantee the successful transmissions.

$$\begin{aligned} d(k,j) &\ge (1+\Delta)d(i,j) \\ d(i,l) &\ge (1+\Delta)d(k,l) \\ d(l,j) &\ge d(i,l) - d(i,j) \\ d(j,l) &\ge d(k,j) - d(k,l) \end{aligned}$$

Adding up these four inequalities, we have

$$d(j,l) \ge \frac{\Delta}{2}(d(i,j) + d(k,l)). \tag{4}$$

(4) implies that for all simultaneous transmissions, disks which are placed around each receiver of radius $\frac{\Delta}{2}$ times the travel distance of each transmission, must be disjoint from each other under the Protocol interference model. For each receiver, at least $1/4$ of its associated disk must lie in the unit torus, thus

$$\sum_{b=1}^{n\lambda(n)T} \sum_{h=1}^{h(b)} \frac{\pi}{4}\Big(\frac{\Delta \cdot l(b,h)}{2}\Big)^2 \le WT \tag{5}$$

From Cauchy-Schwarz inequality, we have

$$\begin{aligned} \Big(\sum_{b=1}^{n\lambda(n)T} \sum_{h=1}^{h(b)} l(b,h)\Big)^2 &\le \sum_{b=1}^{n\lambda(n)T} \sum_{h=1}^{h(b)} (l(b,h))^2 \cdot \sum_{b=1}^{n\lambda(n)T} \sum_{h=1}^{h(b)} 1^2 \\ &\le \sum_{b=1}^{n\lambda(n)T} \sum_{h=1}^{h(b)} (l(b,h))^2 \cdot \frac{nWT}{2} \qquad (6) \\ &\le \frac{8nW^2T^2}{\pi\Delta^2} \qquad (7) \end{aligned}$$

where (6) follows because $\sum_{b=1}^{n\lambda(n)T} h(b) \le \frac{nWT}{2}$ and (7) follows because of (5).

Combining (3) with (7), an upper bound on per node throughput $\lambda(n)$ is then determined as

$$\lambda(n) \le \sqrt{\frac{32W^2R^2}{c_1^2 c_2^2 \pi \Delta^2 n a^2}} = O\Big(\frac{n^{-\frac{\alpha+1}{2}}}{r}\Big) \tag{8}$$

We further propose the following multi-hop routing scheme to derive an achievable lower bound on $\lambda(n)$.

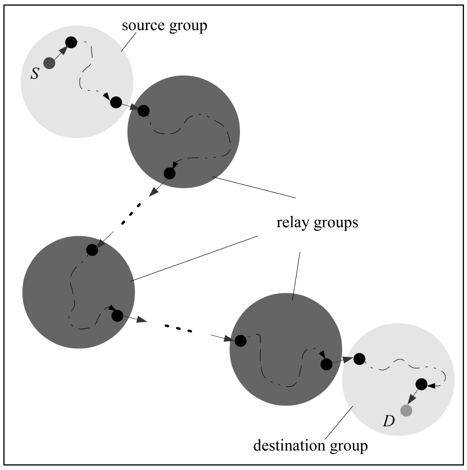


Fig. 2. Illustration of Scheme 1 for the $v = 0$ regime. A packet is transmitted from the source S to the destination D via multiple intermediate relay groups.

Scheme 1 for the $v = 0$ regime: For a time slot and a transmitter $i \in \mathcal{G}(i)$ in an active cell, say cell $\mathcal{C}$:

Case 1: If $\mathcal{C}$ is an inner cell, a receiver j belonging to the same group, i.e., $\mathcal{G}(j) = \mathcal{G}(i)$, is randomly selected from the one-hop neighbors of i. Node i randomly chooses one of the following operations with equal probability.

- Node i delivers a packet which is locally generated at i to node j. Node j will act as a relay for this packet and forward it later to another group.
- Node i forwards a packet which is destined for node j to j. If no such packet exist, i remains idle.

Case 2: If $\mathcal{C}$ is a border cell, a receiver j belonging to another group, i.e., $\mathcal{G}(j) \ne \mathcal{G}(i)$, is randomly selected from the one-hop neighbors of i. Node i randomly chooses one of the following operations with equal probability.

- Node i forwards a packet which is destined for a group other than $\mathcal{G}(i)$ and $\mathcal{G}(j)$ to node j.
- Node i forwards a packet which is destined for group $\mathcal{G}(j)$ to node j. If i carries a packet destined for j, i will forward the packet directly to j.

Fig. 2 illustrates an example of Scheme 1, where a packet is transmitted from the source S to the destination D via multiple intermediate relay groups. Note that under Scheme 1, after a packet leaves its source there will be only one single node carrying the packet at any time slot.

Based on Scheme 1, we are now able to derive an efficient lower bound for $\lambda(n)$. Consider a time slot and let $\mathcal{C}_I$ and $\mathcal{C}_B$ denote the set of inner cells and the set of border cells, respectively. From Scheme 1 we know that

$$\frac{W \cdot P_E}{(2 + \lceil (1+\Delta)\sqrt{8} \rceil)^2}\Big(\sum_{|\mathcal{C}_I|} P_I + \sum_{|\mathcal{C}_B|} P_B\Big) \le n\lambda(n)\Big(\frac{c_2}{2R} + 2\Big) \tag{9}$$

where the left-hand side is the average number of data bits that can be transmitted in the network per time slot based on Scheme 1, and the right-hand side denotes the necessary number of data bits that should be transmitted per time slot in order for Scheme 1 to achieve the throughput $\lambda(n)$.

Together with the fact that in any time slot

$$|\mathcal{C}_I| + |\mathcal{C}_B| = \Theta\Big(\frac{1}{a^2}\Big), \tag{10}$$

an efficient lower bound on throughput $\lambda(n)$ is given by

$$\lambda(n) \geq \frac{c_3 W/a^2}{n(\frac{c_2}{2R}+2)} = \Omega\Big(\frac{n^{-\frac{\alpha+2}{2}}}{r^2}\Big) \tag{11}$$

It is notable that a per node throughput of $\lambda(n) = \Theta(n^{-\frac{\alpha+2}{2}}/r^2)$ is actually achievable by Scheme 1. From the upper bound (8) and the lower bound (11), we can see that

$$\frac{n^{-\frac{\alpha+1}{2}}/r}{n^{-\frac{\alpha+2}{2}}/r^2} = \sqrt{n}\cdot r = \Omega(1)$$

This equation indicates that the order of upper bound in (8) is always no smaller than that of the lower bound in (11). Thus, the two bounds (8) and (11) help us to determine a throughput region as summarized in the following theorem.

Theorem 1: A region of per node throughput in the $\upsilon = 0$ regime is

$$\lambda(n) = \begin{cases} O\Big(\frac{n^{-\frac{\alpha+1}{2}}}{r}\Big) \\ \Omega\Big(\frac{n^{-\frac{\alpha+2}{2}}}{r^2}\Big) \end{cases}$$

It is interesting to observe from Theorem 1 that the upper bound and the lower bound on $\lambda(n)$ actually converge to $\Theta(n^{-\alpha/2})$ when setting $r = \Theta(\frac{1}{\sqrt{n}})$, which indicates that the per node throughput capacity for the regime of $\upsilon = 0$ is just $\lambda(n) = \Theta(n^{-\alpha/2})$, $\alpha \in [0,1]$.

Corollary 1: The per node throughput capacity in the $\upsilon = 0$ regime is

$$\lambda(n) = \Theta(n^{-\alpha/2})$$

Furthermore, such capacity can be achieved by Scheme 1 with the setting of $r = \Theta(1/\sqrt{n})$.

B. Delay Analysis

The above results indicate clearly that the proposed Scheme 1 is efficient in the sense that it is actually throughput capacity achievable. This section further provides an analysis on the delay performance of Scheme 1, such that a flexible throughput-delay tradeoff could be examined.

As shown in Fig. 2 a packet may take multi-hop transmissions to travel from the source to the destination. As indicated in [15], [16] that for a packet at any hop, contention with other packets does not change the scaling order of the total delay with respect to its average service time. Therefore, we neglect the queueing delay and focus only on the average service time at each hop in the following analysis.

One can observe from Fig. 2 that the delivery process of a packet can be actually divided into three parts: in the source group, among relay groups and in the destination group. Let T_S denote the time it takes for the source to deliver the packet to a relay node in the source group, let T_R denote the time it takes for a relay to forward the packet to another relay node, and let T_D denote the time it takes for a relay in the destination group to forward the packet to the destination.

To deliver the packet to a relay, the source needs to be in an inner cell of its group region. The probability that the source is in an inner cell during each time slot can be approximated by $p_0 = \frac{(R-a)^2}{R^2} = 1 - \frac{2a}{R} + \frac{a^2}{R^2}$. Since $a = r/\sqrt{8}$ and $r = O(R)$, we have at least a constant p_0. From Lemma 3, we get

$$\mathbb{E}\{T_S\} = \frac{2}{p_0 P_I} = \Theta(1)$$

Similarly, during each time slot the probability that a relay carrying the packet is in a border cell can be approximated by $p_1 = 1 - p_0 = \frac{2a}{R} - \frac{a^2}{R^2}$. Accordingly, the average time it takes for the relay to forward the packet to another relay node is

$$\mathbb{E}\{T_R\} = \frac{2}{p_1 P_B} = \Theta\Big(\frac{R}{a}\Big)$$

Finally, in order for the last relay to forward the packet to its destination, the relay node needs to be in an inner cell and the destination needs to be in the transmission range of the relay node. Thus, we have

$$\mathbb{E}\{T_D\} = \frac{2R^2}{p_0 r^2} = \Theta\Big(\frac{R^2}{r^2}\Big)$$

Recall that the sample mean of the line connecting the two group centers of a source-destination pair is denoted by constant c_2, so the average number of transmissions for the packet to be forwarded among relay nodes is given by $\frac{c_2}{2R}$. Thus, the average delay $D(n)$ can be determined as

$$\begin{aligned} D(n) &= \mathbb{E}\{T_S\} + \frac{c_2}{2R}\mathbb{E}\{T_R\} + \mathbb{E}\{T_D\} \\ &= \Theta(1) + \frac{c_2}{2R}\Theta\Big(\frac{R}{a}\Big) + \Theta\Big(\frac{R^2}{r^2}\Big) \\ &= \Theta\Big(\max\Big\{\frac{1}{r}, \frac{n^{-\alpha}}{r^2}\Big\}\Big) \end{aligned} \tag{12}$$

Theorem 2: The average delay of Scheme 1 in the $\upsilon = 0$ regime is

$$D(n) = \Theta\Big(\max\Big\{\frac{1}{r}, \frac{n^{-\alpha}}{r^2}\Big\}\Big)$$

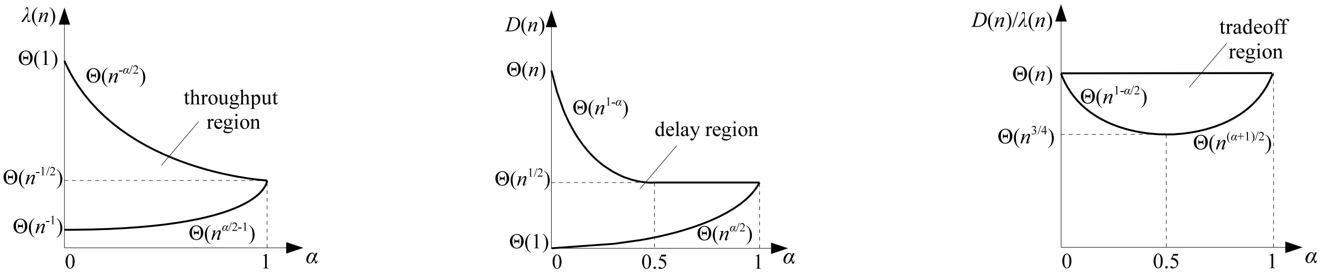
From Theorem 2 and Corollary 1, one can see that when Scheme 1 achieves the per node throughput capacity $\lambda(n) = \Theta(n^{-\alpha/2})$ with setting $r = \Theta(\frac{1}{\sqrt{n}})$, the corresponding average delay becomes $D(n) = \Theta(\max\{n^{1/2}, n^{1-\alpha}\})$. Therefore, we have the following corollary.

Corollary 2: The proposed Scheme 1 achieves the per node throughput capacity $\lambda(n) = \Theta(n^{-\alpha/2})$ in the $\upsilon = 0$ regime, resulting in an average delay

$$D(n) = \Theta(\max\{n^{1/2}, n^{1-\alpha}\})$$

C. Discussions

We summarize in Fig. 3 our results developed for the $\upsilon = 0$ regime. Fig. 3a illustrates the achievable throughput region by varying the transmission range r from $\Omega(1/\sqrt{n})$ to $O(n^{-\alpha/2})$. One can easily observe from Fig. 3a that, the throughput upper bound and lower bound scale as $\Theta(n^{-\alpha/2})$ and $\Theta(n^{\alpha/2-1})$,



(a) $\lambda(n)$ vs. α (b) $D(n)$ vs. α (c) $D(n)/\lambda(n)$ vs. α

Fig. 3. Throughput-delay tradeoff under the correlated mobility for the $v = 0$ regime.

respectively. Fig. 3b illustrates the delay region, in which the delay lower bound scales as $\Theta(n^{\alpha/2})$, while the delay upper bound scales as $\Theta(n^{1-\alpha})$ when $\alpha \in [0, 0.5]$ and remains as $\Theta(n^{1/2})$ when $\alpha \in [0.5, 1]$. Fig. 3c shows that it is possible to achieve a delay-throughput tradeoff much better than the $delay/capacity = O(n)$ tradeoff reported in [7], [14], [18]. Specifically, the delay-throughput tradeoff is between $\Theta(n^{1-\alpha/2})$ and $\Theta(n)$ when $\alpha \in [0, 0.5]$ and is between $\Theta(n^{(\alpha+1)/2})$ and $\Theta(n)$ when $\alpha \in [0.5, 1]$.

Here we provide some further discussions on the throughput and delay under some extreme scenarios.

Scenario I: $\alpha = 0$, the considered network just corresponds to a network under the i.i.d. mobility [5], [10]. When $r = \Theta(1/\sqrt{n})$, from Theorems 1 and 2 we know that the throughput capacity and average delay are reported as $\Theta(1)$ and $\Theta(n)$, respectively, which are consistent with that reported in [5], [10]. When $r = \Theta(1)$, the transmission range can almost cover the whole network area so there are only $\Theta(1)$ simultaneous transmissions during each time slot. As Figs. 3a and 3b indicate that in this case a per node throughput of $\Theta(1/n)$ and an average delay of $\Theta(1)$ will be achieved.

Scenario II: $\alpha = 1$, the considered network corresponds to a special mobile network where nodes are evenly divided into $\Theta(n)$ groups, each group containing $\Theta(1)$ nodes within a disk area of $\Theta(1/n)$. By adopting a transmission range $r = \Theta(n^{-1/2})$, we obtain $\lambda(n) = \Theta(1/\sqrt{n})$ and $D(n) = \Theta(\sqrt{n})$ as shown in Figs. 3a and 3b, which is similar to that established in [14], [19]. It is noticed that the delay-throughput tradeoff $D(n)/\lambda(n) = \Theta(n)$ achieved for $\lambda(n) = \Theta(1/\sqrt{n})$ in such mobile network, actually extends the results in [18], which also considered the case of constant-size packets and showed that the $D(n)/\lambda(n) = \Theta(n)$ tradeoff can only be achieved for $\lambda(n) = O(1/\sqrt{n \log n})$ there.

V. Regime of $v > 0$

In the $v > 0$ regime, each group center moves in the network area at a speed and a direction uniformly selected from $[0, v]$ and $[0, 2\pi)$ in each time slot, respectively. Nodes belonging to a group can only move within the disk area centered at their group center during each time slot.

A. Throughput Region and Throughput Capacity

Similar to the case of $v = 0$, here we first derive an upper bound for the per node throughput $\lambda(n)$, and then propose a new routing scheme and use it to derive a lower bound on $\lambda(n)$, such that the throughout region and throughput capacity for the $v > 0$ regime can be determined.

Recall that $\bar{L}$ denotes the accumulated per bit travel distance averaged over all end-to-end transmitted data bits in a large enough interval $[0, T]$, $h(b)$ denotes the total number of hops taken by bit b, and $l(b, h)$ denotes the travel distance of bit b in hop h. Since each data bit takes at least a constant number of hops, say c_4, to travel from the source to the destination,

$$\bar{L} \geq c_4 r$$

From (1), then we have

$$\sum_{b=1}^{n\lambda(n)T} \sum_{h=1}^{h(b)} l(b, h) \geq c_4 n \lambda(n) T r \tag{13}$$

Notice that node mobility process is independent of data transmissions, thus (4), (5) and (7) also hold for the $v > 0$ regime. Together with (13), an upper bound on $\lambda(n)$ can then be determined as

$$\lambda(n) \leq \sqrt{\frac{8W^2}{\pi \Delta^2 c_4^2 n r^2}} = O\Big(\frac{n^{-1/2}}{r}\Big) \tag{14}$$

Now we proceed to derive an achievable lower bound on $\lambda(n)$. Regarding the scheduling of simultaneous transmissions in each time slot, we still adopt the cell partition based TDMA scheme introduced in Section III. It is easy to see that Lemmas 1, 2, 3 and 4 also hold for the $v > 0$ regime. About the routing issue, we propose the following Scheme 2.

Scheme 2 for the $v > 0$ regime: For a time slot and a transmitter $i \in \mathcal{G}(i)$ in an active cell, say cell $\mathcal{C}$:

Case 1: If $\mathcal{C}$ is an inner cell, a receiver j belonging to the same group, i.e., $\mathcal{G}(j) = \mathcal{G}(i)$, is randomly selected from the one-hop neighbors of i. Node i randomly chooses one of the following operations with equal probability.

- Node i delivers a packet which is locally generated at i to node j. Node j will act as a relay for this packet and forward it later to another group.

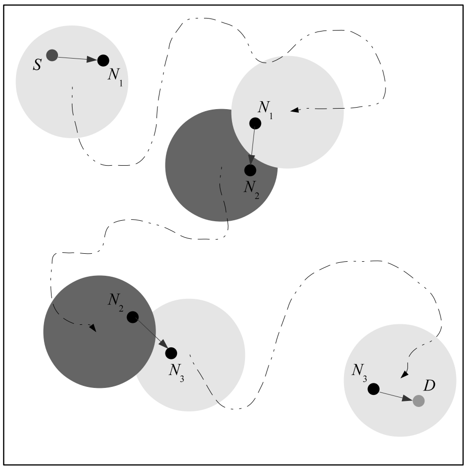


Fig. 4. Illustration of Scheme 2 for the $\upsilon > 0$ regime. A packet is transmitted from the source S to the destination D via multiple intermediate relay nodes N_1, N_2 and N_3.

- Node i forwards a packet which is destined for node j to j. If no such packet exist, i remains idle.

Case 2: If $\mathcal{C}$ is a border cell, a receiver j belonging to another group, i.e., $\mathcal{G}(j) \neq \mathcal{G}(i)$, is randomly selected from the one-hop neighbors of i. Node i randomly chooses one of the following operations with equal probability.

- Node i forwards a packet which is originated from other nodes in the same group as i, i.e., $\mathcal{G}(i) - \{i\}$, to node j.
- Node i forwards a packet which is destined for group $\mathcal{G}(j)$ to node j. If i carries a packet destined for j, i will forward the packet directly to j.

One can see that except the operation of Case 2, Scheme 2 is actually very similar to Scheme 1. Note that in Scheme 2, a transmitter in an active border cell can only transmit a packet originated from nodes in its own group or a packet destined to nodes in the same group as the receiver. Therefore, at most one relay group will be employed for Scheme 2 to deliver a packet while in Scheme 1 multiple relay groups may be employed.

Fig. 4 shows an example of Scheme 2, where a packet is delivered from the source S to the destination D via three intermediate relay nodes N_1, N_2 and N_3. Here relay N_2 belongs to the relay group, while relays N_1 and N_3 belong to the source group and the destination group, respectively.

Based on Scheme 2, we now determine an achievable lower bound on $\lambda(n)$. Recall that $\mathcal{C}_I$ denotes the set of inner cells and $\mathcal{C}_B$ denotes the set of border cells in a time slot. Since each packet takes at most four hops to travel from the source to the destination, we have

$$\frac{W \cdot P_E}{(2+\lceil(1+\Delta)\sqrt{8}\rceil)^2}\Big(\sum_{|\mathcal{C}_I|} P_I + \sum_{|\mathcal{C}_B|} P_B\Big) \leq 4n\lambda(n) \quad (15)$$

According to the features of random direction and i.i.d. models, both group centers and nodes have uniform steady-state distribution in the network [4]. Therefore, (10) also holds for the $\upsilon > 0$ regime. Together with (15), it follows that

$$\lambda(n) \geq \frac{c_5 W/a^2}{4n} = \Omega\Big(\frac{n^{-1}}{r^2}\Big) \quad (16)$$

Similarly, one can easily verify that for any $r = \Omega(1/\sqrt{n})$, the order of upper bound in (14) is always no smaller than that of the lower bound in (16).

Theorem 3: A region of per node throughput in the $\upsilon > 0$ regime is

$$\lambda(n) = \begin{cases} O\big(\frac{n^{-1/2}}{r}\big) \\ \Omega\big(\frac{n^{-1}}{r^2}\big) \end{cases}$$

From Theorem 3 one can easily observe that the upper and lower bounds on $\lambda(n)$ converge to $\lambda(n) = \Theta(1)$ at the setting of $r = \Theta(1/\sqrt{n})$, irrespective of the group settings for α. Therefore, the following corollary follows.

Corollary 3: The per node throughput capacity in the $\upsilon > 0$ regime is

$$\lambda(n) = \Theta(1)$$

Furthermore, such capacity can be achieved by Scheme 2 with the setting $r = \Theta(1/\sqrt{n})$.

Corollary 3 indicates the $\Theta(1)$ per node throughput capacity, which was proved achievable under various independent mobility models [5], [7]–[9], [11], can also be achieved by adopting Scheme 2 under the correlated mobility with $\upsilon > 0$.

B. Delay Analysis

We now proceed to analyze the average delay and corresponding throughput-delay tradeoff for Scheme 2.

As shown in Fig. 4, a packet takes at most four hops to reach its destination under Scheme 2. We denote by T_{SG} the time it takes for the source to deliver the packet to a relay node in the source group, denote by $T_{SG\to RG}$ the time it takes for a relay in the source group to forward the packet to another relay node in a relay group, denote by $T_{RG\to DG}$ the time it takes for a relay in the relay group to forward the packet to a relay node in the destination group, and denote by T_{DG} the time it takes for a relay in the destination group to forward the packet to the destination. Then we have

$$D(n) = \mathbb{E}\{T_{SG}\} + \mathbb{E}\{T_{SG\to RG}\} + \mathbb{E}\{T_{RG\to DG}\} + \mathbb{E}\{T_{DG}\} \quad (17)$$

After a derivation similar to that in Section IV-B, one can easily see that during each time slot, there exists a constant probability for the source to deliver the packet to a relay node, say node N_1. Therefore,

$$\mathbb{E}\{T_{SG}\} = \Theta(1)$$

As proved before, the probability that node N_1 goes to a border cell in each time slot is $\Theta(\frac{a}{R})$. Furthermore, N_1 will deliver the packet to a relay node, say N_2, belonging to another group with probability $\frac{P_B}{2}$. Thus, we have

$$\mathbb{E}\{T_{SG\to RG}\} = \Theta\Big(\frac{2R}{aP_B}\Big) = \Theta\Big(\frac{R}{a}\Big)$$

In order for node N_2 in a relay group to deliver the packet to another relay node in the destination group, the relay group

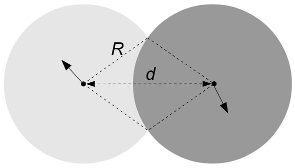


Fig. 5. Illustration of two group regions whose group centers come into a mutual distance of d.

center and the destination group center need to come into a mutual distance $d \leq 2R+r$, as shown in Fig. 5. We refer to the event that the two group centers come into a mutual distance d as a "meeting", and denote by T_{inter} the inter-meeting time. Then we have the following lemma [4].

Lemma 5: For the considered unit torus and any $d \ll 1$ and $v \ll 1$, the inter-meeting time T_{inter} under the random direction mobility model is approximately exponentially distributed with inter-meeting density $\frac{8dv}{\pi}$.

During a meeting of these two group centers, N_2 needs to move to a border cell near the destination group so as to deliver the packet to a relay node belonging to the destination group. If we denote by p_2 the probability that N_2 delivers the packet to a relay, say N_3, belonging to the destination group, we can see that p_2 is actually closely related to d. One can easily verify that when setting $d = R$ we have $p_2 = \Theta(1)$.

According to Lemma 5,

$$\mathbb{E}\{T_{RG\to DG}\} = \Theta\Big(\frac{\pi}{8p_2 Rv}\Big) = \Theta\Big(\frac{1}{Rv}\Big)$$

For the case $v = \Theta(1)$, a node is almost able to uniformly visit the whole network area during each time slot. Therefore

$$\mathbb{E}\{T_{RG\to DG}\} = \Theta\Big(\frac{c_6}{9a^2}\Big) = \Theta\Big(\frac{1}{a^2}\Big)$$

Regarding the time it takes for N_3 to deliver the packet to the destination, using a derivation similar to that in Section IV-B, it follows that

$$\mathbb{E}\{T_{DG}\} = \Theta\Big(\frac{R^2}{r^2}\Big)$$

Combining the above results, for any $v > 0$ and $v = o(1)$,

$$\begin{aligned} D(n) &= \Theta(1) + \Theta\Big(\frac{R}{a}\Big) + \Theta\Big(\frac{1}{Rv}\Big) + \Theta\Big(\frac{R^2}{r^2}\Big) \\ &= \Theta\Big(\frac{R^2}{r^2}\Big) + \Theta\Big(\frac{1}{Rv}\Big) \\ &= \Theta\Big(\max\Big\{\frac{n^{-\alpha}}{r^2}, \frac{n^{\alpha/2}}{v}\Big\}\Big) \end{aligned} \tag{18}$$

Similarly, for any $v = \Theta(1)$, we have

$$D(n) = \Theta\Big(\frac{1}{r^2}\Big) \tag{19}$$

Then we arrive at the following theorem.

Theorem 4: The average delay of Scheme 2 in the $v > 0$ regime is

$$D(n) = \begin{cases} \Theta\big(\max\big\{\frac{n^{-\alpha}}{r^2}, \frac{n^{\alpha/2}}{v}\big\}\big) & \text{if } v = o(1) \\ \Theta\big(\frac{1}{r^2}\big) & \text{if } v = \Theta(1) \end{cases}$$

The following corollary follows from Theorem 4 and Corollary 3 directly.

Corollary 4: The proposed Scheme 2 achieves the per node throughput capacity $\lambda(n) = \Theta(1)$ in the $v > 0$ regime, at the expense of average delay

$$D(n) = \begin{cases} \Theta(\max\{n^{1-\alpha}, n^{\alpha/2}/v\}) & \text{if } v = o(1) \\ \Theta(n) & \text{if } v = \Theta(1) \end{cases}$$

C. Discussions

We summarize in Fig. 6 our results developed for the $v > 0$ regime. Without loss of generality, the moving speed limit v is selected as the same order of magnitude as the transmission range, i.e., $v = \Theta(r)$, so as to clearly illustrate the delay region and throughput-delay tradeoff region.

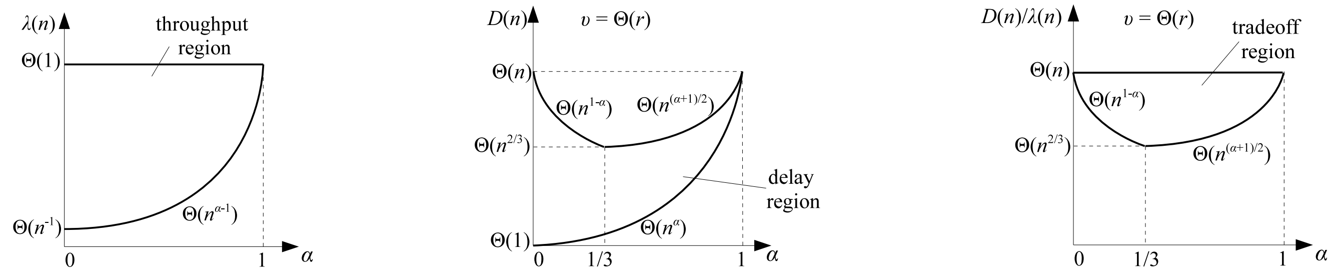
Fig. 6a illustrates the achievable throughput region by varying the transmission range r from $\Omega(1/\sqrt{n})$ to $O(n^{-\alpha/2})$. One can easily observe from Fig. 6a that, the throughput upper bound and lower bound scale as $\Theta(1)$ and $\Theta(n^{\alpha-1})$, respectively. Compared with the results in Fig. 3a, it is interesting to find that by allowing node groups to move around in the network, it is possible to achieve a $\Theta(n^{\alpha/2})$ times improvement in both the throughput upper bound and lower bound. It is further noticed that the throughput upper bound and lower bound established in Theorem 3, is actually independent of the speed limit v.

Fig. 6b illustrates the achievable delay region by Scheme 2. One can observe from Fig. 6b that for $\alpha \in [0, 1]$ the delay lower bound scales as $\Theta(n^{\alpha})$, which is $\Theta(n^{\alpha/2})$ times as that in Fig. 3b. It indicates that the $\Theta(n^{\alpha/2})$ times improvement in throughput (as discussed above) actually comes at the expense of also a $\Theta(n^{\alpha/2})$ times increase in average delay. Regarding the delay upper bound, it scales as $\Theta(n^{1-\alpha})$ when $\alpha \in [0, 1/3]$, and scales as $\Theta(n^{(\alpha+1)/2})$ when $\alpha \in [1/3, 1]$.

Fig. 6c shows the achievable delay-throughput tradeoff region. Similar to that observed in Fig. 3c, we find that in the $v > 0$ regime, it is still possible to achieve a delay-throughput tradeoff much better than the $delay/capacity \geq O(n)$ tradeoff reported under the independent mobility [7], [10], [14]. Specifically, the delay-throughput tradeoff is between $\Theta(n^{1-\alpha})$ and $\Theta(n)$ when $\alpha \in [0, 1/3]$ and is between $\Theta(n^{(\alpha+1)/2})$ and $\Theta(n)$ when $\alpha \in [1/3, 1]$. Note that Fig. 6c only represents the case of $v = \Theta(r)$, and for the general $v = o(1)$, the delay-throughput tradeoff actually scales between $\Theta\big(\max\big\{n^{1-\alpha}, \frac{n^{\alpha/2}}{v}\big\}\big)$ and $\Theta\big(\max\big\{n^{1-\alpha}, \frac{n^{(2-\alpha)/2}}{v}\big\}\big)$.

As discussed in Corollary 3, Scheme 2 achieves the per node throughput capacity $\lambda(n) = \Theta(1)$ in Fig. 6a by setting $r = \Theta(1/\sqrt{n})$, irrespective of the group settings (related to α). A further careful observation of Figs. 6a and 6b indicates that there actually exists an optimum group partition (in order sense), i.e., $\alpha = 1/3$, at which Scheme 2 achieves the throughput capacity $\lambda(n) = \Theta(1)$, an average delay $D(n) = \Theta(n^{2/3})$ and also the optimum tradeoff $D(n)/\lambda(n) = \Theta(n^{2/3})$.

For the setting $\alpha = 1$, the considered network corresponds to a scenario where nodes are evenly divided into $\Theta(n)$ groups with $\Theta(1)$ nodes per group, and each group follows the random



(a) $\lambda(n)$ vs. α (b) $D(n)$ vs. α (c) $D(n)/\lambda(n)$ vs. α

Fig. 6. Throughput-delay tradeoff under the correlated mobility for the $\upsilon > 0$ regime.

direction mobility [4]. As observed from Figs. 6a and 6b, Scheme 2 achieves per node throughput capacity $\lambda(n) = \Theta(1)$ and average delay $D(n) = \Theta(n)$ for the case $\upsilon = \Theta(r)$, which is consistent with that reported in [9], [20].

It is further noticed that under the setting $\upsilon = \Theta(1)$, the considered network corresponds to a network under the i.i.d. mobility. From Corollaries 3 and 4, one can see that Scheme 2 is able to achieve the $\Theta(1)$ per node throughput capacity and $\Theta(n)$ average delay, the same as proved in [5], [10].

VI. Conclusion

In this paper, we have investigated the scaling laws of throughput, delay and their tradeoff in MANETs with correlated node mobility and a general setting of node moving speed. This study provides fundamental insights into how node correlation would affect the throughput and delay performances in MANETs, especially in terms of group size (related to α), moving speed υ and transmission range r. Our results indicate that under both regimes of $\upsilon = 0$ and $\upsilon > 0$, the correlated mobility could always result in a much more efficient delay-throughput tradeoff than that under independent mobility. Most importantly, the results in this paper can serve as an instruction guideline to determine the optimum group partition (i.e., α) so as to achieve the throughput capacity and also the optimum delay-throughput tradeoff under the correlated mobility.

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