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Multicast Delivery Probability of MANETs with Limited Packet Redundancy

Bin Yang, Yulong Shen, Guilin Chen, and Yuanyuan Fan

***Abstract*—The available delivery probability studies for mobile ad hoc networks (MANETs) mainly considered unicast scenario, i.e., a source has only one destination, which cannot support future multicast-intensive applications in such networks. In this paper, we propose a general two-hop relay algorithm with cooperative probability p, packet lifetime τ, packet redundancy f and multicast fanout g. In such an algorithm, source node can replicate a packet to at most f distinct relay nodes, which help to forward the packet to its g destination nodes before τ expires. Specifically, the destination nodes may also forward the packet for each other with cooperative probability p. To study the multicast delivery probability in MANETs, we first develop a Markov chain model to characterize the packet delivery process under the routing algorithm, based on which an analytical expression is then derived for the delivery probability. Finally, simulation and numerical results are presented to illustrate the accuracy of the theoretical delivery probability analysis as well as our theoretical findings.**

***Index Terms*—Mobile Ad Hoc Network, two-hop relay, multicast delivery probability.**

I. Introduction

The mobile ad hoc networks (MANETs) are a kind of self-organizing networks consisting of mobile devices, where packets are delivered from sources to destinations over peer-to-peer wireless links. Multicast in such MANETs is a fundamental traffic model for supporting many practical applications with one-to-many communications [1]–[6], such as messages exchange among a group of soldiers in battlefield, earthquake alarming, video conferencing, multimedia games, etc. To support these multicast-intensive applications in future MANETs, it is critical to explore the multicast delivery probability performance of such networks.

Some preliminary works have been done to study the packet delivery probability, which is defined as the probability that a packet is delivered to its destination before packet lifetime expires. The authors of [7] studied the packet delivery probability in a two-hop relay MANET with packet redundancy. Later, the packet delivery probability was also evaluated in [8] with the consideration of erasure coding technique. We notice that the works of [7] and [8] considered separately the techniques of packet redundancy and erasure coding. Recently, literature [9] further explored the packet delivery probability by combining these two techniques together.

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It is notable that available works aforementioned focused on unicast scenario, i.e., a source has only one destination. Different from these works, this paper explores packet delivery probability under multicast scenario, where a source has multiple destinations. The main contributions of this paper are summarized as follows:

- We propose a general two-hop relay algorithm, under which each packet can be delivered to at most f distinct relay nodes, and its destination nodes may receive the packet with the help of these relay nodes before packet lifetime τ expires. The packet can also be forwarded for each other among destination nodes with cooperative probability p.
- We then develop a two-dimensional Markov chain theoretical framework to depict the packet delivery process under the general two-hop relay algorithm in the concerned MANET. Based on the theoretical framework, a closed-form expression is further derived for expected packet delivery probability.
- We finally provide extensive simulation and numerical results to validate the efficiency of the theoretical packet delivery probability analysis and also to illustrate our theoretical findings.

The rest of this paper is organized as follows. We introduce system model and transmission scheduling in Section II. Section III proposes a general routing algorithm, and then develops a two-dimensional Markov chain theoretical framework related to the general routing algorithm. In Section IV, we derive a closed-form expression for the expected packet delivery probability. Numerical results are provided in Section V. Finally, this paper is concluded in Section VI.

II. System Model and Transmission Scheduling

A. System Model

We consider a time-slotted MANET with n mobile nodes lying on a two-dimensional unit torus. As shown in Fig. 1(a), the network area is evenly divided into $m \times m$ cells [10]. The i.i.d. model [11], [12] is considered for nodes mobility. Under such model, at the beginning of each time slot, every node independently and randomly selects one of the m^2 cells and stays in it for the whole time slot.

The protocol model [13] is adopted here to decide if a transmission between a transmitter and its receiver is successful. Under this model, the transmission from transmitter Tx to receiver Rx is successful iff for any other node Tk that is simultaneously transmitting with node Tx, we have

$$d_{Tk,Rx} \geq (1+\Delta) d_{Tx,Rx} \tag{1}$$

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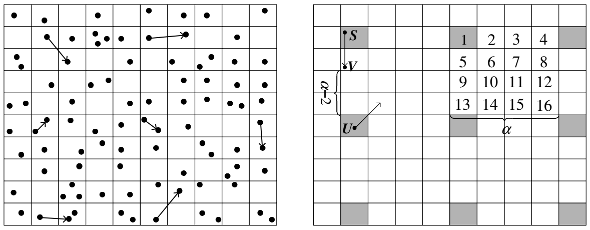

(a) Network model

(b) Illustration of transmission-group based scheduling scheme with $\alpha = 4$.

Fig. 1. Network model and scheduling scheme.

where $d_{Tk,Rx}$ is the distance between node Tk and node Rx, and Δ is a positive constant representing a guard zone to prevent the transmission from being corrupted by interference from simultaneous transmissions.

Similar to [7], we consider a local transmission scenario, where a transmitting node can only forward message to the nodes within the same cell or its eight adjacent cells. Two cells are called adjacent if they share a common point. Thus, the node transmission range r can be determined as $r = \sqrt{8/m}$.

All nodes in MANET are evenly divided into different multicast groups, each of which consists of one source node and g destination nodes [14], [15]. Each node in any multicast group can act as a relay to forward packets of other multicast groups. With cooperative probability p, destination nodes of an identical multicast group forward packets for each other.

B. Transmission Scheduling

To schedule as many simultaneous transmissions as possible without mutually interfering, a transmission-group based scheme [16] is adopted for transmission scheduling.

Transmission-group: A transmission-group is defined as a subset of cells, where any two of them have a vertical and horizontal distance of some multiple of α cells away and all the cells there could transmit simultaneously without interfering with each other. As shown in Fig.1(b) with $\alpha = 4$, there are in total 16 transmission-groups and all the gray cells belong to the same transmission-group.

Let each transmission-group get transmission opportunity (i.e., has link transmissions) alternatively, then each cell will get transmission opportunity in every α^2 time slots. We call a cell that gets a transmission opportunity as active cell. If more than one node locate in an active cell, a transmitting node will be selected randomly from them.

Now, we determine the value of α for our scheduling scheme. As shown in Fig. 1(b), suppose that node S is in an active cell and is transmitting to node V at some time slot. According to the definition of "transmission-group", any another simultaneous transmitting node (say node U) is at least $(\alpha - 2)/m$ away from V. According to formula (1), the following condition should be satisfied to ensure the successful reception of V: $(\alpha - 2)/m \geq (1 + \triangle) \cdot r$, where $r = \sqrt{8}/m$. Thus, the parameter α can be determined as

$$\alpha = min\{\lceil(1 + \triangle)\sqrt{8}\rceil + 2, m\}. \qquad (2)$$

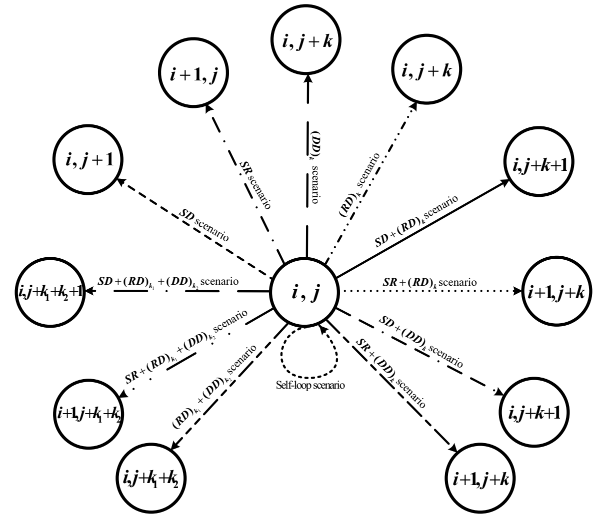

Fig. 2. The transition diagram of a general transient state $(i,\ j)$.

III. Algorithm and Theoretical Framework

A. Algorithm

Algorithm 1 Routing Algorithm:

1. For a transmitter Trx and its receiver Rrx at current time slot.
2. **if** Rrx is a destination of Trx **then**
3. Trx conducts a *source-to-destination* transmission with Rrx;
4. **else if** both Trx and Rrx are in the same multicast group and cooperative probability $p > 0$ **then**
5. Trx conducts a *destination-to-destination* transmission with Rrx;
6. **else if** Trx and Rrx are in different multicast groups **then**
7. Trx conducts the following two transmissions with equal probability;
8. Trx conducts a *source-to-relay* transmission with Rrx {each packet at Trx can be delivered to at most f distinct relay nodes};
9. Trx conducts a *relay-to-destination* transmission with Rrx;
10. **end if**

B. Markov Chain Theoretical Framework

For a tagged multicast group with a source node S and g destination nodes (D_1,D_2,$\cdots$,D_g), and a given packet at S, two-tuple (i, j) is used to denote a general state, under which there are i relay nodes carrying a copy of the packet, and j destination nodes having received the packet, where $0 \leq i \leq f$ and $0 \leq j \leq g$. If $j < g$, then the general state is a transient state; an absorbing state,otherwise. we assume that the tagged multicast group is currently in transient state (i, j), then at the next time slot, only one of the following transition scenarios shown in Fig. 2 may occur:

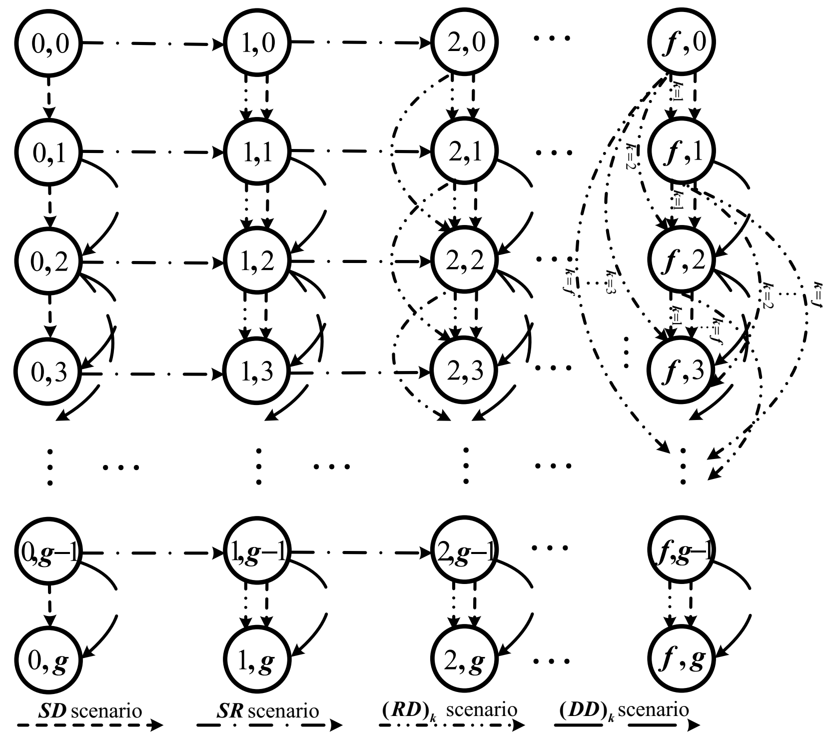

Fig. 3. Absorbing Markov Chain. For each transient state, the following transition scenarios are not shown for simplicity: $SD + (RD)_k$, $SR + (RD)_k$, $SD + (DD)_k$, $SR + (DD)_k$, $(RD)_{k_1} + (DD)_{k_2}$, SR+$(RD)_{k_1} + (DD)_{k_2}$, SD+$(RD)_{k_1} + (DD)_{k_2}$ and Self-loop.

- SD scenario: source-to-destination transmission only.
- SR scenario: source-to-relay transmission only.
- $(DD)_k$ scenario: k simultaneous destination-to-destination transmissions only.
- $(RD)_k$ scenario: k simultaneous relay-to-destination transmissions only.
- $SD + (RD)_k$ scenario: one source-to-destination and k relay-to-destination transmissions only.
- $SR + (RD)_k$ scenario: one source-to-relay and k relay-to-destination transmissions only.
- $SD + (DD)_k$ scenario: one source-to-destination and k destination-to-destination transmissions only.
- $SR + (DD)_k$ scenario: one source-to-relay and k destination-to-destination transmissions only.
- $(RD)_{k_1} + (DD)_{k_2}$ scenario: k_1 relay-to-destination and k_2 destination-to-destination transmissions only.
- $SR + (RD)_{k_1} + (DD)_{k_2}$ scenario: one source-to-relay, k_1 relay-to-destination and k_2 destination-to-destination transmissions only.
- $SD + (RD)_{k_1} + (DD)_{k_2}$ scenario: one source-to-destination, k_1 relay-to-destination and k_2 destination-to-destination transmissions only.
- Self-loop scenario: transition from (i, j) to (i, j).

According to the transition diagram in Fig. 2, we model the packet delivery process under the routing algorithm as a two-dimensional Markov chain,as shown in Fig. 3.

IV. Packet Delivery Probability

For a given packet lifetime τ, the delivery probability of a packet is defined as the ratio of the number of destination nodes having received the packet before the τ expires and the total number of destination nodes g of in a multicast group.

We denote by β the total number of transient states in the Markov chain as shown in Fig. 3, where $\beta = g(f + 1)$. In a left-to-right and top-to-down way, these β transient states and $f + 1$ absorbing states are indexed sequentially as $1, 2, \cdots, \beta$ and $\beta + 1, \beta + 2, \cdots, \beta + f + 1$, respectively.

For a given packet originated from a tagged multicast group, we denote by N_d the packet delivery probability, and then determine the expected value $\mathrm{E}\{N_d\}$ of N_d as

$$\mathrm{E}\{N_d\} = \frac{1}{g} \sum_{k=0}^{g} \sum_{l=1}^{f+1} M(k, l) m_{1,d}, \tag{3}$$

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

$$d = (f + 1)k + l. \tag{4}$$

To obtain $\mathrm{E}\{N_d\}$, we now need to determine $M(k, l)$. Notice that under each state of the kth row in the Markov chain, k destination nodes have received the packet, and then

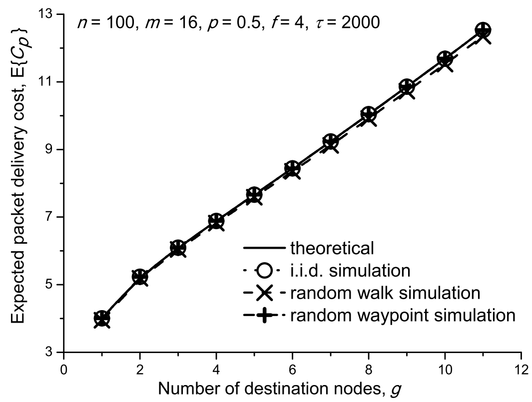

Fig. 4. Comparisons between theoretical results and the simulation ones for model validation.

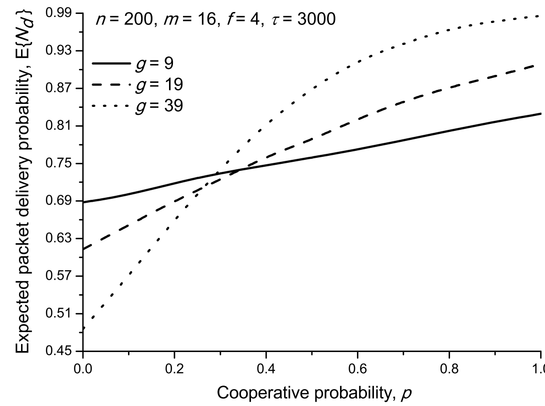

Fig. 5. $\mathrm{E}\{N_d\}$ versus p.

we have

$$M(k,l) = k. \tag{5}$$

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

$$\mathbf{P} = \begin{bmatrix} \mathbf{Q} & \mathbf{R} \\ \mathbf{O} & \mathbf{I} \end{bmatrix}, \tag{6}$$

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

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

$$\mathbf{P}^\tau = \begin{bmatrix} \mathbf{Q}^\tau & \mathbf{N}(\mathbf{I}-\mathbf{Q}^\tau)\mathbf{R} \\ \mathbf{O} & \mathbf{I} \end{bmatrix}, \tag{7}$$

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

$$m_{1,d} = \begin{cases} w_{1,d} & \text{if } 1 \le d \le \beta, \\ b_{1,d} & \text{if } \beta+1 \le d \le \beta+f+1. \end{cases} \tag{8}$$

The derivation processes of transition probabilities in this section are omitted here, which are similar to those in literature [17]. Please refer to [17] for details.

V. Numerical Results

A. Model Validation

We developed a C++ simulator to simulate the packet delivery process under the routing algorithm in MANET. The guard factor is set as $\Delta = 1$, and hence the parameter α is determined as $\alpha = \min\{8, m\}$. Besides the i.i.d. mobility model, we also conduct simulation study under random walk model [18] and random waypoint model [19] in this paper.

We now use extensive simulations to validate the accuracy of our theoretical model. For the setting of $n = 100, m = 16, p = 0.5, f = 4$, and $\tau = 2000$, we summarize the corresponding theoretical and simulation results in Fig. 4. Fig. 4 illustrates the impact of g on expected packet delivery probability. Fig. 4 shows clearly that under i.i.d. mobility model, our theoretical results are very close to the simulation ones, which illustrates that our theoretical model can accurately capture the packet delivery probability performance under the routing algorithm. It is interesting to observe from Fig. 4 that our theoretical model can also capture the performance under the random walk and random waypoint models.

B. Performance Analysis

We summarize theoretical results in Fig. 5 to illustrate the impact of p the expected packet delivery probability $\mathrm{E}\{N_d\}$. Fig. 5 indicates that for each setting of g, the $\mathrm{E}\{N_d\}$ increases monotonously with p. This phenomenon can be explained as follows: when p increases, more destination nodes will willing to forward packets for each other, and thus increasing the packet delivery probability.

To explore the impact of replication parameter f on $\mathrm{E}\{N_d\}$, we summarize the theoretical results in Fig. 6. Fig. 6 indicates that the $\mathrm{E}\{N_d\}$ monotonously increases with f. This is because when f increases, source node obtains more transmission opportunities from source to relays, and thus the transmission opportunities from relays to destinations also increase, which leads to a higher packet delivery probability.

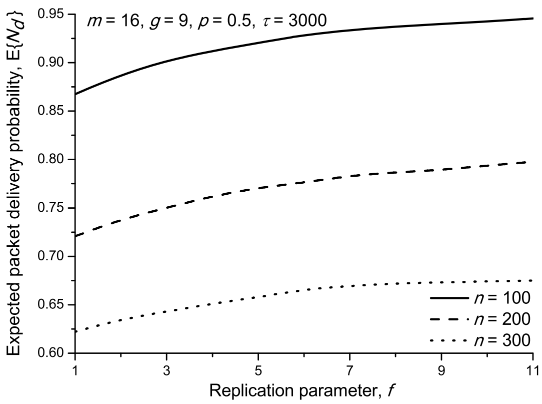

Fig. 6. $\mathrm{E}\{N_d\}$ versus f.

VI. Conclusion

This paper first proposed a general routing algorithm, and then developed a Markov chain theoretical framework to depict packet delivery process under such algorithm. With the help of the theoretical framework, we further derived a closed-form expression for the packet delivery probability. Extensive simulations illustrate the accuracy of theoretical analysis for packet delivery probability. Theoretical results indicate that we can achieve a high packet delivery probability through a proper setting of cooperative probability p.

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