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# Multicast Capacity, Delay and Delay Jitter in Intermittently Connected Mobile Networks

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***Abstract*—Many important real networks can be modeled as intermittently connected mobile networks (ICMNs), like the vehicular ad hoc networks, wildlife tracking and habitat monitoring sensor networks, military networks, etc. However, the fundamental performance limits of ICMNs are still largely unknown so far. This paper explores the capability of these networks to support multicast traffic, where each source node desires to send packets to $k$ distinct destinations and all nodes move according to the generalized hybrid random walk mobility model. We show how the network capacity and related delay/delay jitter for supporting multicast in such ICMNs are scaling with the basic network parameters under three transmission protocols: one-hop relay, two-hop relay without packet redundancy and two-hop relay with packet redundancy.**

## I. Introduction

The intermittently connected mobile networks (ICMNs) are self-autonomous wireless networks without any infrastructure support or centralized management, where nodes are mostly partitioned and can transmit with each other only when they come into intermittent contact. The ICMN serves as a model for many important real network scenarios, like the military networks in battlefield, vehicular ad hoc networks, pocket switched personal networks and wildlife tracking and habitat monitoring networks [1]. Thus, understanding the basic performance limits of ICMNs is crucial for the design, optimization and engineering of such networks.

In ICMN-class networks, the connections from one source node to multiple destination nodes (multicast) will be required to support many important applications there, like the group communications and command delivery in military networks, wireless video conferences, mobile multimedia services [2], real-time traffic information reporting [3], diffusion and update of software patch [4], etc. However, the capability of ICMN-class networks to support multicast traffic remains largely unknown and, to the best our knowledge, only some initial results are available by now [5]. In [5], Lee *et al.* proposed RelayCast to improve the throughput bound of wireless multicast in delay tolerant networks and showed that the RelayCast can achieve a throughput of $\Theta(\min(1, \frac{n}{n_s n_d}))$, where $n_s$ is the number of source nodes and $n_d$ is the number destination nodes associated with each source node. This paper focuses on the study of fundamental performance scaling laws in ICMNs with multicast traffic.

Regarding the performance study of multicast capacity and related delay in mobile wireless networks, recently a lot of works have been done for the general mobile ad hoc networks (MANETs). In [6], Hu *et al.* established the multicast capacity and delay tradeoffs for the two-hop relay algorithms. Zhou *et al.* in [7] analyzed the delay constrained multicast capacity of large-scale MANETs, and proposed a joint coding/scheduling algorithm to achieve a throughput of $\Theta(\min\{1, \sqrt{\frac{D}{n_s}}\})$, where $D$ is the delay constraint and $n_s$ is the number of source nodes. Jose *et al.* explored the impact of mobility on multicast capacity in [8]. More recently, the optimal multicast capacity and delay trade-off in MANETs has also been explored in [9] from a global perspective. It is notable that all these works assume a fully connected MANET and consider a constant number of neighbors in each node's transmission range, so the throughput capacity there is mainly limited by the interference. For an ICMN, however, the nodes are sparsely distributed and mostly partitioned almost all the time, so its throughput capacity depends heavily on the contact rates among nodes. Due to these essential differences between ICMNs and MANETs, the available multicast capacity and delay results of MANETs can not be directly applied to characterize that of the ICMNs.

In this paper, we consider the multicast in a cell partitioned ICMN, where the network area is first evenly divided into $n^\gamma \times n^\gamma$ cells and each cell is then divided into $n^\beta \times n^\beta$ equal subcells ($\gamma, \beta \geq 0$, $\gamma + \beta > 1/2$). All nodes in the ICMN move according to the generalized hybrid random walk (HRW) mobility model [10] and each source node desires to send packets to $k$ distinct destinations. In addition to exploring the conventional throughput capacity and delay performances, we also address the delay jitter, a very important performance metric of multicast applications that was not properly explored in literature. The main results of this paper are as follows.

- For an ICMN adopting the one-hop relay routing, if it operates under the non-cooperative mode (i.e., for a traffic flow, the destination nodes will not help deliver their received packets to other destinations), the multicast capacity is $O(\frac{1}{\log k} n^{-2(\gamma+\beta)})$ while both the delay and delay jitter are $\Omega(\log k \cdot n^{2(\gamma+\beta)})$; when it operates under the cooperative mode (i.e., the destination nodes will also act as relays and help deliver their received packets), the multicast capacity is then $O(n^{-2(\gamma+\beta)})$ while both the delay and delay jitter become $\Omega(\log k \cdot n^{2(\gamma+\beta)})$.

- For an ICMN adopting the two-hop relay routing without packet redundancy (i.e., each packet may be delivered to at most one relay), if it operates under the non-cooperative mode, the multicast capacity is $O(\frac{1}{k \cdot \log k} \cdot n^{1-2(\gamma+\beta)})$ while both the delay and delay jitter are $\Omega(\log k \cdot n^{2(\gamma+\beta)})$; when it operates under the cooperative mode, the multicast capacity is then $O(\frac{1}{k} n^{1-2(\gamma+\beta)})$ while both delay and delay jitter become $\Omega(\log k \cdot n^{2(\gamma+\beta)})$.
- For an ICMN adopting the two-hop relay routing with packet redundancy $f$ (i.e., each packet may be delivered to at most $f$ distinct relays), the multicast capacity is $\Omega(\frac{1}{k \cdot f} \cdot n^{1-2(\gamma+\beta)})$ while the delay and delay jitter become $O\Big(\max\Big\{\log \frac{n-k}{n-k-f}, \frac{\log k}{f}\Big\} \cdot n^{2(\gamma+\beta)}\Big)$ and $\Omega(\frac{\log k}{f} \cdot n^{2(\gamma+\beta)})$, respectively.
- For an ICMN with any relay algorithm, its maximum multicast capacity is determined as $O(\frac{1}{k} \cdot n^{1-2(\gamma+\beta)})$, while for an ICMN adopting any relay algorithm without packet redundancy, both the minimum delay and the minimum delay jitter are determined as $\Omega(\log k \cdot n^{2(\gamma+\beta)})$.

The rest of this paper is outlined as follows. We introduce the system assumptions and definitions in Section II, then explore the multicast capacity, delay and delay jitter performances in Section III, and finally conclude the paper in Section IV.

## II. System Assumptions and Definitions

*Network Model:* The network considered in this paper is assumed to be a unit torus with $n$ mobile nodes in it. Similar to [10]–[12], we assume a time-slotted system and a cell-partitioned network structure. As illustrated in Fig. 1 that the unit torus is first evenly divided into $n^\gamma \times n^\gamma$ cells, and each cell is then divided into $n^\beta \times n^\beta$ equal subcells, where $\gamma \geq 0$, $\beta \geq 0$. As we consider a sparsely distributed ICMN, we set $\gamma + \beta > 1/2$. We further assume that each node adopts a transmission range of $\Theta(n^{-\gamma-\beta})$ and nodes can communicate with each other only when they are within the same subcell. According to the critical connectivity threshold $\Theta(\sqrt{\log n/n})$ in [13], we can see that under such setting the concerned network is ensured to be disconnected with high probability as $n$ scales up. We consider a limit channel bandwidth scenario such that the total number of bits that can be transmitted per time slot inside a subcell is fixed and normalized to one packet.

*Mobility Model:* Nodes move independently inside the network according to the generalized HRW mobility model [10]. As shown in Fig. 1 that at the beginning of each time slot, a node first selects a cell among all the $n^{2\gamma}$ cells and picks a subcell from its $n^{2\beta}$ subcells therein, then moves to the selected subcell and stays inside until the end of the time slot. Notice that the cell and subcell may be selected according to any probability mass function (pmf), and each node may follow its individual pmfs for cell selection and subcell selection. It's easy to see that the generalized HRW covers the hybrid random walk model [12] as a special case.

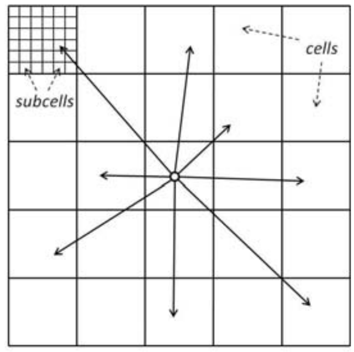


Fig. 1. A cell partitioned network model, where the network region is evenly divided into cells and subcells, and nodes move according to the generalized hybrid random walk mobility model. The subcell division of other cells and the mobility of other nodes are not shown for simplicity.

*Traffic Model:* We consider a multicast scenario in which there are in total $n_s$ source nodes and each source node has a locally generated traffic flow to be delivered to other $k$ randomly and independently selected destination nodes, where $(k+1)n_s \leq n$. For different source nodes, their destination node sets have no common nodes. Except the $(k+1)n_s$ nodes involved in these $n_s$ flows, the remaining $n-(k+1)n_s$ nodes have no traffic to generate or receive and they will serve as pure relays for these flows. We assume that the traffic flow originated at each source node is a Poisson stream with average rate $\lambda$ (packets/slot), where the packet arrival process is independent of node mobility process and all packets arrive at the beginning of time slots.

*Throughput Capacity:* We call a traffic input rate $\lambda$ (packets/slot) feasible or achievable if there exists a spatial and temporal scheduling algorithm such that each node can send at an average rate of $\lambda$ packets per slot to all its $k$ destinations, i.e., under such an input rate the queue length at each node will never increase to infinity as the time goes to infinity. The per node throughput capacity is then defined as the maximum feasible input rate $\lambda$. Without incurring any ambiguity, hereafter we call such capacity as throughput capacity for brevity.

*Delay and Delay Jitter:* Different from [14], [15], we consider in this paper the end-to-end delay of a packet including the queuing delay at its source. The delay of a packet is then defined as the time it takes for the packet to reach all its $k$ destinations after it arrives at its source. The delay jitter for a packet is defined as the time it takes for the packet to reach its last destination after it reaches its first destination. The expected end-to-end delay and expected delay jitter are then obtained by averaging over all packets of the $n_s$ traffic flows in the long term.

*Cooperative Mode and Non-cooperative Mode:* For any traffic flow, if its destination nodes will help deliver their received packets to other destinations, we say there is cooperation in the network and the corresponding relay algorithm is under the cooperative mode. Otherwise, we say there is no cooperation in the network and the corresponding relay algorithm is under non-cooperative mode.

*Order Notations:* Given non-negative functions $f(n)$ and $g(n)$: (1) $f(n) = O(g(n))$ means that there exist positive constant $c$ and integer $N$ such that $f(n) \leq cg(n)$ for all $n > N$. (2) $f(n) = \Omega(g(n))$ means that $g(n) = O(f(n))$. (3) $f(n) = \Theta(g(n))$ means that $f(n) = O(g(n))$ and $f(n) = \Omega(g(n))$. (4) $f(n) = o(g(n))$ means that $\lim_{n\to\infty} \frac{f(n)}{g(n)} = 0$. (5) $f(n) = \omega(g(n))$ means that $g(n) = o(f(n))$.

## III. Multicast Capacity, Delay and Delay Jitter

In this section, we first analyze the intermeeting times between any two nodes when they move according to the generalized HRW mobility model, and then use it to develop the multicast capacity, delay and delay jitter in ICMNs under different relay scenarios.

### A. Intermeeting Times Between Two Nodes

Consider a tagged node, say node $A$, moving according to the generalized HRW mobility model. We denote by $\mathcal{C}$ the set of all $n^{2\gamma}$ cells and denote by $C_A(t) \in \mathcal{C}$ the cell selected by node $A$ for time slot $t$. Hence,

$$\mathbf{C}_A := \{C_A(t); t = 0, 1, \ldots\}$$

is a discrete-time stochastic process which records the moving trajectory of $A$ among $n^{2\gamma}$ cells. Similar to [10], we assume that for any node $A$, it adopts an individual pmf such that $\mathbf{C}_A$ is an irreducible and aperiodic Markov chain process. Then we have the following results regarding the intermeeting times between two nodes [10].

*Theorem 1:* For any two nodes $A$ and $B$, we denote by $\mathbf{I} := \{I(j); j = 1, 2, \ldots\}$ the intermeeting times between $A$ and $B$, and denote by $p_c$ the probability that nodes $A$ and $B$ are in contact conditional on the event that they are in the same cell. If $p_c > 0$ and $\lim_{n\to\infty} p_c = 0$, then we have the following distributional convergence:

$$\lim_{n\to\infty} \Pr\left[\frac{I(2)}{n^{2\gamma}/p_c} \leq x\right] = \begin{cases} 1 - e^{-x} & \text{if } x > 0, \\ 0 & \text{if } x \leq 0. \end{cases} \quad (1)$$

Based on Theorem 1, we can establish the following lemma.

*Lemma 1:* If we set $\beta > 0$ and assume that each node adopts the discrete uniform distribution for subcell selection at the beginning of each time slot, as $n$ scales up the intermeeting times $I(j)$ between any two nodes obeys the following distribution when $j \geq 2$.

$$\Pr[I(j) \leq x] = \begin{cases} 1 - e^{-n^{-2(\gamma+\beta)} \cdot x} & \text{if } x > 0, \\ 0 & \text{if } x \leq 0. \end{cases} \quad (2)$$

*Proof:* Theorem 1 tells us that for sufficiently large $n$, the intermeeting times $I(2)$ can be well approximated using exponential random variables (rvs) with mean $n^{2\gamma}/p_c$. As each node selects a subcell according to the discrete uniform distribution, then $p_c = 1/n^{2\beta}$. It's easy to see that when $\beta > 0$, we have $p_c > 0$ and $\lim_{n\to\infty} p_c = 0$. Thus, after applying Theorem 1, we have that as $n$ scales up, $I(2)$ follows an exponential distribution with mean $n^{2(\gamma+\beta)}$. Since the rvs $I(j)$, $j \geq 2$, are i.i.d. rvs, then (2) follows. ■

*Remark 1:* As indicated in [10] that (1) holds even for nonnegligible values of $p_c$, which implies that as $n$ scales up, (2) can provide an accurate approximation for the intermeeting times $I(j)$, $j \geq 2$. Since $I(1)$ depends also on the initial locations of nodes $A$ and $B$ and does not refer to a real intermeeting time between two consecutive meetings, we consider only the case when $j \geq 2$ in our scaling law analysis.

### B. Under One-hop Relay

Without loss of generality, we focus on a tagged multicast flow in the following analysis. For the tagged flow, we denote by $S$ its source and denote by $\{D_1, D_2, \ldots, D_k\}$ the set of associated destinations.

Under the one-hop relay algorithm, a destination of the tagged flow can only receive each packet either from the source $S$ or from some other destination which has already received the packet. In other words, aside from its source and the destinations, no other nodes will serve as the relay for the tagged flow under the one-hop relay algorithm.

*Case 1: Non-cooperative Mode*

As illustrated in Fig. 2 that when operating under the non-cooperative mode, each destination of the tagged flow can only receive packet(s) from the $S$. Then we have the following theorem.

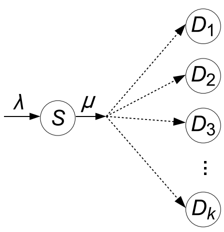


Fig. 2. With the one-hop relay algorithm under non-cooperative mode, a decoupled diagram of the network as seen by the packets transmitted from the tagged source $S$ to the corresponding destinations.

*Theorem 2:* For the one-hop relay algorithm under non-cooperative mode, we denote by $\mu$ the multicast throughput capacity, denote by $T_e$ the end-to-end delay and denote by $J_d$ the delay jitter. If the locally generated traffic at $S$ is a Poisson stream with average rate $\lambda$ (packets/slot), as $n$ scales up

$$\mu = O(\frac{1}{\log k} \cdot n^{-2(\gamma+\beta)}) \quad (3)$$

$$\mathbb{E}\{T_e\} = \Omega(\log k \cdot n^{2(\gamma+\beta)}) \quad (4)$$

$$\mathbb{E}\{J_d\} = \Omega(\log k \cdot n^{2(\gamma+\beta)}) \quad (5)$$

*Proof:* Consider a packet newly arrived at the head-of-line (HoL) of the local-queue of $S$. As $S$ needs to deliver out $k$ copies of this packet (one copy for each destination), we denote by $X_i$ the time it takes $S$ to deliver out the $i_{th}$ copy, where $1 \leq i \leq k$. If we further denote by $X$ the total service time of this packet at $S$, then we have

$$X = \sum_{i=1}^{k} X_i \quad (6)$$

From Lemma 1 we can easily see that the time a destination takes to receive this packet is an exponentially distributed rv with mean $n^{2(\gamma+\beta)}$. Thus, $X_1$ can be treated as the minimum one out of $k$ i.i.d. exponential rvs, and similarly, and $X_i$ can be treated as the minimum one out of $k+1-i$ i.i.d. exponential rvs, where $1 \le i \le k$. Then we have

$$\mathbb{E}\{X_i\} = \frac{1}{k+1-i} n^{2(\gamma+\beta)} \tag{7}$$

By taking the expectation for both sides of (6), we then have

$$\begin{aligned}\mathbb{E}\{X\} &= \sum_{i=1}^{k} \frac{1}{k+1-i} n^{2(\gamma+\beta)} \\ &= n^{2(\gamma+\beta)}(1+\frac{1}{2}+\frac{1}{3}+\cdots+\frac{1}{k}) \\ &= n^{2(\gamma+\beta)}(\ln(k+1)+r_0) \\ &= \Omega(\log k \cdot n^{2(\gamma+\beta)})\end{aligned} \tag{8}$$

where $r_0$ is the *Euler constant*.

Since the service time $X$ can also be treated as the maximum of $k$ exponentially distributed rvs with mean $n^{2(\gamma+\beta)}$, the cumulative distribution function of $X$ is

$$\begin{aligned}\Pr(X \le x) &= (1-e^{-n^{-2(\gamma+\beta)}x})^k \\ &= \sum_{t=0}^{k} \binom{k}{t} (-1)^t e^{-n^{-2(\gamma+\beta)} \cdot t \cdot x}\end{aligned} \tag{9}$$

Then we can see

$$\begin{aligned}\mathbb{E}\{X^2\} &= \sum_{t=1}^{k} \binom{k}{t} (-1)^t \int_0^\infty x^2 \mathrm{d} e^{-n^{-2(\gamma+\beta)} \cdot t \cdot x} \\ &= 2n^{4(\gamma+\beta)} \sum_{t=1}^{k} \binom{k}{t} (-1)^{t-1} \frac{1}{t^2} \\ &= 2n^{4(\gamma+\beta)} \Big(1+\sum_{t=2}^{k} \frac{\log t}{t}\Big) \\ &= O(\log^2 k \cdot n^{4(\gamma+\beta)})\end{aligned} \tag{10}$$

Based on (8) and (10), for the $M/G/1$ queue at node $S$, we can see that the mean residual service time $\mathbb{E}\{R\} = \frac{\mathbb{E}\{X^2\}}{2\mathbb{E}\{X\}}$ is $O(\log k \cdot n^{2(\gamma+\beta)})$. Thus, the mean service rate $\mu$ can be determined as

$$\mu = O(\frac{1}{\log k} \cdot n^{-2(\gamma+\beta)}) \tag{11}$$

Based on the queueing theory [16], the expected end-to-end delay $\mathbb{E}\{T_e\}$ can then be determined as

$$\begin{aligned}\mathbb{E}\{T_e\} &= \frac{\rho_0 \mathbb{E}\{R\}}{1-\rho_0} + \mathbb{E}\{X\} \\ &= \Omega(\log k \cdot n^{2(\gamma+\beta)})\end{aligned} \tag{12}$$

where $\rho_0 = \lambda/\mu$. Regarding the delay jitter $J_d$, we have

$$J_d = \sum_{i=2}^{k} X_i \tag{13}$$

Using a similar derivation, $J_d$ can be determined as

$$\begin{aligned}\mathbb{E}\{J_d\} &= n^{2(\gamma+\beta)}(\ln(k)+r_0) \\ &= \Omega(\log k \cdot n^{2(\gamma+\beta)})\end{aligned} \tag{14}$$

Then we finish the proof for Theorem 2. ■

*Case 2: Cooperative Mode*

Consider a packet newly arrived at the HoL of the local-queue of $S$. As shown in Fig. 3 that when operating under the cooperative mode, except for the first destination which receives this packet from $S$, the other $k-1$ destinations will receive the packet from the first destination. Therefore, after delivering the packet to the first destination, $S$ moves the packet out of the local-queue and proceeds to deliver the next packet waiting right behind it.

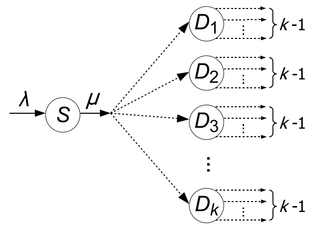


Fig. 3. With the one-hop relay algorithm under the cooperative mode, a decoupled diagram of the network as seen by the packets transmitted from the tagged source $S$ to the corresponding destinations.

*Theorem 3:* For the one-hop relay algorithm under cooperative mode, if the locally generated traffic at $S$ is a Poisson stream with average rate $\lambda$ (packets/slot), as $n$ scales up

$$\mu = O(n^{-2(\gamma+\beta)}) \tag{15}$$

$$\mathbb{E}\{T_e\} = \Omega(\log k \cdot n^{2(\gamma+\beta)}) \tag{16}$$

$$\mathbb{E}\{J_d\} = \Omega(\log k \cdot n^{2(\gamma+\beta)}) \tag{17}$$

*Proof:* For a new HoL packet, it will experience the following two queueing process until received by all $k$ destinations: the queueing process at the local-queue of $S$ and the queueing process at the relay-queues of its first destination. We denote the first sojourn time by $T_s^{(1)}$ and denote the second one by $T_s^{(2)}$.

For the new HoL packet, we first focus on its queueing process at $S$. Since for each packet waiting in the local-queue, $S$ only delivers it to the first destination, the actual service time $X$ at $S$ can then be determined as the time it takes for $S$ to deliver out the first copy, i.e., $X = X_1$. According to (7), we have

$$\mathbb{E}\{X\} = \frac{1}{k} n^{2(\gamma+\beta)} \tag{18}$$

Thus, we have

$$\mathbb{E}\{T_s^{(1)}\} = \frac{1}{1-\rho_1} \frac{n^{2(\gamma+\beta)}}{k} \tag{19}$$

$$= \Omega(\frac{1}{k} n^{2(\gamma+\beta)}) \tag{20}$$

where $\rho_1 = \frac{\lambda}{k} n^{2(\gamma+\beta)}$ and

$$\lambda < k \cdot n^{-2(\gamma+\beta)} \tag{21}$$

Without loss of generality, we simply assume that node $D_1$ is the first destination node to receive this packet. Now we proceed to analyze the queuing process at node $D_1$.

Since the $M/M/1$ queue at the local-queue of $S$ is reversible, the output process from $S$ is also a Poisson stream with average rate $\lambda$ (packets/slot). As each of the $k$ destinations has the same probability to become $D_1$, the actual traffic input rate to $D_1$ is $\frac{\lambda}{k}$. After $D_1$ receives the packet, $D_1$ first duplicates it into $k-1$ copies (one copy for each $D_i$, $2 \leq i \leq k$), then puts a copy to the end of each relay-queue specified for each destination. Notice that the rate of removing a copy from the relay-queues of $D_1$ (i.e., the rate of meeting one specific other destination node) is $n^{-2(\gamma+\beta)}$. Thus, the relay-queue occupancy variation process at $D_1$ can be characterized by a birth/death chain with birth rate $n^{-2(\gamma+\beta)}$ and death rate $\frac{k-1}{k} \cdot \lambda$, which in turn enables the queueing process at $D_1$ to be treated as a $M/M/1$ queue.

With a little abuse of notations, we use $X_i$ to denote the time it takes for the node $D_i$ to receive a copy from $D_1$ (after $D_1$ receives this packet), $2 \leq i \leq k$. Then we have

$$\mathbb{E}\{X_i\} = \frac{1}{n^{-2(\gamma+\beta)} - \frac{k-1}{k} \cdot \lambda} \tag{22}$$

Thus, the sojourn time of this packet at $D_1$ is determined as

$$T_s^{(2)} = \max\{X_2, X_3, \ldots, X_k\} \tag{23}$$

Since $X_i$ ($2 \leq i \leq k$) is an exponentially distributed rv and the rvs $X_2, X_3, \ldots, X_k$ are mutually independent, thus

$$\mathbb{E}\{T_s^{(2)}\} = \frac{\ln k + r_0}{\mathbb{E}\{X_i\}} \tag{24}$$

$$= \Omega\Big(\frac{\log k \cdot n^{2(\gamma+\beta)}}{1-\rho_2}\Big) \tag{25}$$

where $\rho_2 = \frac{k-1}{k}\lambda \cdot n^{2(\gamma+\beta)}$, (24) follows after applying Lemma 2 in [6] and (25) follows after substituting (22) into (24).

Based on (19) and (24), the expected end-to-end delay $\mathbb{E}\{T_e\}$ (of the tagged packet) can be determined as

$$\begin{aligned}\mathbb{E}\{T_e\} &= \mathbb{E}\{T_s^{(1)}\} + \mathbb{E}\{T_s^{(2)}\} \\ &= \frac{1}{1-\rho_1}\frac{n^{2(\gamma+\beta)}}{k} + \frac{\ln k + r_0}{1-\rho_2} n^{2(\gamma+\beta)} \\ &= \Omega\Big(\max\Big\{\frac{1}{k}, \log k\Big\} \cdot n^{2(\gamma+\beta)}\Big) \qquad (26) \\ &= \Omega(\log k \cdot n^{2(\gamma+\beta)}) \qquad (27)\end{aligned}$$

To ensure the stability of the relay-queues at $D_1$, i.e., the relay-queue length will not grow to infinity, we should have

$$\lambda < \frac{k}{k-1} n^{-2(\gamma+\beta)} \tag{28}$$

Combining (21) and (28), the throughput capacity can be determined as

$$\begin{aligned}\mu &= \min\Big\{k \cdot n^{-2(\gamma+\beta)}, \frac{k}{k-1} n^{-2(\gamma+\beta)}\Big\} \\ &= O(n^{-2(\gamma+\beta)}) \qquad (29)\end{aligned}$$

Regarding the delay jitter, it is easy to see that

$$\mathbb{E}\{J_d\} = \mathbb{E}\{T_s^{(2)}\} = \Omega(\log k \cdot n^{2(\gamma+\beta)}) \tag{30}$$

Then we finish the proof for Theorem 3. ■

*Remark 2:* By comparing the multicast capacity, delay and delay jitter derived under the one-hop relay algorithm with the non-cooperative mode and with the cooperative mode, we can see that by allowing the destinations to help deliver their received packets, the throughput capacity is improved from $O(\frac{1}{\log k} \cdot n^{-2(\gamma+\beta)})$ to $O(n^{-2(\gamma+\beta)})$, while the delay and delay jitter performances remain the same as $\Omega(\log k \cdot n^{2(\gamma+\beta)})$ under both modes.

### *C. Under Two-hop Relay Without Packet Redundancy*

Under the two-hop relay algorithm, a node can be simultaneously a source (destination) and a relay for multiple flows. To simply our analysis, we assume that when two nodes need to contend for becoming the transmitter, each of them has the equal probability to become the transmitter. In the case that a transmitter can transmit a packet either as a source ("source-to-relay" transmission) or as a relay ("relay-to-destination" transmission), then it conducts either transmission with the same probability of $1/2$.

*Case 1: Non-cooperative Mode*

As shown in Fig. 4 that when operating under the non-cooperative mode, except the nodes $S$ and $D_i$ ($1 \leq i \leq k$) of the tagged flow all other $n-1-k$ nodes will serve as the relay of the flow. Notice that these $n-1-k$ relays can be further classified into three different groups: the $n_s - 1$ sources, the $(n_s-1)k$ destinations and the $n-(k+1)n_s$ pure relays. If we denote these three groups by $G_1$, $G_2$ and $G_3$, respectively, then we can establish the following theorem.

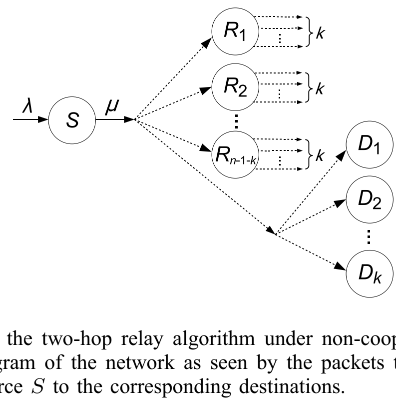


Fig. 4. With the two-hop relay algorithm under non-cooperative mode, a decoupled diagram of the network as seen by the packets transmitted from the tagged source $S$ to the corresponding destinations.

*Theorem 4:* For the two-hop relay algorithm under the non-cooperative mode, if the locally generated traffic at $S$ is a Poisson stream with average rate $\lambda$ (packets/slot), as $n$ scales up we have

$$\mu = O(\frac{1}{k \cdot \log k} \cdot n^{1-2(\gamma+\beta)}) \tag{31}$$

$$\mathbb{E}\{T_e\} = \Omega(\log k \cdot n^{2(\gamma+\beta)}) \tag{32}$$

$$\mathbb{E}\{J_d\} = \Omega(\log k \cdot n^{2(\gamma+\beta)}) \tag{33}$$

*Proof:* Consider a new HoL packet at $S$. Under the two-hop relay algorithm, the packet may reach its destinations either via a node from $G_1$, $G_2$ and $G_3$ or directly from $S$.

We first focus on the cases that this packet is routed from a node of groups $G_1$, $G_2$ and $G_3$. Without loss of generality, we assume that this packet is routed to its destinations via a node (say node $S^{'}$ ) of $G_1$, i.e., a node from the $n_s - 1$ sources. It is easy to see that the end-to-end delay of the packet consists of two parts, the sojourn time in the local-queue of $S$ and the sojourn time in the relay-queues of $S^{'}$. We denote the first sojourn time by $T_s^{(1)}$ and denote the second one by $T_g^{(1)}$.

Notice that the rate for $S$ to deliver out this packet can be determined as

$$n^{-2(\gamma+\beta)}\Big(\frac{n_s-1}{2}+\frac{(n_s-1)k}{2}+(n-(k+1)n_s)+k\Big) = \varphi\cdot n^{-2(\gamma+\beta)} \quad (34)$$

where $\varphi = n - \frac{(k+1)n_s}{2} + \frac{k-1}{2}$.

Thus, the expected sojourn time at $S$ is given by

$$T_s^{(1)} = \frac{\frac{1}{\varphi}n^{2(\gamma+\beta)}}{1-\rho_3} \quad (35)$$

where $\rho_3 = \frac{\lambda}{\varphi}\cdot n^{2(\gamma+\beta)}$ and

$$\lambda < \varphi\cdot n^{-2(\gamma+\beta)} \quad (36)$$

Now we proceed to explore the sojourn time $T_g^{(1)}$ at $S^{'}$. If we denote by $P_g^{(1)}$ the probability that $S$ delivers this packet to $G_1$, then we have

$$P_g^{(1)} = \frac{n_s-1}{2\varphi} \quad (37)$$

The probability that $S$ delivers this packet to $S^{'}$ can then be determined as

$$\frac{n^{-2(\gamma+\beta)}/2}{\varphi\cdot n^{-2(\gamma+\beta)}} = \frac{1}{2\varphi} \quad (38)$$

Thus, the traffic input rate from $S$ into $S^{'}$ is just $\frac{\lambda}{2\varphi}$.

After $S^{'}$ receives this packet, $S^{'}$ first duplicates this packet into $k$ copies, and then puts a copy to the relay-queue specified for each destination of this packet. Thus, the relay-queue occupancy state at $S^{'}$ can be characterized by a birth/death chain with birth rate $\frac{1}{2}n^{-2(\gamma+\beta)}$ and death rate $\frac{k\cdot\lambda}{2\varphi}$. Then the time it takes for a specific destination node of this packet to receive this packet from $S^{'}$ is the sojourn time in the corresponding $M/M/1$ queue at $S^{'}$, i.e., $\frac{2n^{2(\gamma+\beta)}}{1-\rho_4}$, where $\rho_4 = \frac{k\lambda}{\varphi}n^{2(\gamma+\beta)}$ and

$$\lambda < \frac{\varphi}{k}\cdot n^{-2(\gamma+\beta)} \quad (39)$$

Since the sojourn time $T_g^{(1)}$ is the time it takes for the last destination node to receive this packet from $S^{'}$, we have

$$\mathbb{E}\{T_g^{(1)}\} = \frac{2(\ln(k+1)+r_0)}{1-\rho_4}n^{2(\gamma+\beta)} \quad (40)$$

Similarly, if we denote by $P_g^{(2)}$ the probability that this packet is routed via a $G_2$ node, and denote by $T_g^{(2)}$ the sojourn time of this packet in the $G_2$ node, then we have

$$P_g^{(2)} = \frac{(n_s-1)k}{2\varphi} \quad (41)$$

$$\mathbb{E}\{T_g^{(2)}\} = \frac{2(\ln(k+1)+r_0)}{1-\rho_4}n^{2(\gamma+\beta)} \quad (42)$$

If we denote by $P_g^{(3)}$ the probability that this packet is routed via a $G_3$ node, and denote by $T_g^{(3)}$ the sojourn time of this packet in the $G_3$ node, then we have

$$P_g^{(3)} = \frac{n-(k+1)n_s}{\varphi} \quad (43)$$

$$\mathbb{E}\{T_g^{(3)}\} = \frac{\ln(k+1)+r_0}{1-\rho_4}n^{2(\gamma+\beta)} \quad (44)$$

Now we proceed to explore the case that this packet is routed directly from $S$ to its destinations. We denote by $P_s$ the probability that this packet is routed directly by $S$ to its $k$ destinations, and denote by $T_s^{(v)}$ the time it takes $S$ to deliver the packet to the other remaining $k-1$ destinations. It is easy to see that

$$P_s = \frac{k}{\varphi} \quad (45)$$

Using derivations similar to that for Theorem 2, we have

$$\mathbb{E}\{T_s^{(v)}\} = (\ln k + r_0)n^{2(\gamma+\beta)} \quad (46)$$

Thus, the input rate of this part of traffic is determined as

$$P_s\cdot\lambda < \frac{1}{\ln k + r_0}n^{-2(\gamma+\beta)} \quad (47)$$

From (45) we then have

$$\lambda < \frac{\varphi}{k\cdot\log k}n^{-2(\gamma+\beta)} \quad (48)$$

Based on (37), (40), (41), (42), (43), (44), (45) and (46), the expected end-to-end delay can be determined as

$$\begin{aligned}\mathbb{E}\{T_e\} &= \mathbb{E}\{T_s^{(1)}\} + \sum_{i=1}^{3} P_g^{(i)}\cdot\mathbb{E}\{T_g^{(i)}\} + P_s\cdot\mathbb{E}\{T_s^{(v)}\} \\ &= \frac{n^{2(\gamma+\beta)}}{\varphi}\Big(\frac{1}{1-\rho_3} + \frac{n-k-1}{1-\rho_4}\log k + k\cdot\log k\Big) \\ &= \Omega\left(\log k\cdot n^{2(\gamma+\beta)}\cdot\frac{(n-k)c_1+k}{n-\frac{(k+1)n_s}{2}+\frac{k-1}{2}}\right) \\ &= \Omega(\log k\cdot n^{2(\gamma+\beta)})\end{aligned} \quad (49)$$

By combining (36), (39) and (48), the throughput capacity can then be determined as

$$\begin{aligned}\lambda &< \frac{\varphi}{k\cdot\log k}n^{-2(\gamma+\beta)} \\ &= O(\frac{1}{k\cdot\log k}\cdot n^{1-2(\gamma+\beta)})\end{aligned} \quad (50)$$

Regarding the delay jitter $\mathbb{E}\{J_d\}$, we have

$$\mathbb{E}\{J_d\} = \frac{n^{2(\gamma+\beta)}}{\varphi}\Big(\frac{n-k-1}{1-\rho_4}\log k + k\cdot\log k\Big)$$
$$= \Omega(\log k \cdot n^{2(\gamma+\beta)}) \qquad (51)$$

We then finish the proof for Theorem 4. ∎

*Case 2: Cooperative Mode*

As shown in Fig. 5 that when operating under the cooperative mode, the destination node that is the first one to receive a packet will also act as a relay helping forward the received packet to other remnant $k-1$ destinations. From the perspective of the source node $S$, $S$ will not discriminate the $k$ destinations and other $n-1-k$ nodes, which is the basic difference from that of the non-cooperative mode.

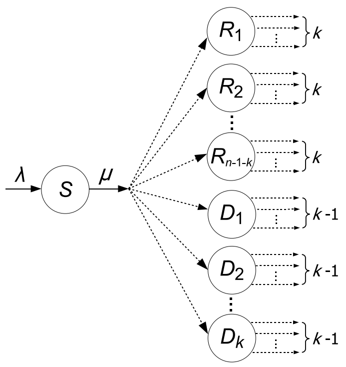


Fig. 5. With the two-hop relay algorithm under cooperative mode, a decoupled diagram of the network as seen by the packets transmitted from the tagged source $S$ to the corresponding destinations.

*Theorem 5:* For the two-hop relay algorithm under the cooperative mode, if the locally generated traffic at $S$ is a Poisson stream with average rate $\lambda$ (packets/slot), as $n$ scales up we have

$$\mu = O(\frac{1}{k}\cdot n^{1-2(\gamma+\beta)}) \qquad (52)$$
$$\mathbb{E}\{T_e\} = \Omega(\log k \cdot n^{2(\gamma+\beta)}) \qquad (53)$$
$$\mathbb{E}\{J_d\} = \Omega(\log k \cdot n^{2(\gamma+\beta)}) \qquad (54)$$

*Proof:* As shown in Fig. 5 that for a new HoL packet at $S$, it may also be routed to its destinations via the destination node that receives it first. If we denote the group of $k$ destinations by $G_4$ and define $G_1$, $G_2$ and $G_3$ in the same way as that in Theorem 4, then we can see that this packet can be routed via a node from $G_1$, $G_2$, $G_3$ or $G_4$ .

By comparing with the packet delivery process under the non-cooperative mode, we can see that the only difference is the case when the packet is routed via a node of $G_4$. If we denote by $P_g^{(4)}$ the probability that this packet is routed via a $G_4$ node, and denote by $T_g^{(4)}$ the sojourn time of this packet in the $G_4$ node, then we have

$$P_g^{(4)} = \frac{k}{\varphi} \qquad (55)$$

Using the derivations similar to that for Theorem 3, we have

$$\mathbb{E}\{T_g^{(4)}\} = \frac{2(\ln k + r_0)}{1-\rho_5}n^{2(\gamma+\beta)} \qquad (56)$$

where $\rho_5 = \frac{2(k-1)\lambda}{\varphi}n^{2(\gamma+\beta)}$ and

$$\lambda < \frac{\varphi}{2(k-1)}n^{-2(\gamma+\beta)} \qquad (57)$$

Thus, the end-to-end delay can be determined as

$$\mathbb{E}\{T_e\} = \mathbb{E}\{T_s^{(1)}\} + \sum_{i=1}^{4} P_g^{(i)}\cdot\mathbb{E}\{T_g^{(i)}\}$$
$$= \frac{n^{2(\gamma+\beta)}}{\varphi}\Big(\frac{1}{1-\rho_3} + \frac{n-k-1}{1-\rho_4}\log k + \frac{2k\log k}{1-\rho_5}\Big)$$
$$= \Omega\left(\log k\cdot n^{2(\gamma+\beta)}\cdot\frac{(n-k)c_1 + k\cdot c_2}{n - \frac{(k+1)n_s}{2} + \frac{k-1}{2}}\right)$$
$$= \Omega(\log k \cdot n^{2(\gamma+\beta)}) \qquad (58)$$

Combining (36), (39) and (57), the throughput capacity can be determined as

$$\lambda < \frac{\varphi}{2(k-1)}n^{-2(\gamma+\beta)}$$
$$= O(\frac{1}{k}\cdot n^{1-2(\gamma+\beta)}) \qquad (59)$$

Regarding the delay jitter $\mathbb{E}\{J_d\}$, we have

$$\mathbb{E}\{J_d\} = \frac{n^{2(\gamma+\beta)}}{\varphi}\Big(\frac{n-k-1}{1-\rho_4}\log k + \frac{2k\log k}{1-\rho_5}\Big)$$
$$= \Omega(\log k \cdot n^{2(\gamma+\beta)}) \qquad (60)$$

This finishes the proof for Theorem 5. ∎

## D. Under Two-hop Relay With Packet Redundancy

As indicated in [11] that throughput can be traded with delay performance by introducing packet redundancy in packet delivery process. In this section, we proceed to explore the multicast capacity, delay and delay jitter under the two-hop relay algorithm with packet redundancy. Specifically, we assume that for each packet, $S$ will deliver it to at most $f$ distinct relays, and each relay will then help forward the packet to all destinations. Since the relay node can only send its carried packet to the destinations, each packet travels at most two hops to reach its destinations. As we do not discriminate the $k$ destinations and other $n-1-k$ nodes, and thus any node which receives a copy from $S$ will act as a relay.

*Theorem 6:* For the two-hop relay algorithm with packet redundancy $f$ (i.e., each packet may be delivered to at most $f$ distinct relays), if the locally generated traffic at $S$ is a Poisson stream with average rate $\lambda$ (packets/slot), as $n$ scales up we have

$$\mu = \Omega(\frac{1}{k\cdot f}\cdot n^{1-2(\gamma+\beta)}) \qquad (61)$$
$$\mathbb{E}\{T_e\} = O\left(\max\left\{\log\frac{n-k}{n-k-f}, \frac{\log k}{f}\right\}\cdot n^{2(\gamma+\beta)}\right) \qquad (62)$$
$$\mathbb{E}\{J_d\} = \Omega(\frac{\log k}{f}\cdot n^{2(\gamma+\beta)}) \qquad (63)$$

*Proof:* Consider a new HoL packet at $S$. From Theorem 5, it is trivial to see that

$$\mu = \Omega(\frac{1}{k \cdot f} \cdot n^{1-2(\gamma+\beta)}) \tag{64}$$

Now we proceed to explore the delay and delay jitter. We simply assume the new HoL packet will experience two processes: first $S$ delivers it to $f$ distinct relay nodes, then the $f$ relay nodes forward it to the destinations. We denote the delay of the first process and the second process by $T_e^{(1)}$ and $T_e^{(2)}$, respectively. It is easy to see that the packet delay derived under this two processes will provide an upper bound for $\mathbb{E}\{T_e\}$. Thus, we have

$$\mathbb{E}\{T_e\} \leq \mathbb{E}\{T_e^{(1)}\} + \mathbb{E}\{T_e^{(2)}\} \tag{65}$$

Regarding the first process, we consider such a case that all the $f$ relays belong to the other $n-1-k$ nodes, i.e., no one from the set $\{D_1, D_2, \dots, D_k\}$ has received a copy. Obviously, the delay derived under this case serves as an upper bound for the $\mathbb{E}\{T_e^{(1)}\}$. Thus, we have

$$\begin{aligned}\mathbb{E}\{T_e^{(1)}\} &\leq n^{2(\gamma+\beta)} \cdot \sum_{i=1}^{f} \frac{1}{n-k-i} \\ &= n^{2(\gamma+\beta)} \Big( \sum_{i=1}^{n-1-k} \frac{1}{i} - \sum_{j=1}^{n-1-k-f} \frac{1}{j} \Big) \\ &= n^{2(\gamma+\beta)} \Big( \ln(n-k) - \ln(n-k-f) \Big) \\ &= n^{2(\gamma+\beta)} \cdot \log \frac{n-k}{n-k-f} \end{aligned} \tag{66}$$

In the second process, we consider such a case that after receiving the packet from relay, any destination node will not help forward its received packet to other remnant destinations. Obviously, the delay derived under this case serves as an upper bound for $\mathbb{E}\{T_e^{(2)}\}$. Thus, we have

$$\begin{aligned}\mathbb{E}\{T_e^{(2)}\} &\leq n^{2(\gamma+\beta)} \cdot \sum_{i=1}^{k} \frac{1}{f(k+1-i)} \\ &= \frac{n^{2(\gamma+\beta)}}{f} (\ln(k+1) + r_0) \\ &= \frac{\log k}{f} \cdot n^{2(\gamma+\beta)} \end{aligned} \tag{67}$$

Combining (65), (66) and (67), then we have

$$\mathbb{E}\{T_e\} = O\Bigg( \max \left\{ \log \frac{n-k}{n-k-f}, \frac{\log k}{f} \right\} \cdot n^{2(\gamma+\beta)} \Bigg) \tag{68}$$

Regarding the delay jitter, we have

$$\begin{aligned}\mathbb{E}\{J_d\} &\geq n^{2(\gamma+\beta)} \cdot \sum_{i=2}^{k} \frac{1}{f(k+1-i)} \\ &= \Omega(\frac{\log k}{f} \cdot n^{2(\gamma+\beta)}) \end{aligned} \tag{69}$$

We then finish the proof for Theorem 6. ■

*E. The Maximum Capacity and Minimum Delay/Delay Jitter*

This section further explores the maximum multicast throughput capacity under any relay algorithm and also the minimum delay/delay jitter under any relay algorithm without packet redundancy.

*Theorem 7:* For the concerned ICMN with any relay algorithm, the maximum multicast throughput capacity is determined as $O(\frac{1}{k} \cdot n^{1-2(\gamma+\beta)})$.

*Proof:* For the tagged flow, the maximum rate of packet delivery depends on the rate of $S$ meeting available relay nodes. The best case is that all the other $n-1$ nodes will help forward packets for $S$. Thus, the maximum rate of packet delivery of this flow into the network is $(n-1)n^{-2(\gamma+\beta)}$. Symmetrically, the network can output packets of this flow with a rate of at most $(n-1)n^{-2(\gamma+\beta)}$. Under the multicast scenario, the reception of one packet requires at least $k$ contacts, so the maximum throughput of the tagged flow can be determined as $O(\frac{1}{k} \cdot n^{1-2(\gamma+\beta)})$. ■

*Theorem 8:* For the concerned ICMN adopting any relay algorithm without packet redundancy, both the minimum delay/delay jitter are determined as $\Omega(\log k \cdot n^{2(\gamma+\beta)})$.

*Proof:* As indicated in [6] that if no redundancy is allowed in the packet delivery process, adopting relay nodes does not help to improve the delay performance. This enables the minimum delay/delay jitter to be derived based on the one-hop relay with non-cooperative mode.

Consider a new HoL packet at $S$. If we denote by $e_j$ the event that by time slot $i-1$, the destination $D_j$ has ever met $S$, where $1 \leq j \leq k$. Thus, the event that by time slot $i-1$ all the destinations except the last one have received the packet, can be expressed as

$$\begin{aligned}&\overline{e_k} \cap e_1 \cap e_2 \cap e_3 \cap \cdots \cap e_{k-1} \\ &= \overline{e_k} \cap (\mathbf{I} - \overline{e_1 \cap e_2 \cap \cdots \cap e_{k-1}}) \\ &= \overline{e_k} - (\overline{e_k} \cap \overline{e_1}) \cup (\overline{e_k} \cap \overline{e_2}) \cup \cdots \cup (\overline{e_k} \cap \overline{e_{k-1}}) \end{aligned} \tag{70}$$

If we denote by $T_{min}$ the minimum delay of this HoL packet, then we have

$$\begin{aligned}\Pr(T_{min} = i) = k \cdot n^{-2(\gamma+\beta)} \Bigg( &(1 - n^{-2(\gamma+\beta)})^{i-1} \\ &- \sum_{j=1}^{k-1} \binom{k-1}{j} (-1)^{j-1} \Big( 1 - (j+1) n^{-2(\gamma+\beta)} \Big)^{i-1} \Bigg) \end{aligned} \tag{71}$$

Based on (71), $\mathbb{E}\{T_{min}\}$ can be determined as

$$\begin{aligned}\mathbb{E}\{T_{min}\} &= \sum_{i=1}^{\infty} i \cdot \Pr(T_{min} = i) \\ &= k \cdot n^{2(\gamma+\beta)} \Bigg( 1 - \binom{k-1}{1} \frac{1}{2^2} + \binom{k-1}{2} \frac{1}{3^2} - \cdots \Bigg) \quad (72) \\ &= n^{2(\gamma+\beta)} \Bigg( \binom{k}{1} - \binom{k}{2} \frac{1}{2} + \binom{k}{3} \frac{1}{3} - \cdots \Bigg) \\ &= \Omega(\log k \cdot n^{2(\gamma+\beta)}) \quad (73) \end{aligned}$$

TABLE I
MULTICAST CAPACITY, DELAY AND DELAY JITTER IN ICMNS.

| Relay Algorithms | Capacity | Delay | Delay Jitter |
|---|---|---|---|
| One-hop, non-cooperative | $O(\frac{1}{\log k}\cdot n^{-2(\gamma+\beta)})$ | $\Omega(\log k\cdot n^{2(\gamma+\beta)})$ | $\Omega(\log k\cdot n^{2(\gamma+\beta)})$ |
| One-hop, cooperative | $O(n^{-2(\gamma+\beta)})$ | $\Omega(\log k\cdot n^{2(\gamma+\beta)})$ | $\Omega(\log k\cdot n^{2(\gamma+\beta)})$ |
| Two-hop, non-cooperative | $O(\frac{1}{k\cdot\log k}\cdot n^{1-2(\gamma+\beta)})$ | $\Omega(\log k\cdot n^{2(\gamma+\beta)})$ | $\Omega(\log k\cdot n^{2(\gamma+\beta)})$ |
| Two-hop, cooperative | $O(\frac{1}{k}\cdot n^{1-2(\gamma+\beta)})$ | $\Omega(\log k\cdot n^{2(\gamma+\beta)})$ | $\Omega(\log k\cdot n^{2(\gamma+\beta)})$ |
| Two-hop, redundancy $f$ | $\Omega(\frac{1}{k\cdot f}\cdot n^{1-2(\gamma+\beta)})$ | $O\Big(\max\Big\{\log\frac{n-k}{n-k-f},\frac{\log k}{f}\Big\}\cdot n^{2(\gamma+\beta)}\Big)$ | $\Omega(\frac{\log k}{f}\cdot n^{2(\gamma+\beta)})$ |

where (72) follows after applying derivations similar to that in [6]. By using a derivation similar to that of the minimum delay, the result for the minimum delay jitter follows. ■

### F. Discussion

We summarize our main results in Table I. As shown in Table I that the delay results derived under both the one-hop relay and the two-hop relay have the same scaling order of $\Omega(\log k\cdot n^{2(\gamma+\beta)})$, which indicates that for an ICMN without packet redundancy, introducing relay in packet delivery process will not help in improving the delay performance. We can also see that for the two relay algorithms under both the non-cooperative mode and cooperative mode, the delay jitter has the same scaling order as the delay. However, if we allow packet redundancy in packet delivery process, the scaling laws of delay and delay jitter are different.

A further careful observation of Table I indicates that for the one-hop relay algorithm, the throughput capacity can be improved by $\log k$ times when allowing the destination cooperation. It is interesting to notice that for the two-hop relay, the capacity of the cooperative mode is also $\log k$ times as that of the non-cooperative mode. Thus, for the concerned ICMN, allowing destination cooperation can help improve the multicast capacity by $\log k$ times. We can also see that when operating under either the non-cooperative mode or the cooperative mode, the capacity of the two-hop relay is always $\frac{n}{k}$ times as that of the one-hop relay. Thus, using extra relay nodes can improve the multicast capacity by $\frac{n}{k}$ times.

Another observation of Table I is that when adopting the two-hop relay under the cooperative mode, the multicast capacity is reported as $O(\frac{1}{k}\cdot n^{1-2(\gamma+\beta)})$. Although we consider an ICMN with $\gamma+\beta>\frac{1}{2}$ in this paper, we can see that as $\gamma+\beta\to\frac{1}{2}$ we will have a multicast capacity of $O(\frac{1}{k})$, which is consistent with the one derived for MANETs in literature.

## IV. CONCLUSION

In this paper, we examined the scaling laws of multicast capacity, delay and delay jitter in ICMNs, where each source desires to send packets to $k$ distinct destinations and all nodes move according to the generalized hybrid random walk mobility model. Our results indicate that for an ICMN without packet redundancy, adopting destination cooperation can improve the multicast capacity by $\log k$ times, while adopting extra relay nodes can improve the multicast capacity by $\frac{n}{k}$ times. It is also interesting to find that although we consider an ICMN with the constraint of $\gamma+\beta>\frac{1}{2}$ here, as $\gamma+\beta\to\frac{1}{2}$ our multicast capacity result actually reduces to $O(\frac{1}{k})$, same as that derived for the MANETs in literature.

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