Generalized Cooperative Multicast in Mobile Ad Hoc Networks

Bin Yang, Yulong Shen, *Member, IEEE*, Xiaohong Jiang, *Senior Member, IEEE*, and Tarik Taleb, *Senior Member, IEEE*

***Abstract*—Cooperative multicast serves as an efficient communication paradigm for supporting multicast-intensive applications in mobile ad hoc networks (MANETs). Available studies on cooperative multicast in MANETs mainly focus on either the full cooperation or the noncooperation, which fail to capture the more general cooperation behaviors among destination nodes. To address this issue, this paper proposes a general cooperative multicast scheme CM(f, g, p, τ) with replication factor f, multicast fanout g, cooperative probability p, and packet lifetime τ. With this scheme, a packet from source node will be replicated to at most f distinct relay nodes, which forward the packet to its g destination nodes, and with probability p a destination node helps to forward the packet. Here, the packet has the lifetime of τ time slots. The scheme is flexible and general, and it covers the full cooperation ($p = 1$) and the noncooperation ($p = 0$) as special cases. A Markov chain theoretical model is further developed to depict the packet delivery process under the new scheme and help us to conduct analytical study on the corresponding expected packet delivery probability and packet delivery cost. Finally, extensive simulation and numerical results are provided for discussions.**

***Index Terms*—Cooperative multicast, mobile ad hoc network, packet delivery probability/cost, two-hop relay.**

I. Introduction

MULTICAST in mobile ad hoc networks (MANETs) is important for supporting many critical applications with one-to-many communications [1]–[5], like message exchanges among a group of soldiers in battlefield, earthquake alarming, video conferencing, etc. Cooperative multicast serves as an efficient communication paradigm, where destination nodes may share their packets with each other. In practice, however, a destination node may act selfishly and refuses to forward packets to other nodes due to its limit power resource. Thus, for an efficient support of future multicast-intensive applications in MANETs [6]–[9], it is critical to take into account the cooperation behaviors of destination nodes in the design of multicast scheme.

Available studies on cooperative multicast in MANETs mainly focus on either the case when all destination nodes are willing to share packets with each other (full cooperation), or the case when none of these nodes is willing to share packets with others (noncooperation). The noncooperative multicast scheme in two-hop relay MANETs is studied in [10]–[13], where [10]–[12] consider the simple independent and identically distributed (i.i.d.) mobility model and [13] considers more general speed-restricted mobility models. Later, the full cooperative multicast scheme is explored in two-hop relay MANETs under i.i.d. mobility model [14], [15]. Recently, the performance of full cooperative and nocooperative multicast schemes is also examined in cognitive radio MANETs [16], which allow unlicensed nodes to exploit the spectrum allocated to licensed nodes in an opportunistic manner.

It is notable that the above studies only represent the two extreme cases of cooperative multicast and could not depict the general cooperative behaviors among destination nodes. Moreover, these studies assume that all packets from source node can be successfully delivered to destination nodes and only investigate the packet delivery performance in terms of capacity and delay. In a real MANET, however, destination nodes may exhibit more general cooperative behaviors and the packet loss may happy (e.g., due to lifetime constraint). Also, the theoretical models in these studies could not be applied in a straightforward way for the performance analysis of MANETs with the considerations of general node cooperative behaviors and packet loss issue.

To address the above limitations, this paper proposes a new and general cooperative multicast scheme and develops corresponding Markov chain theoretical model for performance analysis. The main contributions of this paper are summarized as follows.

1) First, we propose a general cooperative multicast scheme CM(f, g, p, τ) for two-hop relay MANETs, where source node can deliver a packet to at most f distinct relay nodes, which forward the packet to its g destination nodes, and with probability p a destination node also helps to forward

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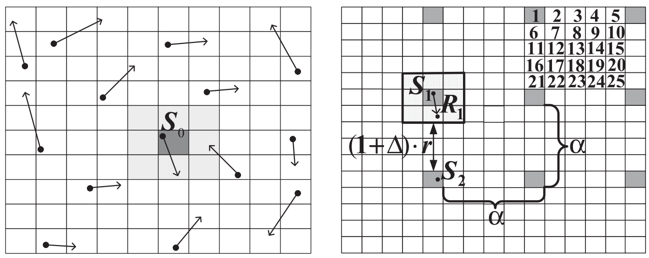

(a) (b)

Fig. 1. Network model and transmission scheduling. (a) Network model. (b) Illustration of transmission-group based scheduling with $m = 15$ and $\alpha = 5$.

the packet before its lifetime τ expires. The scheme is flexible and general, in the sense that we can control transmission behaviors by parameter p and it covers the available full cooperation scheme [14], [15] ($p = 1$) and noncooperation scheme [10]–[13] ($p = 0$) as special cases.

2) We then develop a two-dimensional Markov chain theoretical model to capture the complex packet delivery process under CM(f, g, p, τ). With the help of the theoretical model, we derive the analytical expressions for the expected packet delivery probability and delivery cost.
3) Finally, extensive simulation and theoretical results are provided to validate the theoretical analysis results and to illustrate the network performance under the new multicast scheme.

The rest of this paper is organized as follows. Section II introduces the system models and the definitions of performance metrics. In Section III, we first propose a general cooperative multicast scheme, and then develop a two-dimensional Markov chain theoretical model to depict packet delivery process under such a scheme. In Section IV, analytical expressions are derived for the expected packet delivery probability/cost. Section V provides numerical results to validate the theoretical results and to illustrate our theoretical findings. Finally, we conclude this paper in Section VI.

II. System Models and Performance Metrics

In this section, we first introduce system models and then define some performance metrics involved in this study.

A. System Models

Network and Mobility Models: We consider a time-slotted MANET with n mobile nodes in a unit square of torus boundaries, i.e., a node moving across an edge will immediately appears at the opposite edge of the square. Similar to previous studies[17]–[22], the network area is evenly divided into $m \times m$ cells (squares) as shown in Fig. 1(a). The nodes in the network move according to independent and identically distributed (i.i.d.) mobility model [17], [21], [23]. Under such mobility model, at the beginning of each time slot each node independently and randomly selects a cell to move into and stays in it during the time slot.

Communication Model: All the nodes share a common half-duplex medium for data transmissions, and we adopt the widely used protocol model proposed in [24] to address interference among simultaneous transmissions. Suppose that at time slot t, node i (transmitter) is transmitting to node j (receiver) of its transmission range. To ensure the successful transmission from i to j, for any other simultaneously transmitting node k, the following condition should be satisfied:

$$d_{kj}(t) \geq (1 + \Delta) d_{ij}(t), \tag{1}$$

where $d_{ij}(t)$ denotes the Euclidean distance between i and j at time slot t and $\Delta \geq 0$ models a guard zone to prevent the transmission failure due to interference from other simultaneous transmissions.

We consider a local transmission scenario [25], [26], where the transmission range of each node [e.g., node S_0 shown in Fig. 1(a)] covers the same cell of the node and its eight neighbor cells. In a time slot, the data that can be successfully transmitted is normalized as one packet.

Traffic Model: We consider a multicast traffic model [11], [27], where there are n multicast groups in the network, each of which consists of $g + 1$ nodes including one source node and g destination nodes. Each node is the source node in one multicast group and also a destination node in another multicast group. In a multicast group, each node can serve as a relay node to forward packets originated from other $n - g - 1$ multicast groups, which do not include these ones consisting of $g + 1$ nodes, and each destination node also helps to forward packets originated from the multicast group.

Transmission Scheduling Model: To ensure as many as possible successful simultaneous transmissions, we adopt the transmission-group based scheduling model here [17], [22], [25], [26], [28]. Under the scheduling model, the network cells are divided into α^2 different transmission-groups, and the distance between any two cells in each transmission-group is some integer multiple of α cells along the vertical and horizontal directions, respectively. For example, there are 25 transmission-groups in Fig. 1(b) where all shaded cells with index 1 belong to the same transmission-group. In every α^2 time slots, each transmission-group will become active alternately such that all nodes in each cell (namely active cell) of an active transmission-group are allowed to contend for a transmission opportunity over the common half-duplex medium. Only one node (if any) in each active cell is randomly selected to perform a transmission.

To ensure all simultaneous transmissions to be successful in an active transmission-group, the parameter α is determined as following. Suppose that at current time slot, a transmitter S_1 is transmitting to a receiver R_1 within its transmission range as shown in Fig. 1(b). Since the transmission range of each node covers its own cell and its eight neighbor cells with side length of $1/m$, the maximum distance r between S_1 and R_1 is $\sqrt{8}/m$. Meanwhile, the distance between R_1 and another possible closest simultaneous transmitter S_2 is $(\alpha - 2)/m$. To guarantee the successful transmission between S_1 and R_1, the following condition should be satisfied according to the protocol model [24]:

$$(\alpha - 2)/m \geq (1 + \Delta)\sqrt{8}/m. \tag{2}$$

Algorithm 1: Cooperative Multicast Scheme CM(f, g, p, τ):

```
For a transmitter Tx and its desired receiver Rx in current time slot.
if both Tx and Rx are in the same multicast group, and Tx is a source node in the multicast group then
    Tx performs a source-to-destination transmission with Rx;
end if
if both Tx and Rx are in the same multicast group, and Tx is not a source node in the multicast group then
    With cooperative probability p, Tx performs a destination-to-destination transmission with Rx;
end if
if Tx and Rx are in different multicast groups then
    Tx flips a fair coin;
    if it is head then
        Tx performs a source-to-relay transmission with Rx;
    else
        Tx performs a relay-to-destination transmission with Rx;
    end if
end if
```

Since the value of integer α is no more than m, we have

$$\alpha = \min\{\lceil(1+\Delta)\sqrt{8}+2\rceil, m\}, \tag{3}$$

where $\lceil x \rceil$ is the ceiling function of x.

B. Performance Metrics

Packet Delivery Probability: For a multicast group and packet lifetime τ, the delivery probability of a packet in the multicast group is defined as the ratio of the number of destination nodes that have received the packet before the τ expires to the total number of destination nodes in the multicast group.

Packet Delivery Cost: The delivery cost of a packet is defined as the total transmission power consumed until either the packet lifetime τ expires or all its destination nodes in a multicast group have received the packet.

III. Cooperative Multicast Scheme and Theoretical Model

In this section, we first propose a general cooperative multicast scheme adopting two-hop relay as routing protocol, then develop a Markov chain theoretical model to depict packet delivery process under such a scheme, and derive some related basic probabilities.

A. Cooperative Multicast Scheme

The proposed general cooperative multicast scheme is summarized in Algorithm 1. To support these transmissions in Algorithm 1, we assume that each node has $n+2$ individual queues in its buffer: one *source-queue* used to store locally generated packets waiting for their copies to be delivered, one *already-delivered-queue* used to store these packets whose f copies have already been delivered out but their reception statuses are not confirmed yet, $n-g-1$ *relay-queues* used to store packets originated from other multicast groups (one queue per multicast group), and one *cooperative-queue* used to store packets that will be forwarded to their destination nodes with cooperative probability p. The four types of transmissions in Algorithm 1 are defined as follows.

Source-to-Destination Transmission: Tx delivers to Rx a packet that Rx is requesting, where the packet is chosen as follows: Tx first checks its source-queue, starting from its head-of-line packet, to find the packet; if it fails, then it retrieves the packet from its already-delivered-queue.

Destination-to-Destination Transmission: If there exists a packet that Rx is requesting in the cooperative-queue of Tx, then Tx delivers a copy of the packet to Rx; otherwise, Tx remains idle.

Source-to-Relay Transmission: If Rx does not carry a copy of the head-of-line packet from Tx's source-queue, then Tx delivers a copy of the packet to Rx; otherwise, Tx remains idle. If f copies of the packet have been delivered to different relay nodes, then Tx puts the packet to the end of the already-delivered-queue and then removes it from the source-queue.

Relay-to-Destination Transmission: If there exists a packet that Rx is requesting in the relay-queue intended for Rx, then Tx delivers a copy of the packet to Rx; otherwise, Tx remains idle.

Remark 1: The two-hop relay, since first proposed by Grossglauser and Tse in [29], has been extensively explored in literature and proved to be a simple and efficient routing protocol for MANETs, where the network topology varies dramatically and no contemporaneous end-to-end path may ever exist at any given time instant. Furthermore, under such a routing protocol, the network performance can be analytically studied in the challenging MANETs. This paper explores a general cooperative multicast scheme adopting two-hop relay as routing protocol and analytically studies packet delivery probability/cost performance in the MANETs.

B. Markov Chain Theoretical Model

Without loss of generality, we focus on a tagged multicast group with a source node S and g destination nodes ($D_1, D_2, \ldots, D_g$). For a given packet at the source node S, we use two-tuple (i, j) to denote a general state that i relay nodes are carrying a copy of the packet and j destination nodes have received the packet, where $0 \le i \le f$ and $0 \le j \le g$. If $j < g$, then the general state corresponds to a transient state; otherwise, it is an absorbing state. From the operation of the general cooperative multicast scheme, we know that if the tagged multicast group is currently in transient state (i, j), then only one of twelve transition scenarios shown in Fig. 2 may happen in the next time slot:

1) *SD scenario:* source-to-destination transmission only, i.e., S successfully delivers the packet to a destination node that has not received the packet, while none of relay and destination nodes delivers the packet to other destination nodes. Under this transition scenario, the state (i, j) may transit to $(i, j+1)$.

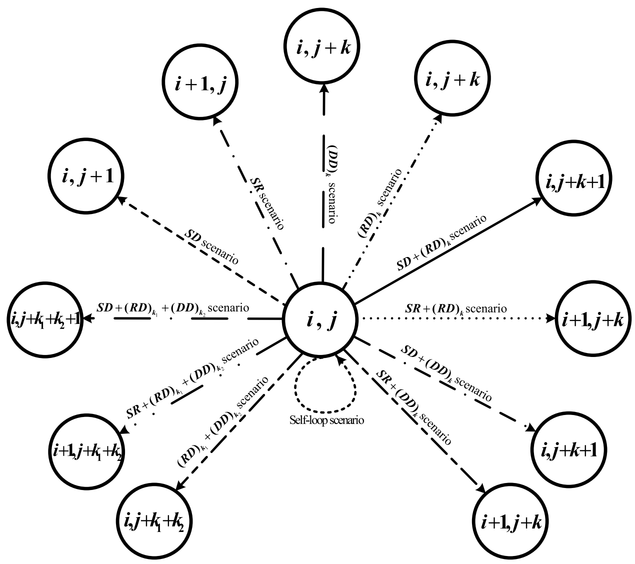

Fig. 2. The transition diagram of a general transient state (i, j).

2) SR *scenario:* source-to-relay transmission only, i.e., S successfully delivers a copy of the packet to a relay node that does not carry the packet, while none of relay and destination nodes delivers the packet to other destination nodes. The state (i, j) may transit to $(i + 1, j)$ under the SR transition scenario.
3) $(DD)_k$ *scenario:* k simultaneous destination-to-destin ation transmissions only, i.e., k destination-to-destin ation transmissions happen simultaneously where each transmission indicates that a destination node successfully delivers the packet to another one that has not received the packet, while other transition scenarios do not happen. Under such a transition scenario, the state (i, j) may transit to $(i, j + k)$.
4) $(RD)_k$ *scenario:* k simultaneous relay-to-destination transmissions only, i.e., k relay-to-destination transmissions happen simultaneously where each transmission indicates that a relay node successfully delivers the packet to a destination node that has not received the packet, while other transition scenarios such as SD, SR and $(DD)_k$ do not happen. Under the $(RD)_k$ scenario, the state (i, j) may transit to $(i, j + k)$, where $1 \leq k \leq i$ and $j + k \leq g$.
5) $SD + (RD)_k$ *scenario:* one source-to-destination and k relay-to-destination transmissions only, i.e., these $k + 1$ transmissions happen simultaneously, while the SR and $(DD)_k$ scenarios do not happen. Under such a scenario, the state (i, j) may transit to $(i, j + k + 1)$, where $1 \leq k \leq i$ and $j + k + 1 \leq g$.
6) $SR + (RD)_k$ *scenario:* one source-to-relay and k relay-to-destination transmissions only, i.e., these $k + 1$ transmissions happen simultaneously, while the SD and $(DD)_k$ scenarios do not happen. Under this scenario, the state (i, j) may transit to $(i + 1, j + k)$, where $1 \leq k \leq i$ and $j + k \leq g$.
7) $SD + (DD)_k$ *scenario:* one source-to-destination and k destination-to-destination transmissions only, i.e., these $k + 1$ transmissions happen simultaneously, while the SR and RD scenarios do not happen. The state (i, j) may transit to $(i, j + k + 1)$ under the scenario, where $1 \leq k \leq j$ and $j + k + 1 \leq g$.
8) $SR + (DD)_k$ *scenario:* one source-to-relay and k destination-to-destination transmissions only, i.e., these $k + 1$ transmissions happen simultaneously, while the SD and RD scenarios do not happen. Under such a scenario, the state (i, j) may transit to $(i + 1, j + k)$, where $1 \leq k \leq j$ and $j + k \leq g$.
9) $(RD)_{k_1} + (DD)_{k_2}$ *scenario:* k_1 relay-to-destination and k_2 destination-to-destination transmissions only, i.e., these $k_1 + k_2$ transmissions happen simultaneously, while the SD and SR scenarios do not happen. Under this scenario, the target state is $(i, j + k_1 + k_2)$, where $1 \leq k_1 \leq i$, $1 \leq k_2 \leq j$ and $j + k_1 + k_2 \leq g$.
10) $SR + (RD)_{k_1} + (DD)_{k_2}$ *scenario:* one source-to-relay, k_1 relay-to-destination and k_2 destination-to-destination transmissions only, i.e., these $k_1 + k_2 + 1$ transmissions happen simultaneously, while the SD scenario does not happen. Under this scenario, the state (i, j) may transit to $(i + 1, j + k_1 + k_2)$, where $1 \leq k_1 \leq i$, $1 \leq k_2 \leq j$ and $j + k_1 + k_2 \leq g$.
11) $SD + (RD)_{k_1} + (DD)_{k_2}$ *scenario:* one source-to-destination, k_1 relay-to-destination and k_2 destination-to-destination transmissions only, i.e., these $k_1 + k_2 + 1$ transmissions happen simultaneously, while the SR scenario does not happen. Under this scenario, the target state is $(i, j + k_1 + k_2 + 1)$, where $1 \leq k_1 \leq i$, $1 \leq k_2 \leq j$ and $j + k_1 + k_2 + 1 \leq g$.
12) *Self-loop scenario:* transition from (i, j) to (i, j), i.e., the packet is not delivered from a node to another.

Based on the transition diagram in Fig. 2, the packet delivery process under the general cooperative multicast scheme is modeled as a discrete-time two-dimensional absorbing Markov chain shown in Fig. 3.

C. Basic Results

We present some basic results related to the general cooperative multicast scheme and the Markov chain theoretical model, which will help us to analyze packet delivery probability/cost performance in Section IV.

Lemma 1: For a tagged multicast group, we use p_1 and p_2 to denote the probability that S performs a source-to-destination transmission, and the probability that S performs a source-to-relay transmission, respectively. Then we have

$$p_1 = \frac{1}{\alpha^2}\left(\sum_{k=1}^{g}\binom{g}{k}\left(\frac{1}{m^2}\right)^k\left(1-\frac{1}{m^2}\right)^{g-k}\cdot\sum_{i=0}^{n-g-1}\varphi(i)\right.$$
$$\frac{1}{k+i+1} + \sum_{k=1}^{g}\binom{g}{k}\left(\frac{8}{m^2}\right)^k\left(1-\frac{9}{m^2}\right)^{g-k}\cdot\sum_{i=0}^{n-g-1}\varphi(i)$$
$$\left.\frac{1}{i+1}\right), \tag{4}$$

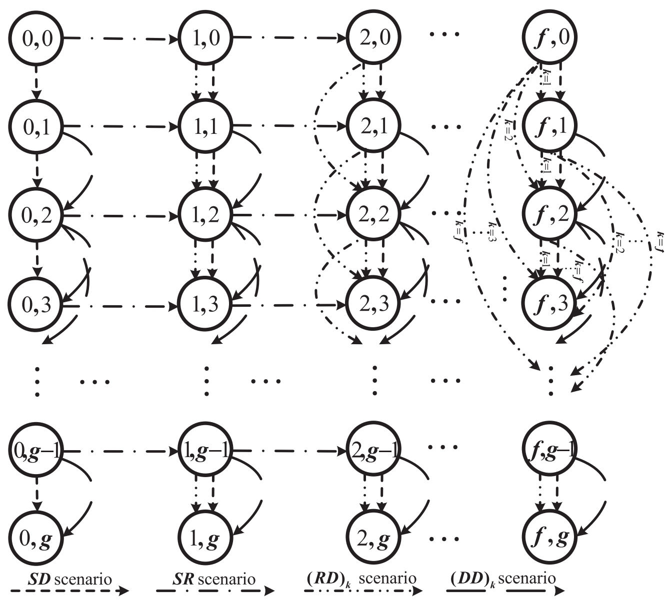

Fig. 3. Absorbing Markov chain for the packet delivery process under the general cooperative multicast scheme. For each transient state, the following transition scenarios are not shown for simplicity: $SD + (RD)_k$, $SR + (RD)_k$, $SD + (DD)_k$, $SR + (DD)_k$, $(RD)_{k_1} + (DD)_{k_2}$, $SR + (RD)_{k_1} + (DD)_{k_2}$, $SD + (RD)_{k_1} + (DD)_{k_2}$ and Self-loop.

$$p_2 = \frac{1}{\alpha^2}\left(1-\frac{9}{m^2}\right)^g \left(\sum_{i=1}^{n-g-1}\binom{n-g-1}{i}\left(\frac{1}{m^2}\right)^i \times \left(1-\frac{1}{m^2}\right)^{n-g-1-i}\frac{1}{i+1} + \sum_{i=1}^{n-g-1}\binom{n-g-1}{i} \times \left(\frac{8}{m^2}\right)^i\left(1-\frac{9}{m^2}\right)^{n-g-1-i}\right), \tag{5}$$

where $\varphi(i) = \binom{n-g-1}{i}(\frac{1}{m^2})^i(1-\frac{1}{m^2})^{n-g-1-i}$.

For the tagged multicast group with source node S and g destination nodes, and a given packet at S, suppose that (i, j) is the transient state of the Markov chain in Fig. 3 in current time slot $(0 \le i \le f,\ 0 \le j \le g-1)$. Under the transient state, we use μ_1, μ_2 and μ_3 to denote the number of destination nodes that have not received the given packet, the number of relay nodes carrying a copy of the packet, and the number of relay nodes carrying no copy of the packet, respectively, which can be easily determined as

$$\mu_1 = g - j, \tag{6}$$

$$\mu_2 = i, \tag{7}$$

$$\mu_3 = n - g - 1 - i. \tag{8}$$

Then we establish the following Lemmas.

Lemma 2: We use $P_{SD}(\mu_1)$ and $P_{SR}(\mu_3)$ to denote the probability that in the next time slot S successfully delivers a copy of the packet to a destination node (i.e., a successful source-to-destination transmission) and the probability that S successfully delivers a copy of the packet to a relay node (i.e., a successful source-to-relay transmission), respectively. Then we have

$$P_{SD}(\mu_1) = \frac{\mu_1}{g}p_1, \tag{9}$$

$$P_{SR}(\mu_3) = \frac{\mu_3}{2(n-g-1)}p_2. \tag{10}$$

Lemma 3: We use $P_{RD}(x, \mu_1, \mu_2)$ to denote the probability that x successful relay-to-destination transmissions will happen simultaneously in the next time slot. Here each transmission indicates that a relay node successfully delivers a copy of the packet to a destination node of the tagged multicast group, and $1 \le x \le \min\{\mu_1, \mu_2\}$. Then we have

$$P_{RD}(x, \mu_1, \mu_2) = \binom{\mu_2}{x}\frac{\binom{\mu_1}{x}}{\binom{g}{x}}\lambda_1\lambda_2\cdots\lambda_i\cdots\lambda_x, \tag{11}$$

where

$$\lambda_i = \begin{cases} \frac{m^2-\alpha^2(i-1)}{2\alpha^2m^2}\sum_{k_i=0}^{l_{i,x}}\binom{l_{i,x}}{k_i}\sum_{h_i=1}^{w_i}\binom{w_i}{h_i}\psi(k_i,h_i), \\ \qquad\qquad \text{if } 1 \le i \le x-1, \\ \frac{m^2-\alpha^2(i-1)}{2\alpha^2m^2}\sum_{k_i=0}^{l_{i,x}}\binom{l_{i,x}}{k_i}\sum_{h_i=1}^{w_i}\binom{w_i}{h_i}\psi(k_i,h_i)(1-\frac{9x}{m^2})^z, \\ \qquad\qquad \text{if } i = x. \end{cases} \tag{12}$$

In Lemma 3, $l_{i,x}$, w_i, z and $\psi(k_i, h_i)$ are defined in the following formulas.

$$l_{i,x} = n - 2g - x - \sum_{j=1}^{i}k_{j-1}, \tag{13}$$

$$w_i = g - \sum_{j=1}^{i}h_{j-1}, \tag{14}$$

$$z_x = n - x - \sum_{j=1}^{x}(k_j + h_j), \tag{15}$$

$$\psi(k_i, h_i) = \sum_{k=0}^{k_i}\binom{k_i}{k}\sum_{h=0}^{h_i}\binom{h_i}{h}\left(\frac{1}{m^2}\right)^{k+h}\left(\frac{8}{m^2}\right)^{k_i+h_i-k-h} \cdot \frac{1}{k+h+1}\frac{h_i}{k_i+h_i}, \tag{16}$$

where $k_0 = 0$ and $h_0 = 0$.

Lemma 4: We use $P_{DD}(x, \mu_1)$ to denote the probability that x successful destination-to-destination transmissions will happen simultaneously in the next time slot, where $1 \le x \le \min\{\mu_1, \lfloor\frac{g}{2}\rfloor\}$ and $\lfloor\frac{g}{2}\rfloor$ is the floor function of $\frac{g}{2}$. Then we have

$$P_{DD}(x, \mu_1) = \binom{g-\mu_1}{x}\frac{\binom{\mu_1}{x}}{\binom{g-x}{x}}\gamma_1\gamma_2\cdots\gamma_i\cdots\gamma_x, \tag{17}$$

where

$$\gamma_i = \begin{cases} p\frac{m^2-\alpha^2(i-1)}{\alpha^2m^2}\sum_{k_i=0}^{l_{i,x}+g+x}\binom{l_{i,x}+g+x}{k_i}\sum_{h_i=1}^{w_i-x}\binom{w_i-x}{h_i}\psi(k_i,h_i), \\ \qquad\qquad \text{if } 1 \le i \le x-1, \\ p\frac{m^2-\alpha^2(i-1)}{\alpha^2m^2}\sum_{k_i=0}^{l_{i,x}+g+x}\binom{l_{i,x}+g+x}{k_i}\sum_{h_i=1}^{w_i-x}\binom{w_i-x}{h_i}\psi(k_i,h_i) \\ \cdot(1-\frac{9x}{m^2})^{z_x}, \qquad \text{if } i = x. \end{cases} \tag{18}$$

The basic idea of the proof of Lemma 3 is summarized as follows. For x relay nodes carrying a copy of the packet originated from the tagged multicast group, we first show how the probability $P_{RD}(x, \mu_1, \mu_2)$ is related to the probability that these x relay nodes perform x relay-to-destination transmissions simultaneously. Then the probability is derived as the product of the probabilities that one of these x relay nodes performs a relay-to-destination transmission, which is determined based on the probabilities of its sub-events. Finally, by summarizing these results, $P_{RD}(x, \mu_1, \mu_2)$ can be derived. The derivations of Lemma 4 is similar to that of Lemma 3. The detailed proofs of these Lemmas can be found in Appendix. In Appendix, we also give some other basic results, the proofs of which are similar to those of Lemmas 3 and 4.

IV. Packet Delivery Probability/Cost Modeling

Based on the Markov chain theoretical model and related basic results, this section derives analytical expressions for the expected packet delivery probability/cost.

A. Expected Packet Delivery Probability

We use β to denote the total number of transient states in the Markov chain shown in Fig. 3. Since all β transient states are evenly divided into g rows and each row has $f+1$ transient states in the Markov chain, we have $\beta = g(f+1)$. We number these β transient states and $f+1$ absorbing states sequentially as $1, 2, \ldots, \beta + f + 1$ in a left-to-right and top-to-down way.

For a given packet originated from a tagged multicast group, we use N_d to denote the packet delivery probability, i.e., the ratio of the number of destination nodes that have received the packet before the lifetime τ expires to the total number of destination nodes g, and then the expected value $\mathrm{E}\{N_d\}$ of N_d can be determined as

$$\mathrm{E}\{N_d\} = \frac{1}{g}\sum_{k=0}^{g}\sum_{l=1}^{f+1} M(k,l) m_{1,d}, \tag{19}$$

where the lth state of the kth row corresponds to the state with index d $(1 \le d \le \beta + f + 1)$ in the Markov chain shown in Fig. 3, $M(k,l)$ denotes the number of destination nodes that have received the packet in state d, $m_{1,d}$ denotes the probability that the Markov chain, starting from the initial state 1, reaches state d after τ time slots, and d is given by

$$d = (f+1)k + l. \tag{20}$$

To derive $\mathrm{E}\{N_d\}$, we first determine $M(k,l)$. Since each state of the kth row in the Markov chain indicates that k destination nodes have received the packet, we have

$$M(k,l) = k. \tag{21}$$

We then determine $m_{1,d}$. Let $\mathbf{P} = (p_{i,j})_{(\beta+f+1)\times(\beta+f+1)}$ be the transition matrix of the Markov chain. The entry $p_{i,j}$ of the matrix $\mathbf{P}$ denotes the transition probability that the Markov chain, starting from state i, will be in state j after 1 time slot. The $\mathbf{P}$ can be rewritten as

$$\mathbf{P} = \begin{bmatrix} \mathbf{Q} & \mathbf{R} \\ \mathbf{O} & \mathbf{I} \end{bmatrix}, \tag{22}$$

where the matrix $\mathbf{Q} = (q_{i,j})_{\beta\times\beta}$ defines the transition probabilities among β transient states, the matrix $\mathbf{R} = (r_{i,j})_{\beta\times(f+1)}$ defines the transition probabilities from β transient states to $f+1$ absorbing states, $\mathbf{O}$ is a $(f+1)$-by-β zero matrix and $\mathbf{I}$ is a $(f+1)$-by-$(f+1)$ identity matrix.

After τ time slots, the τ-step transition matrix $\mathbf{P}^\tau$ of $\mathbf{P}$ can be calculated as

$$\mathbf{P}^\tau = \begin{bmatrix} \mathbf{Q}^\tau & \mathbf{N}(\mathbf{I} - \mathbf{Q}^\tau)\mathbf{R} \\ \mathbf{O} & \mathbf{I} \end{bmatrix} \tag{23}$$

where $\mathbf{N} = (\mathbf{I} - \mathbf{Q})^{-1}$ is the fundamental matrix of the Markov chain, and $\mathbf{I}$ is a β-by-β identity matrix.

We define matrix $\mathbf{W} = (w_{i,j})_{\beta\times\beta}$ as $\mathbf{W} = \mathbf{Q}^\tau$, and define $\mathbf{B} = (b_{i,t})_{\beta\times(f+1)}$ as $\mathbf{B} = \mathbf{N}\cdot(\mathbf{I} - \mathbf{Q}^\tau)\cdot\mathbf{R}$. Since $w_{i,j}$ denotes the probability that the Markov chain reaches transient state j from starting transient state i after τ time slots, and $b_{i,t}$ denotes the probability that the Markov chain reaches absorbing state t from starting transient state i after τ time slots, $m_{1,d}$ is determined as

$$m_{1,d} = \begin{cases} w_{1,d} & \text{if } 1 \le d \le \beta, \\ b_{1,d} & \text{if } \beta + 1 \le d \le \beta + f + 1. \end{cases} \tag{24}$$

B. Expected Packet Delivery Cost

For a given packet originated from a tagged multicast group, we use C_p to denote the packet delivery cost, i.e., the total transmission power consumed until either the lifetime τ expires or all g destination nodes in the tagged multicast group have received the packet, and then the expected value $\mathrm{E}\{C_p\}$ of C_p can be determined as

$$\mathrm{E}\{C_p\} = \sum_{k=0}^{g}\sum_{l=1}^{f+1} C(k,l) m_{1,d}, \tag{25}$$

where $C(k,l)$ denotes the transmission power consumed in the lth state of the kth row in Fig. 3.

Consider one unit transmission power is consumed when a node delivers a packet to another node. Since the lth state of the kth row in the Markov chain indicates that the packet has been delivered to $l-1$ relay nodes and k destination nodes, $C(k,l)$ is determined as

$$C(k,l) = k + l - 1. \tag{26}$$

The unknown matrices $\mathbf{Q}$ and $\mathbf{R}$ can be easily obtained according to the transition probabilities from a state of the Markov chain to another in Fig. 3. The transition probability under each transient scenario in Fig. 2 can be determined as follows:

1) for SD scenario, $P_{SD}(\mu_1) - P_{SD,RD}(1,\mu_1,\mu_2) - P_{SD,DD}(1,\mu_1) + P_{SD,RD,DD}(1,1,\mu_1,\mu_2)$,
2) for SR scenario, $P_{SR}(\mu_3) - P_{SR,RD}(1,\mu_1,\mu_2,\mu_3) - P_{SR,DD}(1,\mu_1,\mu_3) + P_{SR,RD,DD}(1,1,\mu_1,\mu_2)$,
3) for $(DD)_k$ scenario, $P_{DD}(k,\mu_1) - P_{SD,DD}(k,\mu_1) - P_{SR,DD}(k,\mu_1,\mu_3) - P_{RD,DD}(1,k,\mu_1,\mu_2)$,

4) for $(RD)_k$ scenario, $P_{RD}(k, \mu_1, \mu_2) - P_{SD,RD}(k, \mu_1, \mu_2) - P_{SR,RD}(k, \mu_1, \mu_2, \mu_3) - P_{RD,DD}(k, 1, \mu_1, \mu_2)$,
5) for $SD + (RD)_k$ scenario, $P_{SD,RD}(k, \mu_1, \mu_2) - P_{SD,RD,DD}(k, 1, \mu_1, \mu_2)$,
6) for $SR + (RD)_k$ scenario, $P_{SR,RD}(k, \mu_1, \mu_2, \mu_3) - P_{SR,RD,DD}(k, 1, \mu_1, \mu_2)$,
7) for $SD + (DD)_k$ scenario, $P_{SD,DD}(k, \mu_1) - P_{SD,RD,DD}(1, k, \mu_1, \mu_2)$,
8) for $SR + (DD)_k$ scenario, $P_{SR,DD}(k, \mu_1, \mu_3) - P_{SR,RD,DD}(1, k, \mu_1, \mu_2)$,
9) for $(RD)_{k_1} + (DD)_{k_2}$ scenario, $P_{RD,DD}(k_1, k_2, \mu_1, \mu_2) - P_{SD,RD,DD}(k_1, k_2, \mu_1, \mu_2) - P_{SR,RD,DD}(k_1, k_2, \mu_1, \mu_2)$,
10) for $SR + (RD)_{k_1} + (DD)_{k_2}$ scenario, $P_{SR,RD,DD}(k_1, k_2, \mu_1, \mu_2)$,
11) for $SD + (RD)_{k_1} + (DD)_{k_2}$ scenario, $P_{SD,RD,DD}(k_1, k_2, \mu_1, \mu_2)$,
12) and for self-loop scenario, $1 -$ the sum of all the above transition probabilities.

V. Numerical Results

In this section, we first provide simulation studies to validate our theoretical models on packet delivery probability/cost, and then apply these models to explore how system parameters would affect the packet delivery probability/cost in a MANET.

A. Model Validation

A C++ simulator was developed to simulate the packet delivery process under the general cooperative multicast scheme in the considered MANET. We set the guard factor as $\Delta = 1$, and hence the parameter α in transmission scheduling model is determined as $\alpha = \min\{8, m\}$. Besides the i.i.d. mobility model considered in this paper, we also implement the following two mobility models:

1) *Random Walk Model* [30]: At the beginning of every time slot, each node will independently and randomly select one cell among its current cell and its eight neighbor cells with probability $1/9$, and then moves into the selected cell and stays in it for the remaining time slot.
2) *Random Waypoint Model* [31]: At the beginning of every time slot, each node will independently and randomly generate a 2-tuple (x, y), where the x and y are uniformly selected from $[1/m, 3/m]$, and then moves a distance of x and y along the horizontal and vertical directions, respectively.

Extensive simulations have been conducted to validate our theoretical models. For the setting of $n = 100, m = 16, p = 0.5, f = 4$, and $\tau = 2000$, the corresponding theoretical and simulation results are summarized in Fig. 4 to show how the expected packet delivery probability/cost vary as g increases. Each simulated value is calculated as the average value over 10^6 slots. Fig. 4 shows clearly that under i.i.d. mobility model, our theoretical results agree well with the simulation ones, indicating that our theoretical models can accurately predict the packet delivery probability/cost performance under the general cooperative multicast scheme. Another interesting observation from Fig. 4 is that the simulation results under the random walk

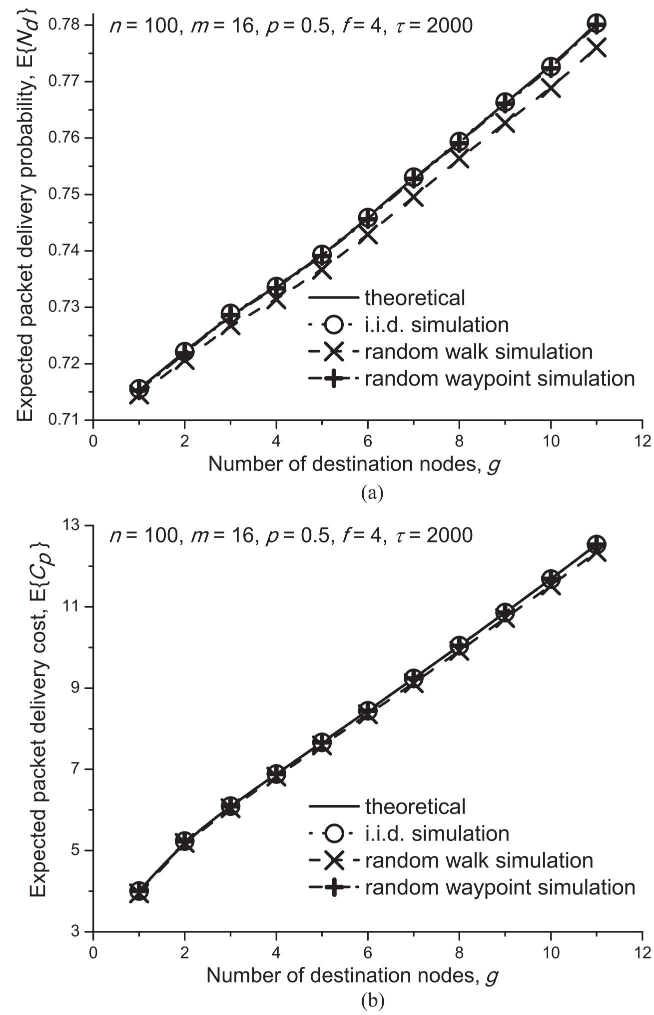

Fig. 4. Comparisons between theoretical results and the simulation ones for model validation. (a) $\mathrm{E}\{N_d\}$ vs. g. (b) $\mathrm{E}\{C_p\}$ vs. g.

and random waypoint models are similar to those under i.i.d. mobility models. Thus, our theoretical models, although are developed under the i.i.d. mobility model, can be used to predict the packet delivery probability/cost behavior under the random walk and random waypoint models as well.

Remark 2: In this paper, these network functions, like i.i.d. node mobility, transmission-group based scheduling scheme and packet delivery process of our cooperative multicast scheme, can be easily implemented by a customized C++ simulator (now publicly available at [32]) without going through a complicated network simulator (like NS3 and OPNET). As shown in [23], [33], for a cell-partitioned network, the average delay and network throughput capacity under the i.i.d. mobility model are also identical to those under other non-i.i.d. mobility models as long as they have the same steady-state distribution of nodes locations, like the random walk and random waypoint mobility models. Therefore, our theoretical models, although were developed for the packet delivery probability under the i.i.d. mobility model, can also be used to predict the packet delivery probability/cost performance in MANETs under the random walk and random waypoint mobility models.

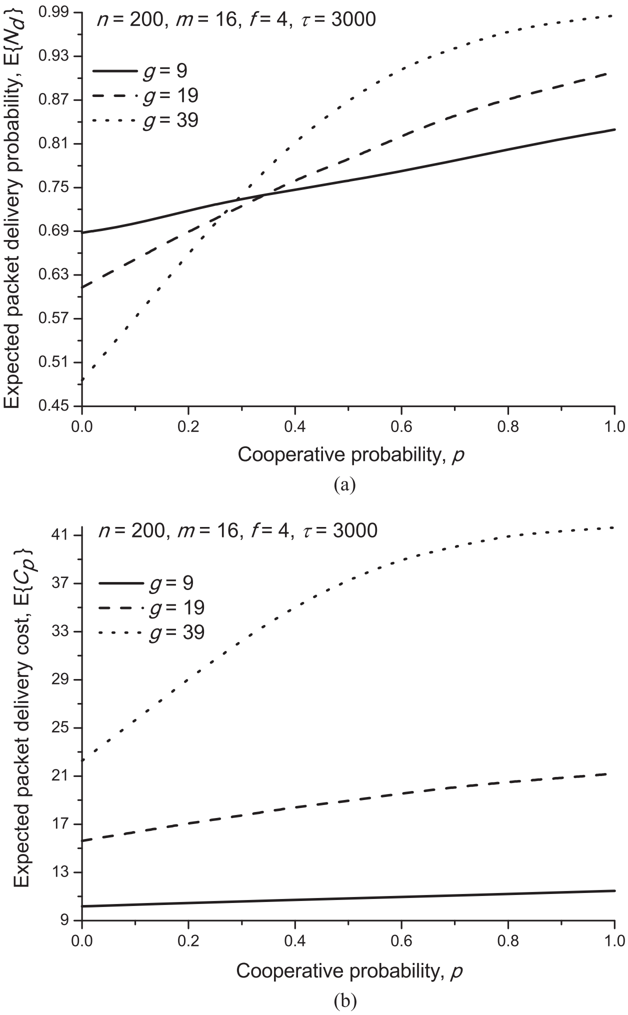

Fig. 5. Performance ($\mathrm{E}\{N_d\}$, $\mathrm{E}\{C_p\}$) versus p. (a) $\mathrm{E}\{N_d\}$ vs. p. (b) $\mathrm{E}\{C_p\}$ vs. p.

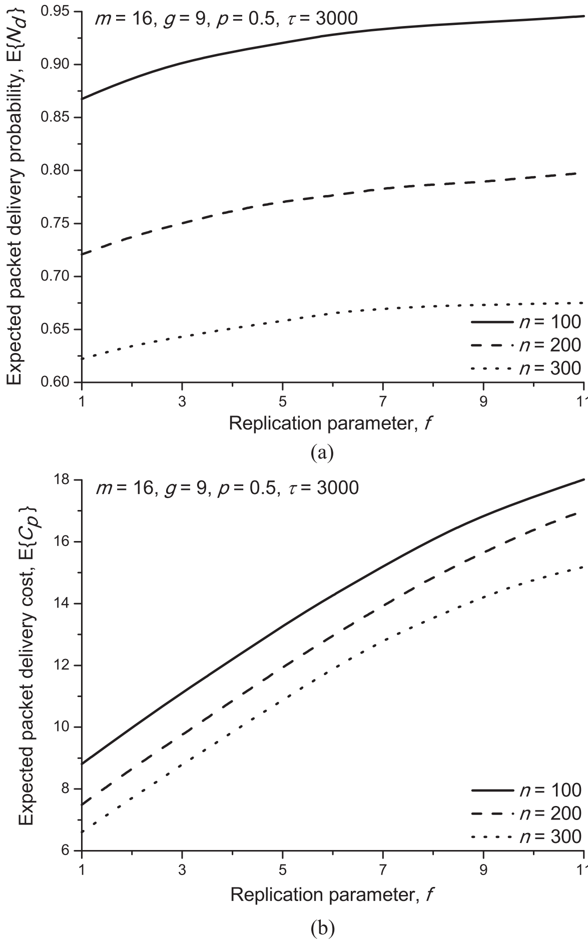

Fig. 6. Performance ($\mathrm{E}\{N_d\}$, $\mathrm{E}\{C_p\}$) versus f. (a) $\mathrm{E}\{N_d\}$ vs. f. (b) $\mathrm{E}\{C_f\}$ vs. f.

B. Performance Analysis

To explore the impact of system parameters on the packet delivery performance, we summarize in Fig. 5 how the expected packet delivery probability/cost ($\mathrm{E}\{N_d\}$, $\mathrm{E}\{C_p\}$) vary with p under a setting of $n = 200$, $m = 16$, $f = 4$, $\tau = 3000$ and $g = \{9, 19, 39\}$. Fig. 5 shows that for a fixed setting of g, as p increases, both the $\mathrm{E}\{N_d\}$ and $\mathrm{E}\{C_p\}$ increase monotonously. This is because an increase of p implies that more destination nodes will willing to forward packets for each other, leading to the increase of packet delivery probability at the cost of power consumption on the destination nodes. The results in Fig. 5 indicate that, in practice, the setting of cooperative probability p should be carefully selected in order to maintain a high delivery probability performance and a relatively low delivery cost.

Fig. 5(a) also illustrates that as g increases, the $\mathrm{E}\{N_d\}$ decreases if p is relatively small; otherwise, it increases. This is because an increase of g leads to both positive and negative effects on $\mathrm{E}\{N_d\}$: On one hand, it increases the probability with which each destination node receives a packet due to destination cooperation; on the other hand, it decreases the probability since destination nodes are less interested in forwarding packet for each other. As shown in Fig. 5(a), when p is relatively small, the latter negative effect dominates; as p further increases, the former positive effect is becoming the dominating one.

We now proceed to explore how the replication parameter f affects the performance ($\mathrm{E}\{N_d\}$, $E\{C_p\}$). For a setting of $n = 200$, $m = 16$, $g = 9$, $p = 0.5$, $\tau = 3000$ and $n = \{100, 200, 300\}$, we summarize in Fig. 6 how $\mathrm{E}\{N_d\}$ and $\mathrm{E}\{C_p\}$ vary with f. Fig. 6 shows that, as f increases, both the $\mathrm{E}\{N_d\}$ and $\mathrm{E}\{C_p\}$ monotonously increases. This is mainly due to that an increase of f will increase transmission opportunities from source node to relay nodes, and thus increases the packet delivery cost and the opportunities that the destination nodes receive the packet from the relay nodes, resulting in a higher packet delivery probability.

Finally, we examine in Fig. 7 how the $\mathrm{E}\{N_d\}$ and $\mathrm{E}\{C_p\}$ vary with the number of nodes n. For a setting of $m = 16$, $g = 7$, $p = 0.5$, $f = 5$ and $\tau = \{800, 1300, 1800\}$, Fig. 7 shows that for a fixed setting of packet lifetime τ, as n increases, both the $\mathrm{E}\{N_d\}$ and $\mathrm{E}\{C_p\}$ first increase and then decrease. Actually, an increase in the number of nodes n has two-fold effects the performance ($\mathrm{E}\{N_d\}$, $E\{C_p\}$). On one hand, when the network is sparse (i.e., n is very small), a bigger n will lead to a higher packet delivery speed at which a packet is distributed out, and

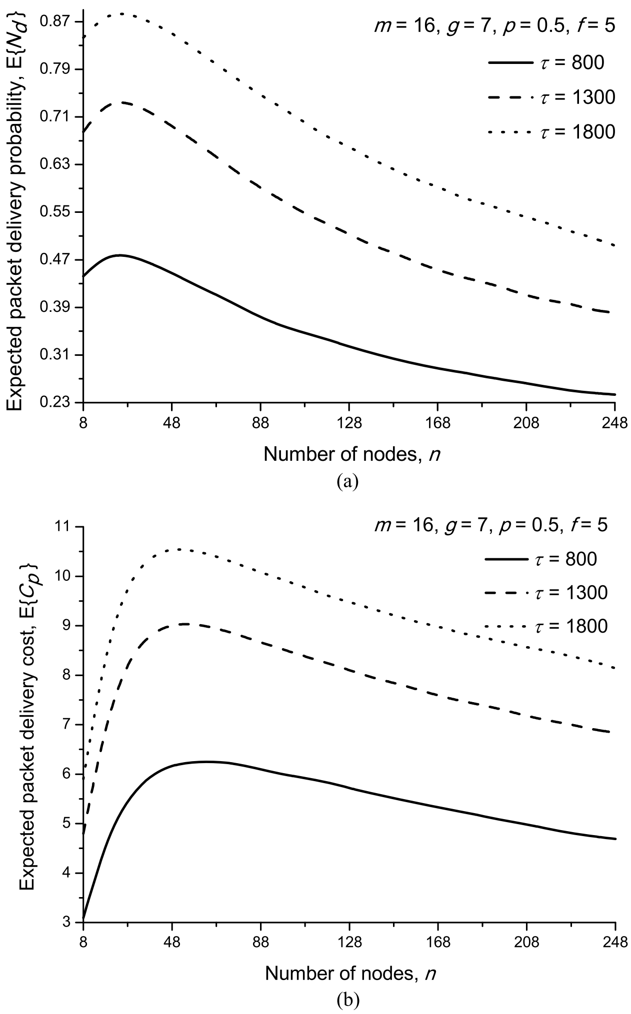

Fig. 7. Performance (E$\{N_d\}$, E$\{C_p\}$) versus n. (a) E$\{N_d\}$ vs. n. (b) E$\{C_f\}$ vs. n.

thus higher packet delivery probability and delivery cost. On the other hand, a bigger n will lead to a lower packet delivery speed due to the effects of wireless interference and medium access contention issues in a crowed network, and thus lower packet delivery probability and delivery cost.

C. Performance Comparison

In this subsection, we compare the packet delivery probability/cost performance of state-of-the-art schemes and that of the general cooperative multicast scheme proposed in this paper. Specifically, we choose two well-known schemes for comparison, namely two-hop relay [14] with full cooperation (scheme A for short) and two-hop relay [13] with noncooperation (scheme B for short) from Section I. The corresponding results are summarized in Fig. 5.

Fig. 5 illustrates the performance comparison between our scheme and scheme A (i.e., the special case of our scheme by setting $p = 1$). As shown in Fig. 5 that for the scheme A, all destination nodes are willing to forward packet for each other, and thus take full advantage of each transmission opportunity to increase the packet delivery probability (E$\{N_d\}$) while incurring high delivery cost (i.e., total transmission power consumed, E$\{C_p\}$). For example, with the setting of $g = 39$ and $p = 1$, E$\{N_d\}$ (resp. E$\{C_p\}$) under scheme A is 0.98 (resp. 41.64), while that is 0.87 (resp. 37.32) by adopting our scheme with the setting of $p = 0.5$.

Fig. 5 also illustrates the performance comparison between our scheme and scheme B (i.e., the special case of our scheme by setting $p = 0$). We can see from Fig. 5 that with the setting of $g = 39$ and $p = 0$, E$\{N_d\}$ (resp. E$\{C_p\}$) under scheme B is 0.48 (resp. 22.27). This is because for the scheme B, destination nodes may waste a lot of transmission opportunities because all of them are not willing to forward packet for each other, resulting in the decreasing of packet delivery probability while conserving their own transmission power consumed.

VI. Conclusion

This paper proposed a general cooperative multicast scheme to fully consider the important issue of destination nodes' cooperative behaviors. A Markov chain theoretical model was developed to depict packet delivery process under the general scheme, based on which and some related basic probabilities, analytical expressions were derived for the packet delivery probability/cost. Extensive simulations illustrate that our theoretical models can accurately predict the packet delivery probability/cost performance under the general scheme. Our results indicate that through a proper setting of cooperative probability p, a high packet delivery probability can be achieved while maintaining a relatively low delivery cost. It is expected that the general scheme can facilitate future MANETs to support various applications with different cooperative desires among destination nodes. One interesting direction is to further extend the developed theoretical model to analyze packet delivery probability/cost performance in multi-hop relay MANETs.

Appendix

Proof of Lemma 1: Source node S can perform a source-to-destination transmission if and only if the following four events happen in the same time slot: 1) S moves into an active cell; 2) There exists at least one destination node of S in the active cell and its eight neighbor cells; 3) There are i other nodes in the active cell (except S and corresponding g destination nodes), $0 \leq i \leq n - g - 1$; 4) S is randomly chosen as a transmitter.

Regarding the second event, suppose that there are k destination nodes of S in the active cell, or no destination node is in the active cell but there exist k destination nodes in the eight neighbor cells of this cell, $k \geq 1$. Notice that these two cases are mutually exclusive. Then the probability that S is chosen as a transmitter is $\frac{1}{k+i+1}$ (resp. $\frac{1}{i+1}$) under the former case (resp. under the latter case). We use q_1 and q_2 to denote the product of probabilities of these four events under the former case and that under the latter case, respectively. Then we have

$$q_1 = \frac{\frac{m^2}{\alpha^2}}{m^2} \sum_{k=1}^{g} \binom{g}{k} \left(\frac{1}{m^2}\right)^k \left(1 - \frac{1}{m^2}\right)^{g-k} \cdot \sum_{i=0}^{n-g-1} \varphi(i) \frac{1}{k+i+1}, \tag{27}$$

$$q_2 = \frac{\frac{m^2}{\alpha^2}}{m^2} \sum_{k=1}^{g} \binom{g}{k} \left(\frac{8}{m^2}\right)^k \left(1 - \frac{9}{m^2}\right)^{g-k} \cdot \sum_{i=0}^{n-g-1} \varphi(i) \frac{1}{i+1} \tag{28}$$

where $\varphi(i) = \binom{n-g-1}{i}(\frac{1}{m^2})^i(1 - \frac{1}{m^2})^{n-g-1-i}$.

The formula (4) can then be derived by adding q_1 and q_2 together.

Similarly, S can perform a source-to-relay transmission if and only if the following four events happen in the same time slot: 1) S moves into an active cell; 2) No destination node of S is in this cell and its eight neighbor cells; 3) There exists at least one other node in this cell and its eight neighbor cells except S; 4) S is randomly chosen as a transmitter.

Regarding the third event, suppose that there are i other nodes in the active cell, or no other node is in this cell but there exist i other nodes in the eight neighbor cells of this cell, $1 \leq i \leq n - g - 1$. Notice that these two cases are mutually exclusive. Then the probability that S is randomly chosen as a transmitter is $\frac{1}{i+1}$ (resp. 1) under the former case (resp. under the latter case). By summing up the product of probabilities of these four events under the former case and that under the latter case, the formula (5) can then be derived.

Proof of Lemma 2: In the next time slot, source node S may deliver a copy of the packet to one of the μ_1 destination nodes that do not receive the packet, which is called an event. Notice that there are μ_1 mutually exclusive events. The probability of such an event is $\frac{p_1}{g}$. By summing up the probabilities of these μ_1 events, we have

$$P_{SD}(\mu_1) = \frac{\mu_1}{g} p_1. \tag{29}$$

Similarly, in the next time slot, S may deliver a copy of the packet to one of μ_3 relay nodes that do not carry a copy of the packet. Notice that these μ_3 events are mutually exclusive, and each event denotes a transmission from S to a single relay node. The probability of such an event is $\frac{p_2}{2(n-g-1)}$. By summing up the probabilities of these μ_3 events, we have

$$P_{SR}(\mu_3) = \frac{\mu_3}{2(n-g-1)} p_2. \tag{30}$$

Proof of Lemma 3: To derive $P_{RD}(x, \mu_1, \mu_2)$, we focus on x specific relay nodes carrying a copy of the packet, and use $P(Tr_1, Tr_2, \ldots, Tr_x)$ to denote the probability that these x relay nodes will perform x relay-to-destination transmissions simultaneously (a community-transmission for short) in the next time slot, where Tr_i denotes a relay-to-destination transmission and $1 \leq i \leq x$.

Each transmitting relay node in a successful community-transmission can deliver a copy of the packet to a destination node, and μ_1 destination nodes have not received the packet in the current time slot. Thus, the probability that a successful community-transmission happens is $\frac{\binom{\mu_1}{x}}{\binom{g}{x}} P(Tr_1, Tr_2, \ldots, Tr_x)$. Since μ_2 relay nodes is carrying the packet currently, there are $\binom{\mu_2}{x}$ distinct community-transmissions. By summing up the probabilities of these $\binom{\mu_2}{x}$ community-transmissions, we have

$$P_{RD}(x, \mu_1, \mu_2) = \binom{\mu_2}{x} \frac{\binom{\mu_1}{x}}{\binom{g}{x}} P(Tr_1, Tr_2, \ldots, Tr_x). \tag{31}$$

The basic idea to determine $P(Tr_1, Tr_2, \ldots, Tr_x)$ is that we first treat the event $(Tr_1, Tr_2, \ldots, Tr_x)$ as x simultaneous but mutually independent relay-to-destination transmissions, then determine the probability that each transmission happens, and finally multiply the probabilities of all x transmissions. First consider a general transmission Tr_i performed by a specific relay node (e.g., R_i), $1 \leq i \leq x - 1$. This transmission will happen if and only if the following five events happen in the same time slot: 1) R_i moves into an active cell; 2) There are in total k_i other nodes in the same cell as R_i and the eight neighbor cells of the cell (except source node S, its g destination nodes, x specific relay nodes, g destination nodes of R_i's local traffic and $\sum_{j=1}^{i} k_{j-1}$ other nodes in the same cells as these $i-1$ specific relay nodes and their neighbor cells, $0 \leq k_i \leq n - 2g - x - \sum_{j=1}^{i} k_{j-1}$, among them k nodes are in the same cell as R_i and the other $k_i - k$ nodes are in the eight neighbor cells of the cell; 3) There are h_i destination nodes of S in the cell and the eight neighbor cells of the cell, among them h destination nodes are in the cell and the other $h_i - h$ destination nodes are in the eight neighbor cells, $1 \leq h_i \leq g - \sum_{j=1}^{i} h_{j-1}$; 4) R_i and one destination node are chosen as a transmitter and a receiver, respectively; 5) R_i chooses to perform relay-to-destination transmission Tr_i with the receiver.

The probabilities that the above events happen are calculated as $\frac{m^2-\alpha^2(i-1)}{\alpha^2 m^2}$, $\sum_{k_i=0}^{l_i}\binom{l_i}{k_i}\sum_{k=0}^{k_i}\binom{k_i}{k}(\frac{1}{m^2})^k(\frac{8}{m^2})^{k_i-k}$, $\sum_{h_i=1}^{w_i}\binom{w_i}{h_i}\sum_{h=0}^{h_i}\binom{h_i}{h}(\frac{1}{m^2})^h(\frac{8}{m^2})^{h_i-h}$, $\frac{1}{k+h+1}\frac{h_i}{k_i+h_i}$, and $\frac{1}{2}$, respectively. Here, $l_i = n - 2g - x - \sum_{j=1}^{i} k_{j-1}$ and $w_i = g - \sum_{j=1}^{i} h_{j-1}$. By multiplying the probabilities of these events, the probability of the transmission Tr_i is derived, where $1 \leq i \leq x - 1$. Similarly, we can also get the probability of the transmission Tr_x. $P(Tr_1, Tr_2, \ldots, Tr_x)$ follows by multiplying the probabilities of these x transmissions. Then (11) is derived by substituting $P(Tr_1, Tr_2, \ldots, Tr_x)$ into (31).

Proof of Lemma 4: To derive $P_{DD}(x, \mu_1)$, we focus on x specific destination nodes, each of which has received the packet. We use Tr_i to denote a destination-to-destination transmission, and use $P(Td_1, Td_2, \ldots, Td_x)$ to denote the probability that these x destination nodes will perform x such transmissions simultaneously (a community-transmission for short) in the next time slot, where $1 \leq i \leq x$.

In a successful community-transmission, each transmitting destination node can deliver a copy of the packet to other destination node. Thus, the probability that a successful community-transmission happens can be determined as $\frac{\binom{\mu_1}{x}}{\binom{g-x}{x}} P(Td_1, Td_2, \ldots, Td_x)$. Since $g - \mu_1$ destination nodes have received the packet in the current time slot, there are in total $\binom{g-\mu_1}{x}$ distinct community-transmissions. By summing up the probabilities of these $\binom{g-\mu_1}{x}$ community-transmissions, we have

$$P_{DD}(x, \mu_1) = \binom{g-\mu_1}{x} \frac{\binom{\mu_1}{x}}{\binom{g-x}{x}} P(Td_1, Td_2, \ldots, Td_x). \tag{32}$$

The basic idea to determine $P(Td_1, Td_2, \ldots, Td_x)$ is that we first treat the event $Td_1, Td_2, \ldots, Td_x$ as x simultaneous yet mutually independent destination-to-destination transmissions, then determine the probability that each transmission happens, and finally multiply the probabilities of all x transmissions. First consider a general transmission Td_i performed by a specific destination node (e.g., D_i), $1 \le i \le x-1$. This transmission will happen if and only if the following five events happen in the same time slot: 1) D_i moves into an active cell; 2) There are in total k_i other nodes in the same cell as D_i and the eight neighbor cells (except the g destination nodes of the tagged multicast group and $\sum_{j=1}^{i} k_{j-1}$ other nodes in the same cells as these $i-1$ specific destination nodes and their neighbor cells), $0 \le k_i \le n-g-\sum_{j=1}^{i} k_{j-1}$, among them k nodes are in the same cell as D_i and the other $k_i - k$ nodes are in the eight neighbor cells of the cell; 3) There are h_i other destination nodes in the cell and the eight neighbor cells of the cell (except the x specific destination nodes), among them h destination nodes are in the cell and the other $h_i - h$ destination nodes are in the eight neighbor cells, $1 \le h_i \le g-x-\sum_{j=1}^{i} h_{j-1}$; 4) D_i and one destination node are chosen as a transmitter and a receiver, respectively; 5) D_i chooses to perform destination-to-destination transmission Td_i with the receiver.

The probabilities that the above events happen are calculated as $\frac{m^2-\alpha^2(i-1)}{\alpha^2 m^2}$, $\sum_{k_i=0}^{l_i}\binom{l_i}{k_i}\sum_{k=0}^{k_i}\binom{k_i}{k}(\frac{1}{m^2})^k(\frac{8}{m^2})^{k_i-k}$, $\sum_{h_i=1}^{w_i}\binom{w_i}{h_i}\sum_{h=0}^{h_i}\binom{h_i}{h}(\frac{1}{m^2})^h(\frac{8}{m^2})^{h_i-h}$, $\frac{1}{k+h+1}\frac{h_i}{k_i+h_i}$, and p, respectively. Here, $l_i = n-g-\sum_{j=1}^{i} k_{j-1}$ and $w_i = g-x-\sum_{j=1}^{i} h_{j-1}$. By multiplying the probabilities of these events, the probability of the transmission Td_i is determined, where $1 \le i \le x-1$. Similarly, we can also get the probability of the transmission Td_x. By multiplying the probabilities of these x transmissions, $P(Td_1, Td_2, \ldots, Td_x)$ follows. Then (17) follows by substituting $P(Td_1, Td_2, \ldots, Td_x)$ into (32).

Other Basic Results: We use $P_{SD,RD}\,(x,\mu_1,\mu_2)$ to denote the probability that a successful source-to-destination transmission and x successful relay-to-destination transmissions will happen simultaneously in the next time slot, where $1 \le x \le \min\{\mu_1 - 1, \mu_2\}$. Then we have

$$P_{SD,RD}(x,\mu_1,\mu_2) = \binom{\mu_2}{x}\frac{\binom{\mu_1}{x+1}}{\binom{g}{x+1}}\rho_1\rho_2\ldots\rho_i\ldots\rho_{x+1}, \quad (33)$$

where

$$\rho_i = \begin{cases} \frac{m^2-\alpha^2(i-1)}{2\alpha^2 m^2}\sum_{k_i=0}^{l_{i,x}-1}\binom{l_{i,x}-1}{k_i}\sum_{h_i=1}^{w_i}\binom{w_i}{h_i}\psi(k_i,h_i), \\ \qquad\qquad \text{if } 1 \le i \le x, \\ \frac{m^2-\alpha^2(i-1)}{\alpha^2 m^2}\sum_{k_i=0}^{l_{i,x}+g-1}\binom{l_{i,x}+g-1}{k_i}\sum_{h_i=1}^{w_i}\binom{w_i}{h_i}\psi(k_i,h_i) \\ \cdot\frac{k_i+h_i}{h_i}(1-\frac{9(x+1)}{m^2})^{z_x-k_i-h_i-1}, \quad \text{if } i = x+1. \end{cases} \quad (34)$$

We use $P_{SR,RD}\,(x,\mu_1,\mu_2,\mu_3)$ to denote the probability that a successful source-to-relay transmission and x successful relay-to-destination transmissions will happen simultaneously in the next time slot, where $1 \le x \le \min\{\mu_1, \mu_2\}$. Then we have

$$P_{SR,RD}(x,\mu_1,\mu_2,\mu_3) = \binom{\mu_2}{x}\frac{\mu_3\binom{\mu_1}{x}}{\binom{g}{x}}\theta_1\theta_2\cdots\theta_i\cdots\theta_{x+1}, \quad (35)$$

where

$$\theta_i = \begin{cases} \frac{m^2-\alpha^2(i-1)}{2\alpha^2 m^2}\sum_{k_i=0}^{l_{i,x}-2}\binom{l_{i,x}-2}{k_i}\sum_{h_i=1}^{w_i}\binom{w_i}{h_i}\psi(k_i,h_i), \\ \qquad\qquad \text{if } 1 \le i \le x, \\ \frac{m^2-\alpha^2(i-1)}{2\alpha^2 m^2}\sum_{k_i=0}^{l_{i,x}+g-2}\binom{l_{i,x}+g-2}{k_i}\sum_{k=0}^{k_i}\binom{k_i}{k}\sum_{r=0}^{1}\binom{1}{r} \\ \cdot(\frac{1}{m^2})^{k+r}(\frac{8}{m^2})^{k_i+1-k-r}\frac{1}{k+r+1}\frac{1}{k_i+1}(1- \\ \frac{9(x+1)}{m^2})^{z_x-k_i-2}, \qquad \text{if } i = x+1. \end{cases} \quad (36)$$

We use $P_{SR,DD}\,(x,\mu_1,\mu_3)$ to denote the probability that a successful source-to-relay transmission and x successful destination-to-destination transmissions will happen simultaneously in the next time slot, where $1 \le x \le \min\{\mu_1, \lfloor\frac{g}{2}\rfloor\}$. Then we have

$$P_{SR,DD}(x,\mu_1,\mu_3) = \binom{g-\mu_1}{x}\frac{\mu_3\binom{\mu_1}{x}}{\binom{g-x}{x}}\delta_1\delta_2\cdots\delta_i\cdots\delta_{x+1}, \quad (37)$$

where

$$\delta_i = \begin{cases} p\frac{m^2-\alpha^2(i-1)}{\alpha^2 m^2}\sum_{k_i=0}^{l_{i,x}+g+x-2}\binom{l_{i,x}+g+x-2}{k_i}\sum_{h_i=1}^{w_i-x}\binom{w_i-x}{h_i} \\ \psi(k_i,h_i), \qquad \text{if } 1 \le i \le x, \\ \frac{m^2-\alpha^2(i-1)}{2\alpha^2 m^2}\sum_{k_i=0}^{l_{i,x}+g+x-2}\binom{l_{i,x}+g+x-2}{k_i}\sum_{k=0}^{k_i}\binom{k_i}{k}\sum_{r=0}^{1}\binom{1}{r} \\ \cdot(\frac{1}{m^2})^{k+r}(\frac{8}{m^2})^{k_i+1-k-r}\frac{1}{k+r+1}\frac{1}{k_i+1}(1- \\ \frac{9(x+1)}{m^2})^{z_x-k_i-2}, \qquad \text{if } i = x+1. \end{cases} \quad (38)$$

We use $P_{SD,DD}\,(x,\mu_1)$ to denote the probability that a successful source-to-destination transmission and x successful destination-to-destination transmissions will happen simultaneously in the next time slot, where $1 \le x \le \min\{\mu_1, \lfloor\frac{g}{2}\rfloor\}$. Then we have

$$P_{SD,DD}(x,\mu_1) = \binom{g-\mu_1}{x}\frac{\binom{\mu_1}{x}}{\binom{g-x}{x}}\varepsilon_1\varepsilon_2\cdots\varepsilon_i\cdots\varepsilon_{x+1}, \quad (39)$$

where

$$\varepsilon_i = \begin{cases} p\frac{m^2-\alpha^2(i-1)}{\alpha^2 m^2}\sum_{k_i=0}^{l_{i,x}+g+x-1}\binom{l_{i,x}+g+x-1}{k_i}\sum_{h_i=1}^{w_i-x}\binom{w_i-x}{h_i} \\ \cdot\psi(k_i,h_i), \qquad \text{if } 1 \le i \le x, \\ \frac{m^2-\alpha^2(i-1)}{\alpha^2 m^2}\sum_{k_i=0}^{l_{i,x}+g+x-1}\binom{l_{i,x}+g+x-1}{k_i}\sum_{h_i=1}^{w_i-x}\binom{w_i-x}{h_i} \\ \cdot\psi(k_i,h_i)\frac{k_i+h_i}{h_i}(1-\frac{9(x+1)}{m^2})^{z_x-k_i-h_i-1}, \text{if } i = x+1. \end{cases} \quad (40)$$

We use $P_{RD,DD}\,(x_1,x_2,\mu_1,\mu_2)$ to denote the probability that x_1 successful relay-to-destination transmissions and x_2 successful destination-to-destination transmissions will happen simultaneously in the next time slot, where $1 \le x_1 \le \min\{\mu_1, \mu_2\}$

and $1 \leq x_2 \leq \min\{\mu_1 - x_1, \lfloor \frac{g-x_1}{2} \rfloor\}$. Then we have

$$P_{RD,DD}(x_1, x_2, \mu_1, \mu_2) = \binom{\mu_2}{x_1}\binom{g-\mu_1}{x_2}\frac{\binom{\mu_1}{x_1+x_2}}{\binom{g-x_2}{x_1+x_2}} \tag{41}$$

$$\cdot\, \vartheta_1\vartheta_2\cdots\vartheta_i\cdots\vartheta_{x_1}\cdots\vartheta_{x_1+x_2}, \tag{42}$$

where

$$\varepsilon_i = \begin{cases} \frac{m^2-\alpha^2(i-1)}{2\alpha^2m^2}\sum_{k_i=0}^{l_{i,x_1}}\binom{l_{i,x_1}}{k_i}\sum_{h_i=1}^{w_i-x_2}\binom{w_i-x_2}{h_i}\psi(k_i,h_i), \\ \qquad \text{if } 1 \leq i \leq x_1, \\ p\frac{m^2-\alpha^2(i-1)}{\alpha^2m^2}\sum_{k_i=0}^{l_{i,x_1}+g}\binom{l_{i,x_1}+g}{k_i}\sum_{h_i=1}^{w_i-x_2}\binom{w_i-x_2}{h_i}\psi(k_i,h_i), \\ \qquad \text{if } x_1 < i \leq x_1+x_2-1, \\ p\frac{m^2-\alpha^2(i-1)}{\alpha^2m^2}\sum_{k_i=0}^{l_{i,x_1}+g}\binom{l_{i,x_1}+g}{k_i}\sum_{h_i=1}^{w_i-x_2}\binom{w_i-x_2}{h_i}\psi(k_i,h_i) \\ \cdot\psi(k_i,h_i)(1-\frac{9(x_1+x_2)}{m^2})^{n-x_1-x_2-\sum_{j=1}^{x_1+x_2}h_j-\sum_{j=1}^{x_1+x_2}k_j}, \\ \qquad \text{if } i = x_1+x_2. \end{cases} \tag{43}$$

We use $P_{SR,RD,DD}\ (x_1, x_2, \mu_1, \mu_2, \mu_3)$ to denote the probability that a source-to-relay transmission, x_1 successful relay-to-destination transmissions and x_2 successful destination-to-destination transmissions will happen simultaneously in the next time slot, where $1 \leq x_1 \leq \min\{\mu_1, \mu_2\}$ and $1 \leq x_2 \leq \min\{\mu_1 - x_1, \lfloor \frac{g-x_1}{2} \rfloor\}$. Then we have

$$P_{SR,RD,DD}(x_1, x_2, \mu_1, \mu_2) = \binom{\mu_2}{x_1}\binom{g-\mu_1}{x_2}\frac{\mu_3\cdot\binom{\mu_1}{x_1+x_2}}{\binom{g-x_2}{x_1+x_2}}$$

$$\cdot\, \zeta_1\zeta_2\cdots\zeta_i\cdots\zeta_{x_1+x_2}\zeta_{x_1+x_2+1}, \tag{44}$$

where

$$\zeta_i = \begin{cases} \frac{m^2-\alpha^2(i-1)}{2\alpha^2m^2}\sum_{k_i=0}^{l_{i,x_1}-2}\binom{l_{i,x_1}-2}{k_i}\sum_{h_i=1}^{w_i-x_2}\binom{w_i-x_2}{h_i}\psi(k_i,h_i), \\ \qquad \text{if } 1 \leq i \leq x_1, \\ p\frac{m^2-\alpha^2(i-1)}{\alpha^2m^2}\sum_{k_i=0}^{l_{i,x_1}+g-2}\binom{l_{i,x_1}+g-2}{k_i}\sum_{h_i=1}^{w_i-x_2}\binom{w_i-x_2}{h_i}\psi(k_i,h_i), \\ \qquad \text{if } x_1 < i \leq x_1+x_2, \\ \frac{m^2-\alpha^2(i-1)}{2\alpha^2m^2}\sum_{k_i=0}^{l_{i,x_1}+g-2}\binom{l_{i,x_1}+g-2}{k_i}\sum_{k=0}^{k_i}\binom{k_i}{k}\sum_{r=0}^{1}\binom{1}{r} \\ \cdot(\frac{1}{m^2})^{k+r}(\frac{8}{m^2})^{k_i+1-k-r}\frac{1}{k+r+1}\frac{1}{k_i+1} \\ (1-\frac{9(x_1+x_2+1)}{m^2})^{n-x_1-x_2-\sum_{j=1}^{x_1+x_2}h_j-\sum_{j=1}^{x_1+x_2+1}k_j-2}, \\ \qquad \text{if } i = x_1+x_2+1. \end{cases} \tag{45}$$

We use $P_{SD,RD,DD}\ (x_1, x_2, \mu_1, \mu_2)$ to denote the probability that a source-to-destination transmission, x_1 successful relay-to-destination transmissions and x_2 successful destination-to-destination transmissions will happen simultaneously in the next time slot, where $1 \leq x_1 \leq \min\{\mu_1, \mu_2\}$ and $1 \leq x_2 \leq \min\{\mu_1 - x_1, \lfloor \frac{g-x_1-1}{2} \rfloor\}$. Then we have

$$P_{SD,RD,DD}(x_1, x_2, \mu_1, \mu_2) = \binom{\mu_2}{x_1}\binom{g-\mu_1}{x_2}\frac{\binom{\mu_1}{x_1+x_2+1}}{\binom{g-x_2}{x_1+x_2+1}}$$

$$\cdot\, \varrho_1\varrho_2\cdots\varrho_i\cdots\varrho_{x_1+x_2}\varrho_{x_1+x_2+1}, \tag{46}$$

where

$$\varrho_i = \begin{cases} \frac{m^2-\alpha^2(i-1)}{2\alpha^2m^2}\sum_{k_i=0}^{l_{i,x_1}-1}\binom{l_{i,x_1}-1}{k_i}\sum_{h_i=1}^{w_i-x_2}\binom{w_i-x_2}{h_i}\psi(k_i,h_i), \\ \qquad \text{if } 1 \leq i \leq x_1, \\ p\frac{m^2-\alpha^2(i-1)}{\alpha^2m^2}\sum_{k_i=0}^{l_{i,x_1}+g-1}\binom{l_{i,x_1}+g-1}{k_i}\sum_{h_i=1}^{w_i-x_2}\binom{w_i-x_2}{h_i} \\ \cdot\psi(k_i,h_i), \qquad \text{if } x_1 < i \leq x_1+x_2, \\ \frac{m^2-\alpha^2(i-1)}{\alpha^2m^2}\sum_{k_i=0}^{l_{i,x_1}+g-1}\binom{l_{i,x_1}+g-1}{k_i}\sum_{h_i=1}^{w_i-x_2}\binom{w_i-x_2}{h_i} \\ \cdot\psi(k_i,h_i)\frac{k_i+h_i}{h_i}(1-\frac{9(x_1+x_2+1)}{m^2})^{z_{x_1+x_2+1}} \\ \qquad \text{if } i = x_1+x_2+1. \end{cases} \tag{47}$$

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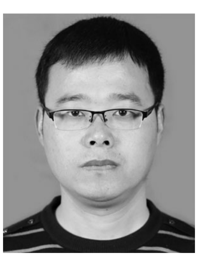

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