The Role of Location Popularity in Multicast Mobile Ad Hoc Networks

Jingjing Luo, Jinbei Zhang, Li Yu, and Xinbing Wang, *Senior Member, IEEE*

***Abstract*—In the asymptotic analysis of large scale mobile networks, most previous works assume that nodes move in all the cells identically. We put forward this line of research by considering location popularity, which is verified by recent experimental studies. Nodes tend to visit some popular locations and go to other locations less frequently. We first analyze its multicast capacity and delay under the traditional 2-hop store-carry and forward paradigm. With different location popularity distributions, network capacity and delay will vary according to the distribution exponent. As the popularity becomes more diverse, less concurrent transmissions are tolerated in the network, which brings down the performance. Observing that transmission opportunity is not fully utilized in popular cells for 2-hop paradigm, we put forward a 3-hop scheme, which is called store-carry-accelerate-forward scheme. In this 3-hop scheme, each packet is first sent to an initial relay, who carries the packets into the popular cells and then broadcasts to multiple nodes to accelerate the delivery. By so doing, we showed that the 3-hop scheme outperforms the 2-hop scheme for all popularity distributions. Furthermore, we study the delay-capacity tradeoffs for multicast under both schemes and the buffer needed for stability requirement. Our results reveals the joint impact of multicast and location heterogeneity on the design of transmission schemes, and may shed new insights for future studies.**

***Index Terms*—Mobile ad hoc networks (MANETs), location popularity, multicast, capacity and delay analysis.**

I. Introduction

BESIDES quick deployment and low cost, higher spectrum utilization is another main advantage of wireless ad hoc networks. With n nodes randomly distributed, the network throughput can achieve $O(\sqrt{n})$ and $\Omega(\sqrt{n/\log n})$[1] in *ad hoc* mode [1]. Compared with transmissions in cellular networks, ad hoc networks employ shorter transmission range and incur less interference, resulting in a better throughput performance. On the other hand, shorter transmission range makes the data to be relayed in a multihop manner, which introduces a larger delay. Higher throughput, combined with the big trend of wireless devices, make *ad hoc* relaying a promising candidate for future communication technology and intrigue great interest in research area in the recent decade.

There are already many previous works trying to search the fundamental limit of ad hoc networks. With percolation theory, it is shown that the optimal network throughput of $\Theta(\sqrt{n})$ is attainable [2]. Joint consideration of *ad hoc* relaying and base station is studied in [3] and [4]. Nevertheless, as a nature property, the role of mobility in ad hoc networks is under intense investigation. In [5], it is shown that the per-node capacity of $\Theta(1)$ is achievable when the nodes move according to an independently and identically distribution (i.i.d.). This tremendous improvement is due to the novel introduction of store-carry and forward paradigm. The opposite side comes from the large delay, which is proved to be $\Theta(n)$ in [6] by modeling the arrival process and departure process as queueing system. Using more relays will decrease the delay, in sacrifice of throughput. The fundamental tradeoffs, i.e., delay/rate $\geq \Theta(n)$, is further established [6]. If the packets are allowed to travel multihop in one timeslot, the delay-capacity tradeoff can be improved [7]. When each node moves around a randomly chosen home point, packets can be transmitted towards the home point hop by hop, and finally delivered to the destinations [8]. More general results on Levy flight and random walk are considered in [9] and [10].

Information may also be delivered to multiple destinations. Using multiple unicast in such scenarios is not efficient, since relays can be shared for different destinations in a same multicast session. By adopting multicast tree as the routing path in static networks [11], the network resource is fully utilized and it is shown that the per-node capacity is $\Theta(\frac{1}{\sqrt{nk}})$ and the delay is $\Theta(\frac{1}{\sqrt{nk\log k}})$. In mobile networks, the throughput will decrease to $\Theta(\frac{1}{k})$ [12], since the total burden of the network will increase compared to unicast scenarios. However, the delay

Manuscript received June 28, 2014; revised October 13, 2014; accepted December 1, 2014. Date of publication December 18, 2014; date of current version April 7, 2015. This work is partially supported by NSF China (No. 61325012, 61271219, 61202373, 61221001, 61428205, 61231010), the China Ministry of Education Doctor Program (No. 20130073110025), the Shanghai Basic Research Key Project (No. 11JC1405100, 133510711300, 12JC1405200), the Shanghai International Cooperation Project: (No. 13510711300), the Research Fund for the Doctoral Program of MOE (No. 20120142110015), and the National Basic Research 973 Program of China (No. 2015CB352403). The associate editor coordinating the review of this paper and approving it for publication was Q. Li.

J. Luo and L. Yu are with the Department of Electronics and Information Engineering, Huazhong University of Science and Technology, Wuhan 430074, China (e-mail: luojingjing@hust.edu.cn; hustlyu@hust.edu.cn).

J. Zhang and X. Wang are with the Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai 200240, China (e-mail: abelchina@sjtu.edu.cn; xwang8@sjtu.edu.cn).

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/TWC.2014.2381250

[1]Given two functions $f(n)$ and $g(n)$: $f(n)=o(g(n))$ means $\lim_{n\to\infty} f(n)/g(n)=0$; $f(n)=O(g(n))$ means $\lim_{n\to\infty} f(n)/g(n)=c<\infty$; if $g(n)=O(f(n))$, $f(n)=\Omega(g(n))$ w.h.p.; if both $f(n)=\Omega(g(n))$ and $f(n)=O(g(n))$, $f(n)=\Theta(g(n))$. $f(n)=\widetilde{\Theta}(g(n))$ means $f(n)=\Theta(g(n))$ when logarithmic terms are ignored.

remains almost the same because the probability of finding a S-D pair in a cell increases. Efficient scheduling algorithms are proposed for delay-constrained multicast networks [13]. Multicast throughput order of network coding is investigated in [14] for both protocol and physical protocols. In cognitive networks, it is shown [15] that the multicast capacity for both primary network and secondary network can achieve the same one as stand-alone networks, at least in order sense.

While various aspects of mobile ad hoc networks have been intensively studied in the previous works, one common feature of these works is that locations are treated identically. For example, nodes are uniformly moving across the whole network, either by i.i.d. mobility, random walk mobility or other mobilities. This assumption can facilitate the already complex analysis and provide some fundamental insights, which include but not limited to store-carry-forward paradigm, and delay-throughput tradeoffs with varying number of relays. As the research goes on, another fundamental question is that how to better model the real circumstance and whether the obtained insights are still valid. Our previous work [16] provides one first step towards this question. More and more location applications, such as Four Square and positioning systems, are adopted and become popular. Therefore, the traces of humans or devices can be recorded and analyzed. With accordance of intuitive, measurement results [17]–[19] show that locations have non-uniform popularity. Users tend to gather in some locations, while visit other locations less frequently. In such scenario, [16] showed that the traditional store-carry-forward paradigm is no longer optimal. This is because the 2-hop paradigm only admits a one-to-one transmission in each cell despite that in the network there are high-popularity cells containing many users. [16] proposed a novel paradigm called "store-carry-accelerate-forward" paradigm by inserting an acceleration hop for routing.

In this paper, we focus on the impact of location popularity on multicast performance of mobile ad hoc networks. The challenge lies in nodes' heterogeneous visitations over cells, thus causing varying number of destinations, relays and source-destination pairs in different cells. On one hand, this may provides many options for scheduling. On the other hand, transmissions in cells become more difficult to illustrate than uniform multicast scenarios and complicates the design of intelligent scheduling schemes. It turns out that the scheduling scheme is closely related to the number of destinations. We first investigate the network performance under the traditional 2-hop scheme and then propose a 3-hop scheme for multicast. Our main contributions can be summarized as follows.

- When the cells have uneven popularity, there may not exist any node in some cells. Therefore, the number of concurrent active cells will decrease, which results in the degraded performance of both multicast capacity and delay in the 2-hop setting scenario. Observing that popular cells are treated the same as other cells, we propose that packets can be broadcasted in popular cells to exploit the potential transmission opportunities.
- For the 3-hop scheme, the delay is effectively reduced while the multicast capacity remains the same as that of the 2-hop scheme. This improvement is greatly benefited from the acceleration mechanism in popular cells. With different number of destinations, the number of popular cells incuring the acceleration of relaying packets will varies. Moreover, the delay will first decrease and then increase when the cells' popularity becomes more diverse.
- We further study the delay-capacity tradeoffs by varying the number of redundancy for one packet, and find the optimal number of redundancies for delay-capacity tradeoff. Moreover, we investigate the minimal buffer needed for each node to achieve the desired performance.

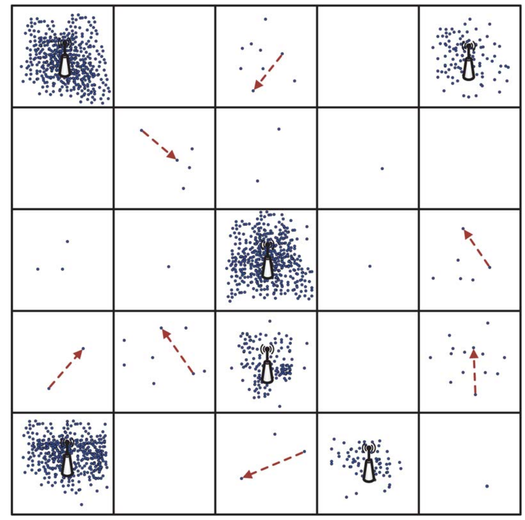


Fig. 1. A cell-partitioned MANET model with cells of different location popularity. A cell with higher popularity attracts more nodes to visit it.

The remainder of this paper is organized as follows. In Section II we present the network model. In Section III, we put forward capacity and delay analysis without redundancy under both 2-hop relay algorithm and our 3-hop relay algorithm. The cases with redundancy are investigated in Section IV. Discussions on the impacts of location popularity and the comparisons between two schemes are laid out in Section V. Finally, we conclude this paper in Section VI.

II. Network Model and Definitions

A. Network Model and Definitions

1) Network Model: We consider a cell-partitioned MANET model as illustrated in Fig. 1. n nodes move independently over a square region of unit area. The square is divided into n nonoverlapping cells, each of same area size. Each cell has its own popularity, based on which mobile nodes independently determine their own cell locations every timeslot. Then the steady state node distribution is heterogeneous over all cells. We assume that nodes communicate using a fixed range $\Theta(\frac{1}{\sqrt{n}})$. Mapped to the cell-partitioned model, nodes can communicate with each other when they are in the same cell. For intra-cell interference problem, we solve it by allowing at most one transmission per cell per timeslot. For what concerns the inter-cell interference problem, we solve it by letting nodes in neighboring cells transmit in orthogonal frequency. The interferences from farther cells are ignored in this paper since the sum of them are proved to be constant in order sense [2]. And it is well known that four frequencies are sufficient to avoid interference [6].

For the location popularity distribution, we consider that it follows a Zipf's law, which is frequently observed by a number of measurement studies [17]–[19]. They found that the visitation frequency over the locations, that measures to what extent users move to the same place over and over, is rather heterogeneous and Zipf-like. Specifically, the probability of a user to visit the i-th most popular location follows $f_i \sim i^{-\alpha}$. This law implies that, having sorted the cells in decreasing order of popularity, a node chooses to locate itself at cell i with probability

$$p_i = \frac{H(n)}{i^{\alpha}}, \qquad 1 \leq i \leq n \tag{1}$$

where α is the exponent of location popularity distribution, and $H(n) = \left(\sum_{i=1}^{n} i^{-\alpha}\right)^{-1}$ is a normalization constant. From this expression, we can obtain the value of $H(n)$ in order sense:

$$H(n) = \begin{cases} \Theta(1), & \alpha > 1 \\ \Theta\left(\frac{1}{\log n}\right), & \alpha = 1 \\ \Theta(n^{\alpha-1}), & \alpha < 1. \end{cases} \tag{2}$$

2) Mobility Model: Time is divided into equal duration, normalized to 1. For nodes' mobility, we propose a location-popularity-based mobility to model topology changes correlated with locations. At the beginning of each timeslot, the position of each node is reshuffled by choosing a cell to locate according to cell's popularity. The node remains in the cell for the entire slot duration. The positions of nodes are totally updated after each timeslot, independently from slot to slot and among nodes. With the help of mobility, packets can be carried by nodes until they reach all the destinations.

3) Traffic Pattern: We analyze the performance of multicast traffic pattern in location-based MANETs. Source-destination (S-D) relationships are determined before transmissions. n nodes are uniformly and independently partitioned into disjoint groups, each of which has $k+1$ nodes. Each node in a group is the source for the other k nodes within the same group and a successful packet transmission means that the packet from a particular node should be sent to all its k destinations. Nodes outside the group can serve as relays for transmissions from the group. In this way, each node is associated with k selected destinations, which are denoted as $D_1, D_2, \ldots, D_k$. And the relationships will not change when nodes move. Note that all the nodes communicate with each other through four orthogonal channels with the same bandwidth.

B. Definitions

Capacity: For node j, suppose a single packet arrives with probability λ_j during the current timeslot, and no packet arrives otherwise. Such an arrival process is defined as Bernoulli process[2] of rate λ_j packets/slot. For the given λ_j rate, the network is stable if there is a scheduling algorithm ensuring that the queue of each node does not grow to infinity as time goes to infinity. Therefore, the per-node capacity[3] of the network is the maximum rate λ that the network can stably support.

Delay: The delay of a packet is the time it takes from the source to reach all its k destinations. The total network delay is averaged over all packets, all multicast groups, and all random network configurations in the long run.

Popular Cell: A cell is defined to be a popular cell if it contains at least $E[n_a]$ nodes. And the number of popular cells is $E[n_p]$. The relationship between $E[n_a]$ and $E[n_p]$ is given by $E[n_a] = \frac{nH(n)}{E^{\alpha}[n_p]}$. Note that $E[n_a]$ varies with α.

III. Capacity and Delay Analysis Without Redundancy

In this section, we first explore the multicast performance of location-based MANETs under the well-known 2-hop scheme without redundancy. Then we take advantage of rich node resource and potential transmissions in popular cells, and propose a novel 3-hop scheme for multicast to improve the delay performance.

A. Capacity and Delay Under 2-Hop Relay Algorithm

In this subsection, we adopt conventional 2-hop relay algorithm[4] introduced by [12] to investigate the multicast throughput and delay. The rationale of the algorithm is described as follows. For a given packet, the source randomly chooses an available node and sends the packet to it. If the receiver is one of the destinations of the packet, the source keeps the packet. Otherwise, it deletes the packet from its buffer. The receiver not belonging the group of the source will act as a relay for the packet. And the packet is carried by the relay until all the destinations receive the packet successfully.The relay can be aware of this from the control information. This is accomplished through a distributed control strategy proposed in [6], which performs control actions in each cell independently. When a given packet is successfully received in a cell, the control strategy enables a feedback to nodes in other cells. And the feedback (i.e., control information) is passed over a reserved bandwidth channel. Note that we allow *single-node reception* in each cell, i.e., each node can communicate with only one node in one timeslot.

Each packet delivered from a source to a relay contains header information telling the relay which k destinations this packet should be transmitted to. According to this information, the relay makes k copies of the packet. Each copy contains the same necessary payload and less header information just indicating its corresponding destination. Based on packets' header information, the algorithm schedules packets to be transmitted and routed in the whole network. Every timeslot, it decides which packet to be delivered without violating the physical constraints of the cell-partitioned network.

[2]Other stochastic input processes with the same average rate can be treated in a similar way, since the capacity region depends only on nodes' steady state distribution. And the arrival process does not affect the region of rates the network can stably support [21].

[3]For briefness, per-node capacity is called capacity hereinafter.

[4]We consider noncooperative mode in this paper, which means that a destination cannot act as a relay for its source.

Since each node can act as relays for nodes from other groups, there will be multiple packets occupying the buffer space [20] of each node. Instead of assuming infinite buffer size, we will calculate the minimal required buffer size which can guarantee network stability. Note that the network is stable if buffers of all the nodes do not overflow. Intuitively, if the buffer is too large, the memory of nodes is wasted. If the buffer is not large enough, packets may be dropped, which will negatively affect the network performance. Moreover, in multicast transmissions, a packet-carrying relay will make k similar duplicates of the packet and store them in its buffer. Does it infer that the required buffer size for multicast is k times the one for unicast? In the following, we will analyze the required buffer size of 2-hop scheme, along with the throughput and delay performance.

First we investigate the fundamental transmission opportunities of the location-based scenario in Fig. 1. Let q_i' represent the probability that cell i contains at least two nodes, and q_i'' represent the probability that there is a S-D pair in cell i. Since the popularity is heterogeneous over all cells, these two probabilities will vary with different cells. Obviously, a more popular cell can attract more nodes to visit it and thus has at least two nodes or S-D pairs with a higher probability. And q_i' and q_i'' can be expressed as

$$q_i' = 1-(1-p_i)^n - np_i(1-p_i)^{n-1}. \tag{3}$$

$$q_i'' = 1-\left[(k+1)p_i(1-p_i)^k + (1-p_i)^{k+1}\right]^{\frac{n}{k+1}}. \tag{4}$$

To derive the expression of q_i', we first consider its opposite events, i.e., there is no node or only one node in cell i. The first event happens with a probability of $(1-p_i)^n$ under the condition that a particular node is in cell i with probability p_i. The second event occurs with a probability of $np_i(1-p_i)^{n-1}$, where n infers that the node in cell i can be any one among all nodes in the network.

As for q_i'', it represents the probability of finding a S-D pair in cell i. Note that in multicast traffic pattern, all the nodes are organized into $\frac{n}{k+1}$ groups and each group has $k+1$ nodes. Since each node is the source of all the other nodes within the same group, any two nodes in a group form a S-D pair. The probability that any S-D pair belonging to a particular group is not in cell i is $(k+1)p_i(1-p_i)^k + (1-p_i)^{k+1}$. Since each group is independent of others, the probability that S-D pairs of all $\frac{n}{k+1}$ groups are not in cell i is $\frac{n}{k+1}$ power of the above quantity, yielding (4).

Let $q' = \frac{1}{n}\sum_{i=1}^{n} q_i'$ be the average probability of finding at least two nodes within a cell, and $q'' = \frac{1}{n}\sum_{i=1}^{n} q_i''$ be the average probability of finding a S-D pair in a cell. Then we can establish the following lemma.

Lemma 1: Consider a cell-partitioned MANET with n nodes and n cells, in which cell i $(1 \le i \le n)$ has a popularity p_i following the Zipf's law. Then, q' and q'' are given by:

$$q' = \begin{cases} \Theta\left(n^{\frac{1-\alpha}{\alpha}}\right), & \alpha > 1 \\ \Theta\left(\frac{\log\log n}{\log n}\right), & \alpha = 1 \\ \Theta(1), & \alpha < 1 \end{cases} \tag{5}$$

$$q'' = \begin{cases} \Theta\left(n^{\frac{1-2\alpha}{2\alpha}} k^{\frac{1}{2\alpha}}\right), & \alpha > 1 \\ \Theta\left(\frac{\sqrt{k}}{\sqrt{n}\log n}\right), & \alpha = 1 \\ \Theta\left(\left(\frac{k}{n}\right)^{\frac{1}{2\alpha}}\right), & \frac{1}{2} < \alpha < 1 \\ \Theta\left(\frac{k\log n}{n}\right), & \alpha = \frac{1}{2} \\ \Theta\left(\frac{k}{n}\right), & \alpha < \frac{1}{2}. \end{cases} \tag{6}$$

Proof: The proof of q' is similar to that in [16] and we omit it here. We focus on the derivation of the expected value of q_i'' in the following. From (4), we have

$$q_i'' = 1-\left[(1-p_i)^k(1+kp_i)\right]^{\frac{n}{k+1}}. \tag{7}$$

When $p_i \ge \frac{1}{2k}$, $q_i'' = \Theta(1)$. When $p_i < \frac{1}{2k}$, let $f = [(1-p_i)^k(1+kp_i)]^{\frac{n}{k+1}}$, then we have

$$\begin{aligned} f &\le \left[\left(1-kp_i+\frac{k(k-1)}{2}p_i^2\right)(1+kp_i)\right]^{\frac{n}{k+1}} \\ &\le \left[1-k^2p_i^2+\frac{k^2p_i^2}{2}(1+kp_i)\right]^{\frac{n}{k+1}} \le \left(1-\frac{k^2p_i^2}{4}\right)^{\frac{n}{k+1}} \end{aligned} \tag{8}$$

where $1-kp_i+\frac{k(k-1)}{2}p_i^2 \ge (1-p_i)^k$ is employed and the last inequation holds when $kp_i \le \frac{1}{2}$.

Since $1-kp_i \le (1-p_i)^k$, we can obtain that

$$f \ge [(1-kp_i)(1+kp_i)]^{\frac{n}{k+1}}. \tag{9}$$

It follows that when $p_i \le \frac{1}{2k}$, we have:

$$1-\left(1-\frac{k^2p_i^2}{4}\right)^{\frac{n}{k+1}} \le q_i'' \le 1-\left(1-k^2p_i^2\right)^{\frac{n}{k+1}}. \tag{10}$$

Let $f_1 = \Theta(1-(1-k^2p_i^2)^{\frac{n}{k+1}})$, then we have

$$\begin{aligned} f_1 &= \Theta\left(1-\left(1-k^2p_i^2\right)^{\frac{n}{k+1}}\right) \\ &= \Theta\left(1-\left(1-k^2p_i^2\right)^{\frac{1}{k^2p_i^2}\cdot\frac{k^2np_i^2}{k+1}}\right) = \Theta\left(1-e^{-\frac{k^2np_i^2}{k+1}}\right) \end{aligned} \tag{11}$$

If $\frac{k^2np_i^2}{k+1} \ge 1$, i falls in the interval of $((kH(n))^{\frac{1}{\alpha}}, (\frac{H^2(n)nk^2}{k+1})^{\frac{1}{2\alpha}}]$. In this case, f_1 is of constant order, i.e., $f_1 = \Theta(1)$. Otherwise, i falls in the interval of $((\frac{H^2(n)nk^2}{k+1})^{\frac{1}{2\alpha}}, n]$ and $f_1 = \Theta(\frac{k^2np_i^2}{k+1})$.

From the definition of q'', we have

$$nq'' = \sum_{p_i\in\left(0,\frac{1}{2k}\right)} f_1 + \sum_{p_i\in\left[\frac{1}{2k},1\right]} \Theta(1). \tag{12}$$

Since location popularity p_i depends on α, we derive nq'' on different values of α, which can be summarized as follows:

Case 1: $\alpha > 1$, $p_i = \Theta(\frac{1}{i^\alpha})$

$$\sum_{p_i\in\left(0,\frac{1}{2k}\right)} f_1 + \sum_{p_i\in\left[\frac{1}{2k},1\right]} \Theta(1)$$

$$= \sum_{i\in\left[1,\left(\frac{nk^2}{k+1}\right)^{\frac{1}{2\alpha}}\right]} \Theta(1) + \sum_{i\in\left(\left(\frac{nk^2}{k+1}\right)^{\frac{1}{2\alpha}},n\right]} \Theta\left(\frac{k^2np_i^2}{k+1}\right)$$
$$= \Theta\left(\left(\frac{nk^2}{k+1}\right)^{\frac{1}{2\alpha}}\right) + \Theta\left(\frac{nk^2}{k+1}\int_{i=\left(\frac{nk^2}{k+1}\right)^{\frac{1}{2\alpha}}}^{n}\frac{1}{i^{2\alpha}}di\right)$$
$$= \Theta\left(\left(\frac{nk^2}{k+1}\right)^{\frac{1}{2\alpha}}\right). \quad (13)$$

Case 2: $\alpha = 1$, $p_i = \Theta(\frac{1}{i\log n})$

$$\sum_{p_i\in\left(0,\frac{1}{2k}\right)} f_1 + \sum_{p_i\in\left[\frac{1}{2k},1\right]} \Theta(1)$$
$$= \sum_{i\in\left[1,\frac{k}{\log n}\sqrt{\frac{n}{k+1}}\right]} \Theta(1) + \sum_{i\in\left(\frac{k}{\log n}\sqrt{\frac{n}{k+1}},n\right]} \Theta\left(\frac{k^2n}{i^2(k+1)\log^2 n}\right)$$
$$= \Theta\left(\frac{k}{\log n}\sqrt{\frac{n}{k+1}}\right). \quad (14)$$

Case 3: $\alpha < 1$, $p_i = \Theta(\frac{n^{\alpha-1}}{i^{\alpha}})$

$$\sum_{p_i\in\left(0,\frac{1}{2k}\right)} f_1 + \sum_{p_i\in\left[\frac{1}{2k},1\right]} \Theta(1)$$
$$= \sum_{i\in[1,n_3]} \Theta(1) + \sum_{i\in(n_3,n]} \Theta\left(\frac{k^2n}{k+1}\cdot\left(\frac{n^{\alpha-1}}{i^{\alpha}}\right)^2\right)$$
$$= \Theta\left(\left(\sqrt{\frac{n}{k+1}}\cdot kn^{\alpha-1}\right)^{\frac{1}{\alpha}}\right) + \frac{k^2n^{2\alpha-1}}{k+1}\int_{i=n_3}^{n}\frac{1}{i^{2\alpha}}di \quad (15)$$

where $n_3 = (\sqrt{\frac{n}{k+1}}\cdot kn^{\alpha-1})^{\frac{1}{\alpha}}$.

Equation (15) can be calculated by further dividing the case into the three following sub-cases: $\alpha \in [0, \frac{1}{2})$, $\alpha = \frac{1}{2}$, and $\alpha \in (\frac{1}{2}, 1)$. The detailed calculation is omitted here. ■

Lemma 2: Suppose $Y_1, Y_2, \ldots, Y_k (k \geq 1)$ are continuous i.i.d. exponential variables with expectation of $1/a$, and denote $Y_{max} = max\{Y_1, Y_2, \ldots, Y_k\}$, then we have $E\{Y_{max}\} = \Theta(\log k/a)$.

The detailed proof is reported in [12].

Theorem 1: Consider a cell-partitioned MANET with n nodes and n cells, in which the popularity of cell $i (1 \leq i \leq n)$ is p_i following the Zipf's law. Assume nodes independently choose cells according to cells' popularity every timeslot. Then under the 2-hop relay algorithm without redundancy, the average delay of a packet behaves asymptotically as

$$W = \begin{cases} \Theta\left(nk^{\frac{\alpha-1}{\alpha}}\log k\right), & \alpha > 1 \\ \Theta(n\log k), & \alpha \leq 1 \end{cases} \quad (16)$$

and the capacity is

$$\lambda = \begin{cases} \Theta\left(\frac{n^{\frac{1-\alpha}{\alpha}}}{k}\right), & \alpha > 1 \\ \Theta\left(\frac{\log\log n}{k\log n}\right), & \alpha = 1 \\ \Theta\left(\frac{1}{k}\right), & \alpha < 1 \end{cases} \quad (17)$$

and the minimal required buffer size of each node is

$$n_b = \begin{cases} \Theta\left(\left(\frac{n}{k}\right)^{\frac{1}{\alpha}}k\log k\right), & \alpha > 1 \\ \Theta\left(\frac{n\log\log n}{\log n}\log k\right), & \alpha = 1 \\ \Theta(n\log k), & \alpha < 1. \end{cases} \quad (18)$$

When the 2-hop scheme is adopted, we say that the network is stable if all nodes communicate at rate $\lambda \leq \frac{\mu}{k}$, where $\mu = \frac{q'+q''}{2}$. Here we provide the main ideas underlying the proof.

Proof: Assume that packets arrive at each node with the same data rate λ. Since each packet should be made k similar copies, the sum rate of new entered packets into the network is $nk\lambda$. It is shown in [21] that when nodes change cells in a reshuffled and independent fashion, the capacity region depends only on nodes' steady state distribution. In view of this, we can derive the upper bound of transmission rate according to the node distribution. If S and D are in the same cell, the packet can be transmitted directly. While the total number of cells containing at least a S-D pair is nq'' in a timeslot, the sum rate of single-hop S-D transmissions is bounded by nq''. Then the left cells with at least two nodes can support the packet delivery along 2-hop "source-relay-destinations" (S-R-D) path. It follows that the sum rate of this 2-hop transfers is at most $\frac{n(q'-q'')}{2}$. Therefore, we have $nk\lambda \leq nq'' + \frac{n(q'-q'')}{2}$. If the arrival rate λ satisfies this inequation, the network stability can be guaranteed. Plug (5) and (6) into the inequation, we can obtain the expression (17).

Then we analyze the average delay. According to the proposed routing scheme, a given packet is routed along two possible paths: the direct "S-D" single-hop path and the "S-R-D" 2-hop path. Since the average probability of finding a S-D pair in a cell is q''(6), there are at most $\Theta(\frac{\sqrt{k}}{\sqrt{n}\log n})$ fraction of packets delivered in a "S-D" manner every timeslot. Obviously, the probability that a packet is directly delivered to all its k destinations by the source is extremely small, which indicates that "S-D" single-hop transmissions do not affect the delay performance in order sense. Thus the vast majority of packets are transmitted along "S-R-D" 2-hop path. In this case, the delay is composed of two parts: (i) source-relay (S-R) delay W_{sr}, which represents the expected waiting time required for a source to be scheduled for transmissions. For a particular source, every timeslot it is scheduled for a transmission in cell i with probability $\frac{1}{np_i}$ since np_i nodes in it get the opportunity equally. The waiting time in cell i is thus geometrically distributed with mean np_i. By weighting the delay that occurs in all cells, we can achieve the average waiting time as $W_{sr} = \sum_{i=1}^{n} np_i^2$; (ii) relay-destinations (R-Ds) delay W_{rd}, which is the time it takes for the relay node to reach all k destinations. And W_{rd} is determined by the maximum value among all the waiting times $W_{rd}^1, W_{rd}^2, \ldots, W_{rd}^k$ of these k destinations. Next we focus on deriving the average delay of a successful R-D transmission.

In some cells, the relay may encounter more than one destinations. This event happens more often in popular cells. Under the constraint that the 2-hop algorithm only admits a one-to-one transmission in a cell every timeslot, there are two cases for a successful R-D transmission. If the relay encounters only one destination in cell i, the probability of a successful R-D transmission is $p_i^2 \cdot \frac{1}{np_i}$, which is given by the probability that the relay gets a transmission opportunity multiplied by the conditional probability that the relay and the destination encounter in cell i. The former probability is $\frac{1}{np_i}$ and the latter probability is p_i^2. If the relay meets multiple destinations, the probability of a successful R-D transmission in cell i decreases to $p_i^2 \cdot \frac{1}{np_i} \cdot \frac{1}{kp_i}$ due to the fact that kp_i destinations get the opportunity of receiving the packet equally.

Based on the analysis above, we can obtain the average probability p_{rd} that the relay successfully communicates with any destination.

$$\begin{aligned} p_{rd} &= \sum_{i\in\{i:kp_i\le 1\}} p_i^2 \cdot \frac{1}{np_i} + \sum_{i\in\{i:kp_i>1\}} p_i^2 \cdot \frac{1}{np_i} \cdot \frac{1}{kp_i} \\ &= \sum_{i\in\left[(kH(n))^{\frac{1}{\alpha}},n\right]} \frac{p_i}{n} + \sum_{i\in\left[1,(kH(n))^{\frac{1}{\alpha}}\right)} \frac{1}{nk} \\ &= \Theta\left(\frac{H^{\frac{1}{\alpha}}(n)}{nk^{\frac{\alpha-1}{\alpha}}}\right) + \int_{i=(kH(n))^{1/\alpha}}^{n} \frac{H(n)}{ni^{\alpha}}. \end{aligned} \tag{19}$$

It follows that

$$p_{rd} = \begin{cases} \frac{1}{nk^{\frac{\alpha-1}{\alpha}}}, & \alpha > 1 \\ \frac{1}{n}, & \alpha \le 1. \end{cases} \tag{20}$$

Based on (20), we can then derive the expectation of the waiting times $W_{rd}^1, W_{rd}^2, \ldots, W_{rd}^k$, which is equal to the inverse of p_{rd}. From lemma 2, we can obtain the maximum value among all R-D waiting times. Combined with the fact that S-R delay is $O(n)$, we can achieve the total network delay which is shown in (16).

Since each node can serve as a relay for the other $n-k-1$ nodes equally, it can be modeled as a node that has $n-k-1$ parallel subqueues buffering packets intended for different destinations. Suppose subqueue j $(j = 1,2,\ldots,n-k-1)$ stores packets intended for a certain node, it can be regarded as a Bernoulli/Bernoulli queue with input rate $\lambda'_j = \frac{\lambda_j k}{n-k-1}$ (for that node, there are k sources and the other $n-k-1$ nodes act as relay for it equally) and service rate $\mu'_j = \frac{1}{W}$ (because each packet needs at most W timeslots to be successfully transmitted). The resulting occupancy at subqueue j is thus $\bar{L}_j = \frac{\rho'_j(1-\lambda'_j)}{1-\rho'_j}$, where $\rho'_j \triangleq \frac{\lambda'_j}{\mu'_j}$. Since it holds for each subqueue, the required buffer size of each node is equivalent to the sum queue length of all subqueues, i.e., $n_b = \sum_{j=1}^{n-k-1} \bar{L}_j$, yielding (18). ■

Remark: In previous analysis, we only consider one-to-one communication in one cell. When there are multiple destinations in one cell, only one of them can receive the packet and therefore degrades the performance. If multi-reception is allowed, the capacity will remain the same. And a destination can receive its packet in cell i when 1) the packet's relay is also in the cell, 2) have transmission opportunity to broadcast, and 3) the relay transmits the destination's packet, not others'. For cell i, this probability can be seen as $p_i \cdot p_i \cdot \frac{1}{np_i} \cdot \frac{1}{np_i}$, which equals to. Therefore the delay will decrease to $n \log k$.

B. Capacity and Delay Under 3-Hop Relay Algorithm

From the 2-hop relay algorithm, we can observe that the delay performance is mainly constrained by the second phase of the routing, since a R-D transmission rarely happens. This is due to the fact that the algorithm only admits a one-to-one transmission every timeslot in a popular cell even though there are a number of nodes in it. It turns out that within a popular cell, it is beneficial to employ a multi-node reception strategy, i.e., if a node in a popular cell is scheduled to transmit, it broadcasts packets to all nodes within the same cell. Intuitively, this strategy can increase the packet replication speed. Inspired by this, we propose a modified relay algorithm to improve the delay performance without impacting the overall network capacity negatively. This algorithm can utilize the potential transmission opportunities in popular cells and restrict packets to 3-hop paths.

Considering the high node density feature of popular cells, we deploy an access point (AP) in the center of each popular cell, on the purpose of alleviating the heavy traffic load to guarantee the network stability. This is in accordance with practical scenarios. Note that each node within the cell can reach the AP by a single hop and at most $O(\frac{1}{\sqrt{n}})$ fraction of cells are required to be deployed with an AP, indicating a small deployment cost.

3-Hop Relay Algorithm: During a timeslot, for each cell with at least two nodes:

1) If there is a S-D pair in the cell, select a pair randomly. If there is a new
2) packet for the destination, transmit it and then delete it from the source's buffer. Else remain idle.
3) If no S-D pair exists in the cell, randomly designate a node in the cell as sender.
   i) *Broadcast Transmission*: If it is a popular cell, let the sender transmit all the packets in its buffer to other nodes in the cell via the AP. If a packet is received by all its destinations successfully,[5] delete the packet from the buffers of all nodes holding it. Else remain idle.
   ii) If the cell is not a popular one, randomly choose one node as receiver in the cell. Do the following options with equal probability:
      - *Source-to-Relay Transmission*: If the sender has a newly generated packet, send the packet to the designated receiver. Else remain idle.
      - *Relay-to-Destination Transmission*: If the sender has a packet relayed for the designated receiver, transmit it. If all the destinations of this packet have received it, drop the packet from the buffers of all nodes holding it. Else remain idle.

As shown in Fig. 2, each node can act as three roles in the network: source, intermediate relay and destination. Similar as the arrival process, we use Bernoulli process to describe the service process. That is, with probability μ a node is scheduled to transmit in the current timeslot, and it remains idle otherwise.

[5]We assume that all nodes can be aware of this from the control information passed over a reserved bandwidth channel.

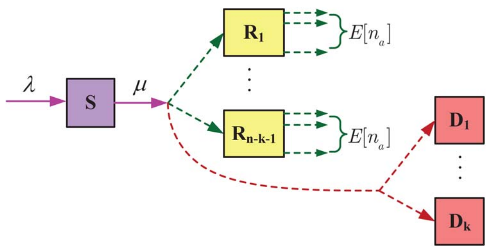


Fig. 2. A diagram of the network as seen by the packets transmitted from a single source to k destinations.

We assume μ is equal to the time average rate of transmission opportunities of a source.

Theorem 2: Consider the same assumptions for the network as Theorem 1. If the exogenous arrival process to node j is a Bernoulli process of rate λ_j satisfying $\lambda_j < \mu/k$, then under the 3-hop relay algorithm without redundancy, the network is stable and the average delay W_j for the traffic of node j satisfies:

$$E[W_j] = \begin{cases} \Theta\left(n^{\frac{\alpha}{1+\alpha}} \cdot (\log k)^{\frac{1}{1+\alpha}}\right), & \alpha > 1 \\ \Theta(\sqrt{n \log n \log k}), & \alpha = 1 \\ \Theta\left((n \log k)^{\frac{1}{1+\alpha}}\right), & \alpha < 1 \end{cases} \quad (21)$$

where $\mu = \frac{q' + 2q''}{3}$ and the minimal required buffer size of each node is

$$n_b = \begin{cases} \Theta\left(n^{\frac{1}{\alpha(1+\alpha)}} \cdot (\log k)^{\frac{1}{1+\alpha}}\right), & \alpha > 1 \\ \Theta\left(\sqrt{\frac{n \log k}{\log n}} \cdot \log \log n\right), & \alpha = 1 \\ \Theta\left((n \log k)^{\frac{1}{1+\alpha}}\right), & \alpha < 1. \end{cases} \quad (22)$$

Proof: As depicted in Fig. 2, a source node j can be represented as a Bernoulli/Bernoulli queue with input rate λ_j and service rate μ. First, we derive the transmission probability of source j under this algorithm.

Denote r_1 as the rate at which the source transmits to one of its destinations directly. Denote r_2 as the rate at which the source transmits to one of its relays. Therefore, we have $\mu = r_1 + r_2$. Since at rate r_2 the relay nodes are scheduled to broadcast in popular cells or transmit to the destinations,[6] the total rate of transmission opportunities over the network is $n(r_1 + 3r_2)$ every timeslot. By cumulating the probability of cells containing at least two nodes (indicate a potential transmission opportunity), we can obtain

$$\textstyle\sum_{i=1}^{n} q_i' = n(r_1 + 3r_2). \quad (23)$$

Recall that q_i'' is the probability that cell i contains a S-D pair. Since the algorithm schedules the S-D transmissions whenever possible, then r_1 satisfies:

$$\textstyle\sum_{i=1}^{n} q_i'' = n r_1. \quad (24)$$

[6]This is due to the fact that the relay algorithm schedules transmissions into and out of relay nodes with equal probability.

From (23) and (24), it follows that $r_1 = q''$, $r_2 = \frac{q' - q''}{3}$. Hence, the service rate of the source node is given by

$$\mu = r_1 + r_2 = \frac{q' + 2q''}{3}. \quad (25)$$

Based on the derived service rate of source j, we then analyze the average delay $E[W_j]$ for the packets from source j. It is worth mentioning that because of the traffic pattern and the probability of S-D transfers and non-S-D transfers we calculate, S-D transfers will not affect the delay in order sense and therefore we only consider non-S-D transfers in the following. From Fig. 2, we can find that there are two relay roles for individual nodes. To distinguish, we define relay nodes generated in ordinary cells as *initial relays*, and relay nodes generated in popular cells as *accelerated relays*. Hence, in the 3-hop routing scheme, the packet delay is composed of three parts: the waiting time at source W_s, initial relay W_{ir}, and accelerated relay W_{ar}.

Since source j can be represented as a Bernoulli/Bernoulli queue with arrival rate λ_j and service rate μ, the expected number of occupancy packets at source j is $\bar{L}_s = \frac{\rho(1-\lambda_j)}{1-\rho}$, where $\rho \triangleq \frac{\lambda_j}{\mu}$. From Little's theorem, we can achieve the average waiting time in the source as $E[W_s] = \frac{\bar{L}_s}{\lambda_j} = \frac{1-\lambda_j}{\mu - \lambda_j}$. Moreover, since the queue is reversible, the departure process is also a Bernoulli process of rate λ_j.

Then we derive the arrival rate λ_{ir} and service rate μ_{ir} of the initial relay. A given packet from the departure process of source j is forwarded to the initial relay with probability $\frac{r_2}{\mu(n-k-1)}$. This is because in an ordinary cell, the packet is transmitted to a relay node with probability $\frac{r_2}{\mu}$, and $n-k-1$ relay nodes share the opportunity equally. Therefore, the arrival rate of the initial relay is $\lambda_{ir} = \frac{\lambda_j r_2}{\mu(n-k-1)}$. On the other hand, a broadcast transmission opportunity arises for the initial relay with probability $\mu_{ir} = \frac{r_2 E[n_p]}{n}$. The probability is determined by the following factors: (a) the initial relay enters a popular cell with probability $\frac{E[n_a]E[n_p]}{n}$, (b) it is designated as sender in a popular with probability $\frac{1}{E[n_a]}$ since there are average $E[n_a]$ nodes in it, and (c) the initial relay operates in broadcast mode with probability r_2.

Note that packet arrivals and transmission opportunities are mutually exclusive events in a initial relay node. Hence, the discrete time Markov chain for queue occupancy in the relay node can be regarded as a simple birth-death chain which is identical to a continuous-time M/M/1 queue with arrival rate λ_{ir} and service rate μ_{ir}. This holds for all initial relay nodes, and the resulting occupancy at any initial relay is thus $\bar{L}_{irelay} = \frac{\lambda_{ir}}{\mu_{ir} - \lambda_{ir}}$. From Little's theorem, the average waiting time at the initial relay is $E[W_{ir}] = \frac{\bar{L}_{irelay}}{\lambda_{ir}} = \frac{1}{\mu_{ir} - \lambda_{ir}}$. Note that the initial relay will encounter average $\frac{kE[n_a]}{n}$ destinations in a popular cell, which implies that $\frac{kE[n_a]}{n}$ destinations can obtain the packet during a broadcast transmission.

A broadcast transmission in a popular cell will result in $E[n_a] - \frac{kE[n_a]}{n}$ nodes carrying the duplicates of a given packet. These nodes will act as accelerated relays and be restricted to communicate only with the destinations of the packet. Each duplicate has redundant data in its header indicating which k destinations this packet should be delivered to. This information guides each accelerated relay to make k copies of the packet, and each copy contains less redundant data indicating its corresponding destination in the header. Recall that we define every $k+1$ nodes as a group, where each node acts as a source for the other k nodes within the group. Thus, each node can help relaying packets to other $n-k-1$ destinations. Based on this observation, we model each node with $n-k-1$ parallel subqueues, each of which buffers packets for a designated destination. For each subqueue, there are k sources (because in a group each node is a source for the other k nodes and each node has k sources). Suppose an initial relay communicates with an accelerated relay with probability p_{ar}, then every timeslot each subqueue in the accelerated relay receives a packet with probability $1-(1-p_{ar})^k$, which equals kp_{ar}.

Then the duplicates of the packet will wait at these accelerated relays until all the destinations receive the packet. Every timeslot, an accelerated relay independently receives packets from an initial relay with probability $\lambda_{ar}=\frac{\lambda_{ir}n}{E[n_p]}\cdot\frac{E[n_a]E[n_p]}{n}$. The probability is constituted by: (a) an initial relay stores average $\frac{\lambda_{ir}n}{E[n_p]}$ packets before it gets a broadcast opportunity in popular cells, and all the packets in its buffer will be delivered to nodes in the same popular cell[7]; (b) a node moves into a popular cell and acts as an accelerated relay with probability $\frac{E[n_a]E[n_p]}{n}$. Combined with the fact that there are k sources for each subqueue, the arrival rate of each subqueue in an accelerated relay is $k\lambda_{ar}$. Meanwhile, each subqueue of one of the $E[n_a]-\frac{kE[n_a]}{n}$ accelerated relay nodes is scheduled for a potential packet transmission to a destination with probability $u_{ar}=\frac{r_2E[n_a](1-\frac{k}{n})}{n-k-1}$. This is because: (a) a "relay-to-destination" opportunity arises in an accelerated relay with probability r_2, (b) an accelerated relay can transmit packets to $n-k-1$ destinations except nodes in the same group, and (c) each of the $E[n_a]-\frac{kE[n_a]}{n}$ accelerated relays containing the duplicates of the packet is equally likely.

Similarly, the discrete-time Markov chain for each subqueue in an accelerated relay can be treated as a continuous-time M/M/1 queue with input rate $k\lambda_{ar}$ and service rate μ_{ar}. Due to the nature of the M/M/1 queue, the expected number of occupancy packets in such a queue can be expressed as $\bar{L}_{arelay}=\frac{k\lambda_{ar}}{\mu_{ar}-k\lambda ar}$. From Little's theorem, the average waiting time at an accelerated relay to destination $h(1\le h\le k)$ is thus $E[W_{ar}^h]=\frac{\bar{L}_{arelay}}{k\lambda_{ar}}=\frac{1}{\mu_{ar}-k\lambda_{ar}}$. The resulting waiting time of the third hop, W_{ar}, is determined by the maximum value of waiting time set $\mathcal{W}_{ar}=\{W_{ar}^1,W_{ar}^2,\dots,W_{ar}^k\}$. Since each waiting time in the set is an exponential distributed variable with an expectation of $E[W_{ar}^h]$, we can obtain that $E[W_{ar}]=\frac{\log k}{\mu_{ar}-k\lambda_{ar}}$ by Lemma 2.

[7]With the assistance of AP, all the packets in the buffer can be served instantly once an opportunity arises for the relay to connect with an AP. In this way, the transmission stability at the second stage can be ensured.

Based on the analysis above, we can achieve the average delay for the traffic of node j as

$$\begin{aligned}E[W_j]&=E[W_s]+E[W_{ir}]+E[W_{ar}]\\&=\frac{1-\lambda_j}{\mu-\lambda_j}+\frac{1}{\frac{r_2E[n_p]}{n}-\frac{\lambda_jr_2}{\mu(n-k-1)}}+\frac{\log k}{\frac{r_2E[n_a]\left(1-\frac{k}{n}\right)}{n-k-1}-\frac{\lambda_jr_2E[n_a]k}{\mu(n-k-1)}}\\&=\frac{1-\lambda_j}{\mu-\lambda_j}+\Theta\left(\frac{\mu n(n-k-1)}{\mu E[n_p](n-k-1)-\lambda_jn}\right)\\&\quad+\Theta\left(\frac{\mu(n-k-1)\log k}{\mu E[n_a]-\lambda_jE[n_a]k}\right)\\&=\Theta\left(\frac{n}{E[n_p]}\right)+\Theta\left(\frac{n\log k}{E[n_a]}\right).\end{aligned}\tag{26}$$

Since the relationship between $E[n_a]$ and $E[n_p]$ can be expressed as $E[n_a]=\frac{nH(n)}{E^\alpha[n_p]}$, we have

$$E[W_j]=\Theta\left(\frac{n}{E[n_p]}+\frac{E^\alpha[n_p]}{H(n)}\log k\right)\ge\Theta\left(\frac{n^{\frac{\alpha}{1+\alpha}}}{\left(\frac{H(n)}{\log k}\right)^{\frac{1}{1+\alpha}}}\right).\tag{27}$$

where the equality holds when $E[n_p]=\Theta(\frac{nH(n)}{\log k})^{\frac{1}{1+\alpha}}$ and $E[n_a]=\Theta((nH(n))^{\frac{1}{1+\alpha}}\cdot(\log k)^{\frac{\alpha}{1+\alpha}})$. Combining (2) and (27), we obtain the average delay in order sense.

To guarantee the stability of the network, the arrival rate should be less than the service rate at any stage of the network. Then we have

$$\begin{cases}\mu-\lambda_j>0\\\frac{r_2E[n_p]}{n}-\frac{\lambda_jr_2}{\mu(n-k-1)}>0\\\frac{r_2E[n_a]\left(1-\frac{k}{n}\right)}{n-k-1}-\frac{\lambda_jr_2E[n_a]k}{\mu(n-k-1)}>0\end{cases}\tag{28}$$

yielding the stability condition $\lambda_j<\frac{\mu}{k}$.

For the minimal needed buffer size of each node under the 3-hop scheme, we analyze it from the perspective of the whole network. Specifically, to ensure the network stability, the sum of new packets generated from popular cells should be less than the sum of packets served by ordinary cells in any timeslot. Once a packet is delivered to all its k destinations, each relay carrying the packet will delete all the corresponding duplicates from its buffer, leading to $k(E[n_a]-\frac{kE[n_a]}{n})$ served duplicates. We thus have

$$E[n_a]E[n_p]n_b\le\frac{nq'-E[n_p]}{k}\cdot k\left(E[n_a]-\frac{kE[n_a]}{n}\right).\tag{29}$$

Therein the factor $nq'-E[n_p]$ represents the number of ordinary cells which have at least two nodes and can support packet transmissions. To complete a multicast transmission, a packet should be transmitted k times on average. And each relay node from popular cells makes k copies of a packet. It follows that $n_b=\Theta(\frac{nq'}{E[n_p]})$. From (5) in Lemma 1, we can obtain the value of n_b. ■

IV. Capacity and Delay Analysis With Redundancy

In the previous two proposed algorithms, no redundancy is employed, e.g., for a given packet, only one node will act as a relay.[8] Obviously, if more nodes become initial relays for the packet, the chances of encountering destinations will increase and the delay will be further improved. In this section, we investigate the capacity and delay under 2-hop and 3-hop algorithms with redundancy, respectively.

A. Capacity and Delay Under 2-Hop Relay Algorithm

First we briefly describe the algorithm. For a given packet, the source keeps sending duplicates of it to different nodes until m relay nodes obtain the packet. Once a relay holding the duplicate encounters one of the destinations and gets a transmission opportunity, it delivers the packet to the destination. After all the destinations receive the packet, the packet will be dropped from the buffers of all these relays, which know this by the control information passed over a reserved bandwidth channel.

Theorem 3: The 2-hop algorithm with redundancy can achieve a minimal delay of

$$E[W]=\begin{cases}\Theta\left(nk^{\frac{\alpha-1}{2\alpha}}\sqrt{\log k}\right), & \alpha>1\\ \Theta\left(\frac{n\sqrt{\log k}}{\log n}\right), & \alpha=1\\ \Theta(n^{\alpha}\sqrt{\log k}), & \frac{1}{2}<\alpha<1\\ \Theta(\sqrt{n\log n\log k}), & \alpha=\frac{1}{2}\\ \Theta(\sqrt{n\log k}), & \alpha<\frac{1}{2}\end{cases} \quad (30)$$

with corresponding capacity

$$\lambda=\begin{cases}\Theta\left(\frac{n^{\frac{1-\alpha}{\alpha}}}{k\sqrt{\log k}}\right), & \alpha>1\\ \Theta\left(\frac{\log\log n}{k\sqrt{\log k}\log^2 n}\right), & \alpha=1\\ \Theta\left(\frac{1}{n^{1-\alpha}k\sqrt{\log k}}\right), & \frac{1}{2}<\alpha<1\\ \Theta\left(\frac{\sqrt{\log n}}{k\sqrt{n\log k}}\right), & \alpha=\frac{1}{2}\\ \Theta\left(\frac{1}{k\sqrt{n\log k}}\right), & \alpha<\frac{1}{2}\end{cases} \quad (31)$$

and the redundancy m is given by

$$m=\begin{cases}\Theta\left(k^{\frac{\alpha-1}{2\alpha}}\sqrt{\log k}\right), & \alpha>1\\ \Theta\left(\log n\sqrt{\log k}\right), & \alpha=1\\ \Theta\left(n^{1-\alpha}\sqrt{\log k}\right), & \frac{1}{2}<\alpha<1\\ \Theta\left(\sqrt{\frac{n\log k}{\log n}}\right), & \alpha=\frac{1}{2}\\ \Theta\left(\sqrt{n\log k}\right), & \alpha<\frac{1}{2}.\end{cases} \quad (32)$$

Proof: Suppose each node sends at the same data rate λ. Since each packet will be retransmitted m times to distinct relay nodes and each relay node will make k copies corresponding to different destinations, the total rate of packets entering the network is $nkm\lambda$. Therefore, we have $nkm\lambda \le nq'' + \frac{n(q'-q'')}{2}$ under 2-hop algorithm with redundancy, yielding the per-node capacity.

[8]Here relay refers to initial relay when 3-hop algorithm is considered.

Then we analyze the average delay. For a given packet, the delay is mainly composed of two parts: i) source-relays delay, which is the time required for the source to deliver the duplicate of the packet to m different nodes. Under 2-hop relay algorithm with redundancy, a source is scheduled for "S-R" transmission in cell i with probability $\alpha_1^i\alpha_2^i$, where α_1^i is the probability that the source gets an opportunity to transmit in cell i ($\alpha_1^i=\frac{1}{np_i}$ since there are np_i nodes in it), and α_2^i is the probability that the source is scheduled to operate in "S-R" transmission ($\alpha_2^i=1/2$). The waiting time of being scheduled for "S-R" transmission in cell i is thus $2np_i$. Since a source is in cell i with probability p_i, the average waiting time that a source sends a duplicate to a new node is $\sum_{i=1}^n 2np_i^2$. Under the condition that the source should distribute m duplicates, the average S-R delay is $\sum_{i=1}^n 2nmp_i^2$. ii) relays-destinations delay, which is the time that all the destinations receive the packet conditioned on the event that m relays hold the duplicates of the packet. The probability that some relay reaches some destination is given by $\sum_{i=1}^n \beta_1^i\beta_2^i\beta_3^i\beta_4^i$. Here β_1^i represents the probability that one of these relays meets one of the destinations in cell $i(\beta_1^i=p_i^2)$, β_2^i represents the probability that the relay is scheduled to be a sender in cell i ($\beta_2^i=\frac{1}{np_i}$ similar to the previous analysis), β_3^i represents the probability that some destination gets the opportunity of receiving the packet in cell i ($\beta_3^i=\frac{1}{kp_i}$ since kp_i destinations in it get the receiving opportunity equally) and β_4^i represents the probability that the relay operates in "R-D" transmission ($\beta_4^i=1/2$). Since there are m duplicate-carrying nodes of the packet, every time slot, the probability p'_{rd} that one of m relays communicates with one of the destinations is

$$\begin{aligned}p'_{rd}&=\sum_{i\in\{i:kp_i\le 1\}} p_i^2\cdot\frac{m}{np_i}+\sum_{i\in\{i:kp_i>1\}} m\cdot p_i^2\cdot\frac{1}{np_i}\cdot\frac{1}{kp_i}\\ &=\sum_{i\in\left[(kH(n))^{1/\alpha},n\right]}\frac{mp_i}{n}+\sum_{i\in\left[1,(kH(n))^{1/\alpha}\right)}\frac{m}{nk}\\ &=\Theta\left(\frac{mH^{\frac{1}{\alpha}}(n)}{nk^{\frac{\alpha-1}{\alpha}}}\right)+\int_{i=(kH(n))^{1/\alpha}}^{n}\frac{mH(n)}{ni^{\alpha}}.\end{aligned} \quad (33)$$

It follows that the probability equals to mp_{rd}, where p_{rd} is given in (20).

Combined with the fact that the average time that all k destinations obtain the packet is $\log k$ times of the inverse of this probability, we have

$$E[W]=\Theta\left(\sum_{i=1}^n nmp_i^2\right)+\Theta\left(\frac{\log k}{mp_{rd}}\right)\ge\sqrt{\frac{n\log k\sum_{i=1}^n p_i^2}{p_{rd}}} \quad (34)$$

where the equality holds when $m=\sqrt{\frac{\log k}{np_{rd}\sum_{i=1}^n p_i^2}}$. ■

B. Capacity and Delay Under 3-Hop Relay Algorithm

For a given packet, the 3-hop relay algorithm with redundancy proceeds in three phases. In the first phase, the packet is replicated and delivered to m initial relays. In the second phase, once a duplicate-carrying node moves into a popular cell and gets a transmission opportunity, it broadcasts the packet via the

AP in the cell. After the duplicates are broadcasted in l distinct popular cells, all the nodes holding the duplicate remove it from their buffers. In the third phase, nodes receiving the duplicate in popular cells serve as accelerated relays for the packet until all the destinations receive the packet.

Theorem 4: The 3-hop relay algorithm with m redundancy can achieve an average delay

$$E[W] = \begin{cases} \Theta\left(\frac{n^{\frac{\alpha}{1+\alpha}}}{\sqrt{m}} \cdot \left(\frac{\log k}{H(n)}\right)^{\frac{1}{1+\alpha}}\right), & m \le E^2[n_a] \\ \Theta\left(\frac{\log k}{mp_{rd}}\right), & m > E^2[n_a] \end{cases} \tag{35}$$

with corresponding capacity of $\Theta(\frac{q'+q''}{km})$, where m varies from 1 to n and p_{rd} is given in (20).

Proof: For a given packet, assume that there are m nodes holding the duplicate initially. After these duplicates are spread in l popular cells, the number of accelerated relay nodes for the packet will increase to $lE[n_a]$. However, there may exist a case that the packet transmission cannot benefit from the acceleration. Specifically, if $m > lE[n_a]$, the acceleration is meaningless and the 3-hop algorithm degenerates into 2-hop algorithm. Since every timeslot packets arrive at each node at the same arrival rate λ and each packet has mk copies, the total number of new packets entering the network per timeslot is $nkm\lambda$. Therefore, we have $nkm\lambda \le nq'' + \frac{n(q'-q'')}{2}$ when $m > lE[n_a]$. In case $m \le lE[n_a]$, the acceleration can contribute to the packet delivery. Then most of the routings go along the 3-hop "source-initial relays-accelerated relays-destinations" path. Following the same analysis, we have $nkm\lambda \le nq'' + \frac{n(q'-q'')}{3}$. Generally, we can come to the conclusion that $\lambda \le \Theta(\frac{q'+q''}{km})$.

Then we derive the average delay. Again consider the two cases mentioned above. When $m \le lE[n_a]$, the time required for a given packet to reach its k destinations is at most $W = W_1 + W_2$. Here W_1 denotes the time it takes for the duplicates to be broadcasted in l different popular cells. And W_2 denotes the time required for all k destinations to obtain the packet conditioned on the event that there are $lE[n_a]$ duplicate-carrying nodes. Next we bound the expectations of W_1 and W_2, which are expressed by $E[W_1]$ and $E[W_2]$, respectively.

To compute $E[W_1]$, denote $P(W_1)$ as the probability that l duplicate-holding nodes enter distinct popular cells and get transmission opportunities, given that there are m nodes initially holding the duplicate of the packet. The probability of a node moving into a popular cell is $\frac{E[n_a]E[n_p]}{n}$. When a node is in a popular cell, it is scheduled for a broadcast transmission with probability $\frac{1}{E[n_a]}$. As l nodes are required to broadcast the packet in popular cells and each of the m initial duplicate-holding nodes are equally likely, we have $P(W_1) = \Theta(\frac{m}{l} \cdot \frac{E[n_a]E[n_p]}{n} \cdot \frac{1}{E[n_a]})$. Thus $E[W_1]$ is equal to the inverse of this quantity, i.e., $E[W_1] = \Theta(\frac{ln}{mE[n_p]})$.

To compute $E[W_2]$, denote $P(W_2)$ as the probability that one of k destinations receives the packet given that there are $lE[n_a]$ nodes carrying its duplicates. $P(W_2)$ is derived by the probability that some accelerated relay communicates with some destination $(\sum_{i=1}^{n}(p_i^2 \cdot \frac{1}{np_i}))$ multiplied by $lE[n_a]$ (there are $lE[n_a]$ nodes that serve as relays for this packet). Given that $\sum_{i=1}^{n} p_i = 1$, this quantity equals $\Theta(\frac{lE[n_a]}{n})$. Therefore, the average delay of sending the packet to each destination is $\Theta(\frac{n}{lE[n_a]})$. By Lemma 2, we have that the average waiting time of reaching all k destinations in this part is $E[W_2] = \Theta(\frac{n\log k}{lE[n_a]})$.

Based on the above analysis, we can obtain that

$$E[W] = \Theta\left(\frac{ln}{mE[n_P]}\right) + \Theta\left(\frac{n\log k}{lE[n_a]}\right) \ge \Theta\left(\frac{n^{\frac{\alpha}{1+\alpha}}}{\sqrt{m}} \cdot \left(\frac{\log k}{H(n)}\right)^{\frac{1}{1+\alpha}}\right) \tag{36}$$

where the equality holds when $l = \sqrt{m}$ under the condition that $E[n_a] = \Theta((nH(n))^{\frac{1}{1+\alpha}} \cdot (\log k)^{\frac{\alpha}{1+\alpha}})$ and $E[n_p] = \Theta(\frac{nH(n)}{\log k})^{\frac{1}{1+\alpha}}$.

For case $m > lE[n_a]$, the average delay is the time it takes for all k destinations to obtain the packet successfully when initial m duplicates are present. Following the same analysis in Theorem 3, we can obtain that a duplicate-carrying node reaches some destination in a cell with probability p_{rd}. Since there are m relay nodes for it, the probability increases to mp_{rd}. Then the average waiting time of each destination is $\Theta(\frac{1}{mp_{rd}})$ and the average delay of reaching all k destinations is $\Theta(\frac{\log k}{mp_{rd}})$. ■

V. Discussion

A. Multicast Performance Without Redundancy

In this subsection, we draw a comparison of multicast performance between 2-hop scheme and 3-hop scheme, both without redundancy. Moreover, we discuss the impacts of location popularity and multicast on their performance.

Capacity: From Fig. 3(a), we can observe that 3-hop scheme and 2-hop scheme achieve the same capacity performance. Specifically, both of them can achieve $\tilde{\Theta}(\frac{1}{k})$ capacity when $\alpha \le 1$. And the capacity decreases as α when $\alpha > 1$. The reason is as follows. When $\alpha \le 1$, the majority of nodes are in ordinary cells due to the fact that the network diversity is moderate. Then most of the cells and nodes are active for transmissions in this region, leading to a high utilization on node resource and thus high capacity. When $\alpha > 1$, the node distribution becomes more heterogeneous over cells, that is, there are more nodes in popular cells and less nodes in ordinary cells. As a result, the number of idle cells increases and the capacity decays. Besides, compared with the unicast capacity in [16], we find that the capacity of these two schemes diminishes by a factor of $1/k$. This is essentially due to the fact that a packet should be delivered to k destinations in multicast transmissions. Particularly, when $\alpha = 0$, we find that the multicast capacity of uniform mobile scenarios is a special case of our results. And when $k = 1$, the results of this paper can recover the unicast results in [16].

Delay: As illustrated in Fig. 3(b), 3-hop scheme outperforms 2-hop scheme in delay aspect for any α. Note that such an improvement is not at the sacrifice of capacity. The key reason of this improvement is that the acceleration mechanism in 3-hop scheme can effectively exploit the rich node resource in popular cells and generate multiple relays, which significantly boost the opportunities of encountering destinations.

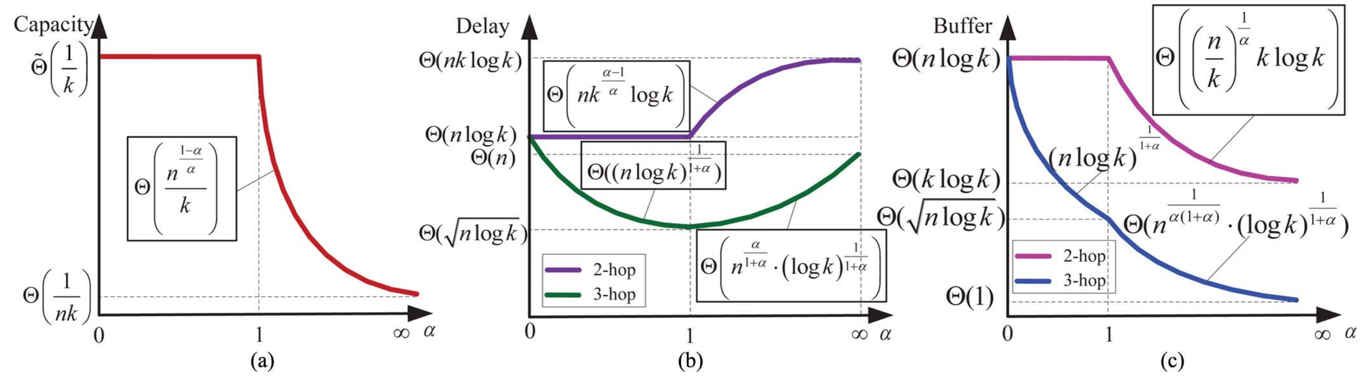


Fig. 3. Multicast performance of two schemes without redundancy for different values of α.

Moreover, location popularity has a great impact on the delay performance of 2-hop and 3-hop scheme. For 2-hop scheme, in region $\alpha \in [0,1]$, delay keeps unchanged, while in region $\alpha \in (1,\infty)$, delay performance gets worse when α becomes larger. Intuitively, this is because as α increases in this region, more nodes along with more destinations of a given packet move to popular cells. Transmissions are more likely to happen in popular cells. Once a transmission opportunity arises for a relay node in a popular cell, one-to-one transmission is permitted despite that there are multiple destinations in it. It implies that the average waiting time of each destination becomes larger when more nodes gather in popular cells. For 3-hop scheme, the best delay performance is achieved when $\alpha = 1$. And the delay increases when α either decreases in region $\alpha \in [0,1)$ or increases in region $\alpha \in (1,\infty)$. The intuitive explanation is as follows. In region $\alpha|! \in [0,1)$, location diversity becomes more smooth when α becomes smaller, leading to less nodes gathering in popular cells and more uniform nodes visitations. Then for a given packet, the number of duplicates generated in a popular cell decreases and the acceleration effect of popular cells will be weakened. As a result, the time to complete R-D transmissions grows. In region $\alpha \in (1,\infty)$, as α increases, nodes are more heterogeneously distributed in the network. Since more nodes move into a small number of popular cells, the time to be scheduled for a broadcast transmission in a popular cell becomes longer.

Compared with the delay performance of unicast, we find that for 2-hop scheme, delay increases by a factor of $\log k$ when $\alpha \leq 1$ and $k^{\frac{\alpha-1}{\alpha}} \log k$ when $\alpha > 1$. It indicates that location popularity has a negative impact on delay performance if we employ traditional 2-hop scheme for multicast. Compared with the delay of 3-hop scheme for unicast, delay increases by a factor of $(\log k)^{\frac{1}{1+\alpha}}$ for any α. This factor decreases with α, which implies that location popularity can contribute to closing the gap between the delay of unicast and multicast under 3-hop scheme. When $k = 1$, the results of this paper can recover the unicast delay results in [16].

Buffer: From Fig. 3(c), we can find that the minimal required buffer size for multicast transmissions satisfies $buffer = k \times capacity \times delay$ in location heterogeneity scenarios. Moreover, even though 3-hop scheme achieves better performance than 2-hop scheme, it requires smaller buffer space. It implies that the 3-hop scheme has higher information delivery efficiency and brings less backlog.

For 2-hop scheme, the buffer size is independent of α when $\alpha \leq 1$, and decreases as α when $\alpha > 1$, due to the reduction of transmission opportunities. It is worth mentioning that when $\alpha = \infty$, the required buffer size depends only the number of destinations. For 3-hop scheme, the buffer size decreases with α. The diminution of the buffer size is totally caused by quicker acceleration of transmissions in popular cells for $\alpha \leq 1$, while it is mainly dominated by the decay of transmission opportunities for $\alpha > 1$. When $\alpha = \infty$, all nodes crowd into the most popular cell. Then any node getting a transmission opportunity can broadcast the packet to all the nodes within the same cell, while nodes not belonging the group will drop the packet. In other words, a multicast transmission can complete in one transmission opportunity and only $\Theta(1)$ buffer size is needed for each node.

B. Multicast Performance With Redundancy

2-Hop Scheme: From Theorem 1 and Theorem 3, we see that 2-hop scheme with redundancy has better delay performance than 2-hop scheme without redundancy, with a sacrifice of capacity. The ratio between delay and capacity satisfies

$$\frac{E[W]}{\lambda} \geq \begin{cases} \Theta\left(n^{\frac{2\alpha-1}{\alpha}} k^{\frac{3\alpha-1}{2\alpha}} \log k\right), & \alpha > 1 \\ \Theta\left(\frac{nk \log k \log n}{\log\log n}\right), & \alpha = 1 \\ \Theta(nk \log k), & \alpha < 1 \end{cases} \tag{37}$$

which increases with α.

Moreover, as observed from Theorem 3, we can find that redundant packets transmissions can help reduce delay when α is small, and when α increases, their effects weaken. It indicates that redundancy cannot improve the performance effectively in location heterogeneity scenario when 2-hop scheme is employed. When $\alpha = 0$, our results can recover the fundamental trade-off for motioncast which is established in uniform scenarios, i.e., delay/rate $\geq \Theta(nk \log k)$ with $\Theta(\sqrt{n \log k})$ redundancy.

3-Hop Scheme: It is shown in Theorem 2 and Theorem 4 that when redundancy m is less than $E^2[n_a]$, redundant packets transmissions can further improve the delay performance of 3-hop scheme. And the improvement also comes at the expense of capacity. Interestingly, when m exceeds the threshold, the 3-hop scheme with redundancy will behave like the 2-hop scheme with redundancy and its performance will largely deteriorate. This is because when the number of initial duplicates is large enough, the acceleration mechanism of 3-hop scheme does not work and 3-hop scheme degenerates into 2-hop scheme, resulting in a large waste of node resource in popular cells.

Specially, when $m \leq E^2[n_a]$, the ratio between delay and capacity satisfies

$$\frac{E[W]}{\lambda} \geq \begin{cases} \Theta\left(n^{\frac{2\alpha^2-1}{\alpha(1+\alpha)}} k(\log k)^{\frac{1}{1+\alpha}}\right), & \alpha > 1 \\ \Theta\left(\frac{k\sqrt{n\log k}(\log n)^{\frac{3}{2}}}{\log\log n}\right), & \alpha = 1 \\ \Theta\left((n\log k)^{\frac{1}{1+\alpha}} k\right), & \alpha < 1 \end{cases} \tag{38}$$

where $E[n_a]$ is given by

$$E[n_a] = \begin{cases} \Theta\left(n^{\frac{1}{1+\alpha}} (\log k)^{\frac{\alpha}{1+\alpha}}\right), & \alpha > 1 \\ \Theta\left(\sqrt{\frac{n\log k}{\log n}}\right), & \alpha = 1 \\ \Theta\left((n\log k)^{\frac{\alpha}{1+\alpha}}\right), & \alpha < 1. \end{cases} \tag{39}$$

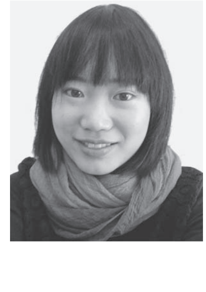
Compared to 2-hop scheme with redundancy, the delay/capacity ratio of 3-hop scheme decreases up to a factor of $\tilde{\Theta}(\sqrt{n\log k})$, which further verifies that 3-hop scheme can serve for multicast transmissions in location heterogeneity scenarios better. Moreover, we can achieve the best delay-capacity tradeoff when $\alpha = 1$. The intuitive explanation is as follows. The capacity is mainly contributed by transmissions in ordinary cells, while the delay improvement benefits from the transmissions in popular cells. When α is small, transmissions in ordinary cells are dominant. And when α is large, transmissions in popular cells play a main role. The best balance of transmissions between ordinary cells and popular cells appears when $\alpha = 1$, which implies an optimal tradeoff in such a scheme.

VI. Conclusion

In this paper, we study multicast performance of location-based MANETs, where users' mobility follows a location popularity distribution. We first investigate the delay, capacity and required buffer size under traditional 2-hop store-carry-forward paradigm. And we find that location popularity has a negative impact on delay and capacity performance. As the nodes' distribution becomes more diverse, the throughput will decrease and so does the buffer needed. Compared with unicast scenario, the capacity decreases by a factor of $1/k$, while delay remains almost unchanged when location diversity is moderate and increases with k when location diversity is sharp. Observed that traditional 2-hop scheme does not perform well in location heterogeneity scenarios, we further propose a 3-hop store-carry-accelerate-forward scheme for multicast scheduling. We show that the delay can improve up to a factor of $\Theta(\sqrt{n\log k})$ for some settings, without the expense of capacity. Moreover, it requires smaller buffer space than the 2-hop scheme, which indicates that it has a higher information delivery efficiency. For future work, it is interesting to investigate the performance of time-varying location popularity scenarios.

References

[1] P. Gupta and P. R. Kumar, "The capacity of wireless networks," *IEEE Trans. Inf. Theory*, vol. 46, no. 2, pp. 388–404, Mar. 2000.
[2] M. Franceschetti, O. Dousse, D. N. Tse, and P. Thiran, "Closing the gap in the capacity of wireless networks via percolation theory," *IEEE Trans. Inf. Theory*, vol. 53, no. 3, pp. 1009–1018, Mar. 2007.
[3] P. Li and Y. Fang, "The capacity of heterogeneous wireless networks," in *Proc. IEEE INFOCOM*, San Diego, CA, USA, Mar. 2010, pp. 1–9.
[4] W. Huang, X. Wang, and Q. Zhang, "Capacity scaling in mobile wireless Ad Hoc network with infrastructure support," in *Proc. IEEE ICDCS*, Genoa, Italy, Jun. 2010, pp. 848–857.
[5] M. Grossglauser and D. N. C. Tse, "Mobility increases the capacity of ad hoc wireless networks," *IEEE/ACM Trans. Netw.*, vol. 10, no. 4, pp. 477–486, Aug. 2002.
[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] X. Lin and N. B. Shroff, "The fundamental capacity-delay tradeoff in large mobile wireless networks," in *Proc. MedHocNet*, Bodrum, Turkey, Jun. 2004, pp. 1–13.
[8] M. Garetto and E. Leonardi, "Restricted mobility improves delay-throughput tradeoffs in mobile ad hoc networks," *IEEE Trans. Inf. Theory*, vol. 56, no. 10, pp. 5016–5029, Oct. 2010.
[9] K. Yoora, L. Kyunghan, N. B. Shroff, and R. Injong, "Revisiting delay-capacity tradeoffs for mobile networks: The delay is overestimated," in *Proc. IEEE INFOCOM*, Orlando, FL, USA, Mar. 2012, pp. 3041–3045.
[10] A. E. 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.
[11] X. Li, "Multicast capacity of wireless ad hoc networks," *IEEE/ACM Trans. Netw.*, vol. 17, no. 3, pp. 950–961, Jun. 2009.
[12] X. Wang, W. Huang, S. Wang, J. Zhang, and C. Hu, "Delay and capacity tradeoff analysis for motioncast," *IEEE/ACM Trans. Netw.*, vol. 19, no. 5, pp. 1354–1367, Oct. 2011.
[13] S. Zhou and L. Ying, "On delay constrained multicast capacity of large-scale mobile ad-hoc networks," in *Proc. IEEE INFOCOM*, San Diego, CA, USA, Mar. 2010, pp. 1–5.
[14] S. Karande, Z. Wang, H. Sadjadpour, and J. Garcia-Luna-Aceves, "Multicast throughput order of network coding in wireless ad-hoc networks," *IEEE Trans. Commun.*, vol. 59, no. 2, pp. 497–506, Feb. 2011.
[15] C. Wang, S. Tang, X. Li, and C. Jiang, "Multicast capacity scaling laws for multihop cognitive networks," *IEEE Trans. Mobile Comput.*, vol. 11, no. 11, pp. 1627–1639, Nov. 2012.
[16] J. Luo, J. Zhang, L. Yu, and X. Wang, "Impact of location popularity on throughput and delay in mobile ad hoc networks," *IEEE Trans. Mobile Comput.*, vol. 14, no. 5, pp. 1004–1017, May 2015.
[17] M. C. Gonzalez, C. A. Hidalgo, and A.-L. Barabasi, "Understanding individual human mobility patterns," *Nature*, vol. 453, pp. 779–782, Jun. 2008.
[18] C. Song, T. Koren, P. Wang, and A. Barabasi, "Modeling the scaling properties of human mobility," *Nature Phys.*, vol. 6, pp. 818–823, 2010.
[19] L. Pappalardo, S. Rinzivillo, Z. Qu, D. Pedreschi, and F. Giannotti, "Understanding the patterns of car travel," *Eur. Phys. J. Special Topics*, vol. 215, no. 1, pp. 61–73, 2013.
[20] M. Aamir and M. A. Zaidi, "A buffer management scheme for packet queues in MANET," *Tsinghua Sci. Technol.*, vol. 18, no. 6, pp. 543–553, Dec. 2013.
[21] M. J. Neely, E. Modiano, and C. E. Rohrs, "Dynamic power allocation and routing for time varying wireless networks," *IEEE J. Sel. Areas Commun.*, vol. 23, no. 1, pp. 89–103, Jan. 2005.



Jingjing Luo received the B.S. degree from the Department of Electronics and Information Engineering, Huazhong University of Science and Technology, Wuhan, China, in 2010, and is currently pursuing the Ph.D. degree in the Department of Electronics and Information Engineering, Huazhong University of Science and Technology, Wuhan, China.

Her current research interests include capacity scaling law and mobility models in wireless networks.

Jinbei Zhang received the B.S. degree in electronic engineering from Xidian University, Xi'an, China, in 2010, and is currently pursuing the Ph.D. degree in electronic engineering at Shanghai Jiao Tong University, Shanghai, China.

His current research interests include network security, capacity scaling law and mobility models in wireless networks.

Li Yu received the B.S. and Ph.D. degrees both from the Department of Electronics and Information Engineering, Huazhong University of Science and Technology, Wuhan, China, in 1992 and 1999, respectively. Currently, she is a Professor and serves as the Director of the Multimedia and Communication Network Center, Department of Electronics and Information Engineering, Huazhong University of Science and Technology, Wuhan.

Xinbing Wang (S'01–M'06–SM'12) received the B.S. degree (with hons.) from the Department of Automation, Shanghai Jiaotong University, Shanghai, China, in 1998, the M.S. degree from the Department of Computer Science and Technology, Tsinghua University, Beijing, China, in 2001, and the Ph.D. degree major in electrical and computer engineering, minor in mathematics from North Carolina State University, Raleigh, NC, USA, in 2006. Currently, he is a Professor in the Department of Electronic Engineering, Shanghai Jiaotong University, Shanghai, China. He has been an Associate Editor for IEEE/ACM TRANSACTIONS ON NETWORKING and IEEE TRANSACTIONS ON MOBILE COMPUTING, and a member of the Technical Program Committees of several conferences including ACM MobiCom 2012, ACM MobiHoc 2012 and 2013, and IEEE INFOCOM 2009–2014.