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Group-based Two-hop Relay with Redundancy in MANETs

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***Abstract*—Two-hop relay is a class of attractive routing protocols for mobile ad hoc networks (MANETs) due to its efficiency and simplicity. This paper extends the conventional two-hop relay and proposes a more general group-based two-hop relay algorithm with redundancy. In such an algorithm with redundancy f and group size g (2HR-(f, g) for short), each packet is delivered to at most f distinct relay nodes and can be accepted by its destination if it is among the group of g packets the destination is currently requesting. The 2HR-(f, g) covers the available two-hop relay protocols as special cases, like the in-order protocols ($f \geq 1$, $g = 1$), the out-of-order protocols with redundancy ($f > 1$, $g = \infty$) or without redundancy ($f = 1$, $g = \infty$), and it enables a more flexible control of packet delivery process to be made in the challenging MANET environment. A general theoretical framework is further developed to explore how the control parameters f and g affect the expected packet delivery delay in an 2HR-(f, g) MANET, where the important medium contention, interference and traffic contention issues are carefully incorporated into the analysis. Finally, extensive simulation and theoretical results are provided to demonstrate the efficiency of the 2HR-(f, g) scheme and the corresponding theoretical framework.**

I. Introduction

Since the seminal work of Grossglauser and Tse [1], the two-hop relay and its variants have become a class of attractive routing protocols for mobile ad hoc networks (MANETs). In the two-hop relay routing the source transmits packets to the mobiles (relays) it encounters; relays transmit the packets only if they come in contact with the destination. Thus, each packet travels at most two hops to reach its destination.

For its efficiency and simplicity, the two-hop relay algorithm has been widely employed in the MANETs. The algorithms in [1]–[3] can be regarded as the out-of-order routing without redundancy, where a packet has at most one copy and will be accepted by its destination as long as it is "fresh" (never received before). The two-hop relays in [4], [5] also adopt the out-of-order reception but allow each packet to have multiple copies (i.e., with redundancy). Recently, some new two-hop relay algorithms have been proposed in [6]–[8] where each packet should be received in-order at its destination. For a detailed survey, please refer to the [8] and reference therein.

Notice that due to node mobility in a MANET, the meeting time and thus the data transmission time between any two nodes is actually very short, which significantly limits the number of bits that can be delivered in such a transmission. Therefore, in MANETs a message is usually divided into multiple small fragments in the delivery process. For the two-hop relay routing with out-of-order reception, an early arrived message-fragment may need to wait a long time (if not expired) before becoming useful, and each mobile node should potentially carry an infinite buffer to accommodate all possible arrivals, which may not be practical for the MANETs. For the strict in-order reception ones, on the other hand, a lot of precious reception chances may be wasted, resulting in a significant reduction in throughput.

To have a more flexible control of packet delivery process and a nice trade-off between strict in-order reception and complete out-of-order reception, this paper proposes a general group-based two-hop relay with redundancy. The main contributions of this paper are summarized as follows.

- This paper proposes an 2HR-(f, g) algorithm in Section II, where each packet is delivered to at most f distinct relay nodes and can be accepted by its destination if it is among the group of g packets the destination is currently requesting. This algorithm covers all the available two-hop routing protocols as special cases, like the strictly in-order ones [6]–[8] ($f \geq 1$, $g = 1$), the out-of-order ones with redundancy [4], [5] ($f > 1$, $g = \infty$) or without redundancy [1]–[3] ($f = 1$, $g = \infty$).
- We further develop a general Markov chain-based theoretical framework in Section III to model the message delivery process and explore how the f and g would affect the expected packet delivery delay. By setting $g = 1$, our framework reduces to some available models developed for two-hop relay [9]–[12].
- With the help of the theoretical framework, in Section III, closed-form expressions are developed for the packet delivery delay with a careful consideration of the important medium contention, interference and traffic contention issues. Finally, extensive simulation and theoretical results are provided in Section IV for validation of the new relay scheme and the theoretical framework.

II. The 2HR-(f, g) Algorithm and Transmission Scheduling

A. System Models

The network we consider in this paper consists of n mobile nodes inside a unit square, which is evenly divided into $m \times m$

cells. We focus on a slotted system and a fast mobility scenario [13], where only one-hop transmissions are possible within each time slot, and the total number of bits transmitted per slot is fixed and normalized to 1 packet here. The nodes independently roams from cell to cell and follows the bi-dimensional i.i.d. mobility model [6]. At the beginning of each time slot, each node independently and uniformly selects a destination cell among all m^2 cells and stays in it for the whole time slot. The protocol model with guarding factor Δ is adopted as the interference model [14]. We further assume a permutation traffic pattern in the saturated case, where each node is a source and at the same time a destination of some other node, and each source node always has packets waiting for delivery.

B. The 2HR-(f, g) Algorithm

Since each node can be a potential relay for other $n-2$ flows (except the two flows originating from and destined for itself), we assume that each node maintains n individual queues at its buffer, one local-queue for storing the packets that are locally generated at the node and waiting for copy-distribution, one already-sent-queue for storing packets whose f replicas have already been distributed but reception status are not confirmed yet (from destination node), and $n-2$ parallel relay-queues for storing packets of other flows (one queue per flow).

For each flow, the source node divides packets waiting at the local-queue into consecutive groups, with g packets per group, and labels each packet P with a *send group number* $SG(P)$ and *sequence number* $SN(P)$ $(1 \leq SN(P) \leq g)$, so that the packet P can be efficiently retrieved from the queue buffers using the tag $(SG(P), SN(P))$. Similarly, the destination node maintains a *request group number* RG and *indicator bits* IN. The IN is a g-bit binary and used to record the reception status for packets of group RG, with $IN \& B_i = 0$ indicating that the i_{th} packet of group RG has already been received, otherwise not yet, where the B_i is a g-bit binary with all bits set as 0 except the i_{th} bit.

Each packet is delivered to at most f distinct relay nodes, while a relay node can carry at most one "fresh" packet from a particular group. A packet is called "fresh" iff none of its duplicate versions has been received by the destination. Given that a relay is carrying a packet of some group, if the packet is "fresh", then the relay is called a fresh relay node for the concerned group, otherwise an eligible relay candidate.

Without loss of generality, we focus on a tagged flow and denote its source node and destination node as S and D, respectively. Then the 2HR-(f, g) algorithm can be summarized as follows.

The 2HR-(f, g) Algorithm: For the tagged flow, every time the S gets a transmission opportunity, it operates as follows:

Step 1: (Source-to-Destination) Check if the node D is among its one-hop neighbors. If so, it initiates a handshake with the D to get the RG and IN. Then it transmits a fresh packet directly to the D, which is selected as follows: it first checks packets in its local-queue, i.e., whether the head of its local-queue packet P_h is eligible, if not it continues to check the packet waiting right behind P_h; if neither of the two packets is eligible, it tries to retrieve some fresh packet from the already-sent-queue.

Step 2: Otherwise, if the node D is not among the one-hop neighbors of S, the node S randomly chooses one of the following two operations to perform:

- (Source-to-Relay) It first randomly selects one node (say R) from its current one-hop neighbors, then initiates a handshake with R to check whether the R is an eligible relay candidate. If so, it delivers a new copy of P_h to the R; otherwise it remains idle for this time slot.
- (Relay-to-Destination) It acts as a relay and randomly selects one node (say V) as the receiver from its one-hop neighbors. It first initiates a handshake with the V to get the $RG(V)$ and IN, then checks in its relay-queue specified for the V whether there exists a fresh packet of group $RG(V)$. If so, it delivers this packet to the V; otherwise it remains idle for this time slot.

Notice that in the above Source-to-Relay transmission, every time the S sends out a copy of P_h it checks whether f copies of P_h have already been delivered. If yes, it puts P_h to the end of the already-sent-queue and then moves ahead the remaining packets in the local-queue. At the relay node, the P_h is put at the end of its relay-queue dedicated to the node D. Thus, each packet may have at most $f+1$ copies (including the one in the already-sent-queue of its source node).

Remark 1: By proper setting of the two control parameters, i.e., redundancy f and group size g, the 2HR-(f, g) algorithm is able to cover all the available two-hop relays as special cases, like the out-of-order ones with redundancy [4], [5] ($f > 1$, $g = \infty$) or without redundancy [1]–[3] ($f = 1$, $g = \infty$), and the strictly in-order ones [6]–[8] ($f \geq 1$, $g = 1$).

Remark 2: In the 2HR-(f, g) algorithm, if the destination node D is requesting for group i, any fresh packet belonging to the group i is eligible for reception. However, it will start to receive packets of the group $i+1$ only after all packets of the group i have been received. It's easy to see that, the inter-group packet reception at node D is strictly in-group-order while the intra-group packet reception is totally out-of-order. Thus, the packet delivery process can be flexibly controlled by the two parameters f and g.

C. Transmission Scheduling

We consider a local transmission scenario, in which a node in some cell can only send packets to the nodes in the same cell or its eight adjacent cells. Two cells are called adjacent if they share a common point. Thus, the maximum distance between a transmitting node (transmitter) and a receiving node (receiver) is $\sqrt{8}/m$, so we set the communication range as $r = \sqrt{8}/m$. Due to the wireless interference, only cells that are sufficiently far away could simultaneously transmit without interfering each other. To support as many simultaneous transmissions as possible, similar to the "equivalence class" in the [15] we define here the "concurrent-set".

Concurrent-set: As illustrated by the shaded cells in Fig. 1, a concurrent-set is a subset of cells in which any two cells have

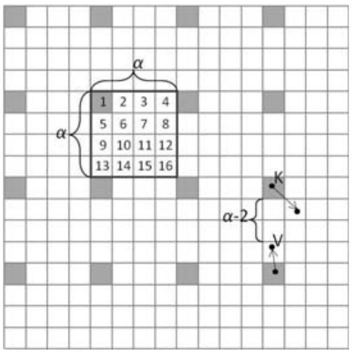
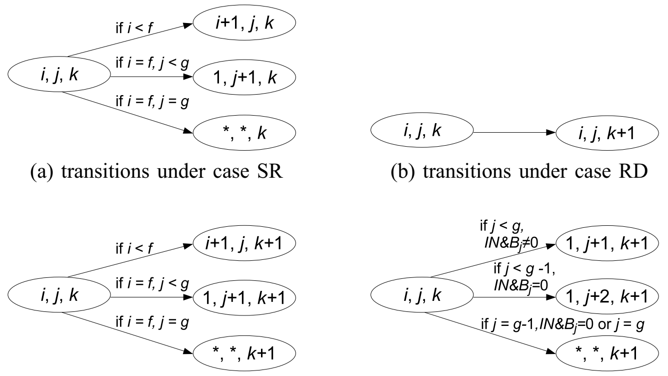


Fig. 1. An example of a concurrent-set of cells with $\alpha = 4$. The cells are divided into 16 different concurrent-sets and the shaded cells all belong to the same concurrent-set, i.e., the concurrent-set 1. The distribution of all the remaining nodes in the unit square is not shown for simplicity.



(a) transitions under case SR

(b) transitions under case RD

(c) transitions under case SR+RD

(d) transitions under case SD

Fig. 2. The transition diagram of the state (i, j, k), where $1 \leq i \leq f$, $1 \leq j \leq g$ and $0 \leq k < g$.

a vertical and horizontal distance of some multiple of α cells, and all the cells there can transmit simultaneously without interfering each other.

To guarantee the simultaneous transmissions in a concurrent-set without interfering each other, the parameter α should be set properly. As shown in the Fig. 1, suppose that during some time slot, the node V is scheduled to receive a packet. According to the definition of "concurrent-set", we know that except the transmitting node of V, another transmitting node (say node K) in the same concurrent-set is at least $(\alpha - 2)/m$ away from V. The condition that K will not interfere with the reception at V is that, $(\alpha - 2)/m \geq (1 + \Delta) \cdot r$. By substituting $r = \sqrt{8}/m$, we obtain that $\alpha \geq (1 + \Delta)\sqrt{8} + 2$. As α is an integer and $\alpha \leq m$, we set

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

where $\lceil x \rceil$ returns the smallest integer not less than x.

Notice that each cell will become active (i.e., get transmission opportunity) in every α^2 time slots. If there are more than one node inside an active cell, a transmitting node is selected randomly from them. The selected node then follows the 2HR-(f, g) algorithm for packet transmission.

III. The Markov Chain-based Framework and Expected Packet Delivery Delay

A. A Markov Chain-based Theoretical Framework

For a tagged packet group at the source node S, we define a three-tuple (i, j, k), which denotes the state that the S is delivering the i_{th} $(1 \leq i \leq f)$ copy for the j_{th} $(1 \leq j \leq g)$ packet and the destination node D has received k $(0 \leq k < g)$ packets. We further use $(*, *, k)$ to denote the state that the S has already finished copy distribution for packets of the tagged group while the D has only received k $(0 \leq k < g)$ packets of them. Then according to the 2HR-(f, g) algorithm, for any node pair S and D in state (i, j, k) at some time slot, only one of the following transmission cases will happen in the next time slot.

- (case SR) source-to-relay transmission only, i.e., the S successfully delivers the i_{th} copy to a new relay while none of the relays delivers a fresh packet to the D;
- (case RD) relay-to-destination transmission only, i.e., some relay node successfully delivers a fresh packet to node D while S fails to deliver out the i_{th} copy to a new relay node;
- (case SR+RD) both source-to-relay and relay-to-destination transmissions, i.e., these two transmissions happen simultaneously;
- (case SD) source-to-destination transmission, i.e., the S successfully delivers out a fresh packet to the D.

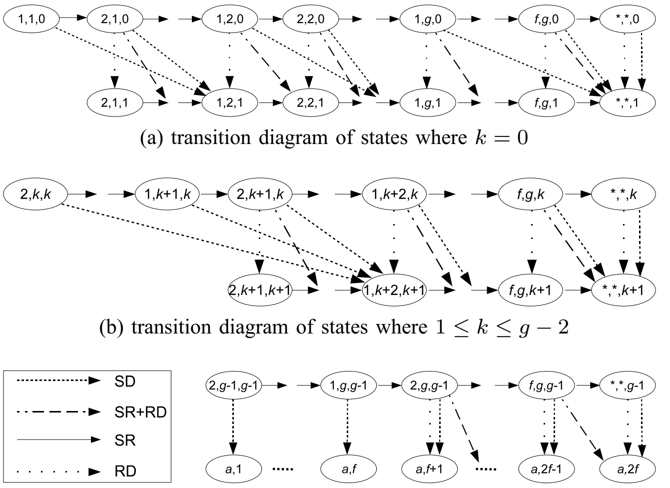
Thus, the packet delivery process of the tagged group can be modeled as a discrete-time finite-state absorbing Markov chain. As indicated in [9], [11], it is tough to accurately model the delivery process of even a single packet when $f > 1$ and $g = 1$, the general settings of f and g here makes this task much more difficult.

The first challenging task is to define the transitions among neighboring transient states. As shown in the Fig. 2, for a general state (i, j, k), even under the same transmission case (SR, RD, SR+RD or SD), the target state varies significantly, which depends not only on the concrete values of i, j and k, but also on the reception status of the j_{th} packet, i.e., $IN\&B_j$.

Based on the observation that in a large MANET, the probability of source-to-destination transmission is negligible when in comparison with that of source-to-relay or relay-to-destination transmission, and in order to simplify the analysis, we make the following assumption:

Assumption 1: We assume that for any state (i, j, k) where $1 \leq i \leq f$, $1 \leq j < g$ and $0 \leq k < j$, the target state under the transmission case SD is the state $(1, j + 1, k + 1)$.

Notice that the only simplification by the Assumption 1 is to neglect the case of $IN\&B_j = 0$ when $k < j < g$ in Fig. 2d. Obviously, this simplification slightly "slows down" the absorbing speed of actual delivery process. In light of the fact that $Pr(A \cap B) \leq Pr(A)$ where $Pr(A)$ denotes the probability of event A, the probability of this "slowing down" is much smaller than that of source-to-destination



(a) transition diagram of states where $k = 0$

(b) transition diagram of states where $1 \le k \le g-2$

(c) transition diagram of states where $k = g-1$

Fig. 3. Transition diagram of the Markov chain for the general 2HR-(f, g) algorithm. For each transient state, the transition back to itself is not shown for simplicity.

transmission. Thus, the Assumption 1 is reasonable and the developed theoretical framework is ensured justifiable.

Another challenging task is to derive the exact transition probabilities for each transient state, which depend on the actual number of fresh relay nodes and eligible relay candidates. The main reason is due to the complicate network dynamics during the delivery process, where a fine-grained definition of transient state may help generate an accurate derivation for transition probability, but unavoidably results in a steep increase in the size of its state space. Thus, in order to keep the Markov chain tractable and derive closed-form results, we use the three-tuple (i, j, k) to denote a transient state.

We further denote by (a, t) the t_{th} absorbing state, $t \in [1, 2f]$, and now we are ready to illustrate the transition diagram of the absorbing Markov chain. As indicated in the Fig. 3, there are g rows of transient states, with L_k transient states in the k_{th} row where

$$L_k = \begin{cases} (g+1-k)f & \text{if } 1 \le k \le g-1 \\ g \cdot f + 1 & \text{if } k = 0 \end{cases} \tag{1}$$

Remark 3: As shown in the Fig. 3, the Markov-chain based framework achieves the minimal size of state space. Specifically, there are β transient states

$$\beta = \frac{f}{2}(g^2 + 3g - 2) + 1 \tag{2}$$

and $2f$ absorbing states in the absorbing Markov chain, which depends only on the control parameters f and g. By setting $g = 1$, our framework reduces into the models developed in the [9]–[12].

Lemma 1: For the t_{th} transient state in the k_{th} row, $k \in [1, g-1]$, the number of corresponding fresh relay nodes is lower bounded by l_r and upper bounded by u_r where

$$l_r = t - f \tag{3}$$
$$u_r = t - t\%f \tag{4}$$

Lemma 2: For the t_{th} transient state in the k_{th} row, $k \in [1, g-1]$, the number of corresponding eligible relay candidates is lower bounded by l_o and upper bounded by u_o where

$$l_o = n - 2 - t - (k-1)f \tag{5}$$
$$u_o = n - 2 - t + f \tag{6}$$

B. The Expected Packet Delivery Delay

Recall that the performance metric of interest is the expected packet delivery delay under the general 2HR-(f, g) algorithm, we denote it as $\mathbb{E}\{T_p\}$ and derive closed-form expressions for the $\mathbb{E}\{T_p\}$ in this subsection.

Definition 1: For any packet group (say group i) at the source node S, the delivery delay of packet group i is the time elapsed from the time slot when the S moved the first packet of group i into the head-of-line at its local-queue, to the time slot when the destination node D received the last packet of group i, given that $RG(D) = i$.

If we denote by $T(f, g)$ the delivery delay of a packet group under the 2HR-(f, g) relay algorithm, then we have

$$\mathbb{E}\{T_p\} = \frac{\mathbb{E}\{T(f, g)\}}{g} \tag{7}$$

Before presenting our main analytical results, we first provide the analysis of some basic probabilities.

Lemma 3: For a time slot and one given source node, we use p_1 and p_2 to denote the probability that the source conducts a Source-to-Destination transmission and the probability that the source conducts a Source-to-Relay or Relay-to-Destination transmission, respectively. Then we have

$$p_1 = \frac{1}{\alpha^2}\left(\frac{9n - m^2}{n(n-1)} - \left(1 - \frac{1}{m^2}\right)^{n-1} \frac{8n + 1 - m^2}{n(n-1)}\right) \tag{8}$$

$$p_2 = \frac{1}{\alpha^2}\left(\frac{m^2 - 9}{n-1}\left(1 - \left(1 - \frac{1}{m^2}\right)^{n-1}\right) - \left(1 - \frac{9}{m^2}\right)^{n-1}\right) \tag{9}$$

Lemma 4: For a time slot and one given source node S which is delivering copies for some packet group i, given that there are t_1 fresh relay nodes of group i, t_2 eligible relay candidates and $RG(D) = i$, we use $P_r(t_1)$, $P_d(t_2)$ and $P_s(t_1, t_2)$ to denote the probability that the destination node D will receive a fresh packet, the probability that the S will successfully deliver out a copy to some new relay in the next time slot and the probability of simultaneous source-to-relay and relay-to-destination transmissions in the next time slot, respectively. Then we have

$$P_r(t_1) = p_1 + \frac{t_1}{2(n-2)} p_2 \tag{10}$$

$$P_d(t_2) = \frac{t_2}{2(n-2)} p_2 \tag{11}$$

$$P_s(t_1, t_2) = \frac{t_1 t_2 (m^2 - \alpha^2)}{4 m^2 \alpha^4} \sum_{k=0}^{n-5} \binom{n-5}{k} h(k) \cdot \left\{ \sum_{t=0}^{n-4-k} \binom{n-4-k}{t} h(t) \left(1 - \frac{18}{m^2}\right)^{n-4-k-t} \right\} \tag{12}$$

where

$$h(x) = \frac{9\left(\frac{9}{m^2}\right)^{x+1} - 8\left(\frac{8}{m^2}\right)^{x+1}}{(x+1)(x+2)} \quad (13)$$

The proofs of Lemma 1, 2, 3 and 4 are omitted here due to space limit, and please refer to the [16] for proofs.

Based on the Markov chain-based theoretical framework developed in the Section III-A, we are now ready to derive closed-form expressions for the $\mathbb{E}\{T_p\}$.

As there are g rows of transient states in the Markov chain, we index these transient states sequentially using 1, 2, ..., β, first from left to right then from top to down. Let random variable b_i denote the time it takes the chain to become absorbed given that the chain starts in the i_{th} transient state ($1 \leq i \leq \beta$). Thus, the $T(f, g)$ can be determined as

$$T(f, g) = b_1 \quad (14)$$

Let $\mathbf{N}$ denote the fundamental matrix of the Markov chain in the Fig. 3. Note that the matrix $\mathbf{N}$ is of size $\beta \times \beta$, and from the (2), it's easy to see that as the parameter f (resp. the parameter g) increases by a factor of t, the β increases by a factor of nearly t (resp. by a factor of nearly t^2). Thus, it is hard to directly derive the $\mathbf{N}$ for general settings of f and g.

Here we instead divide the matrix $\mathbf{N}$ into g-by-g blocks with blocks in the k_{th} ($1 \leq k \leq g$) row corresponding to transient states in the $(k-1)_{th}$ row of the Markov chain. Based on this block partition, the ij-entry $\mathbf{N}_{tk}(i, j)$ of the tk-block $\mathbf{N}_{tk}$ can be regarded as the expected number of times in the j_{th} transient state of the $(k-1)_{th}$ row given that the chain starts from the i_{th} transient state of the $(t-1)_{th}$ row. Therefore, given that the chain starts in the state $(1, 1, 0)$ (i.e., $i = 1$, $t = 1$), we have

$$\mathbb{E}\{b_1\} = \sum_{k=1}^{g} \sum_{j=1}^{L_{k-1}} \mathbf{N}_{1k}(1, j) \quad (15)$$

Combining with the (7) and (14), it follows

$$\mathbb{E}\{T_p\} = \frac{1}{g} \sum_{k=1}^{g} \sum_{j=1}^{L_{k-1}} \mathbf{N}_{1k}(1, j) \quad (16)$$

The (16) says that in order to derive the $\mathbb{E}\{T_p\}$, we need to first derive the matrix $\mathbf{N}$. Since

$$\mathbf{N} = (\mathbf{I} - \mathbf{Q})^{-1} \quad (17)$$

where the $\mathbf{Q}$ is the β-by-β matrix defined for transition probabilities among transient states in the canonical form of the transition matrix [17].

The derivations of the matrix $\mathbf{Q}$ and $(\mathbf{I} - \mathbf{Q})^{-1}$ are omitted here, and please refer to the [16] for details.

IV. Numerical Results

A. Simulation Setting

A simulator in C++ was developed to simulate the packet delivery process in a 2HR-(f, g) MANET, which is now available at [18]. The simulated expected delivery delay was calculated as the average value of 10^2 batches of simulation results, where each batch consists of 10^4 random and independent simulations.

TABLE I

Comparison between simulation and theoretical results for model validation under the setting of $m = 8, n = 100$, Simulated / Theoretical

$f \backslash g$	1	6	8	12
1	908.3/908.1	859.2/859.1	841.5/841.8	810.1/810.3
2	891.9/892.3	827.8/828.2	806.7/807.7	770.9/773.2
3	880.7/881.2	817.7/819.1	798.2/801.3	767.5/774.6
4	871.2/873.5	817.5/821.6	802.8/809.1	780.5/794.3
5	868.9/868.2	824.1/829.6	813.4/822.9	799.1/819.7
6	864.5/864.6	831.2/839.4	824.4/837.7	817.1/843.0
7	862.2/862.1	838.7/848.9	834.7/850.9	831.5/861.3
8	859.9/860.5	845.4/857.1	843.0/861.6	842.9/874.8

B. Theoretical vs. Simulated Results

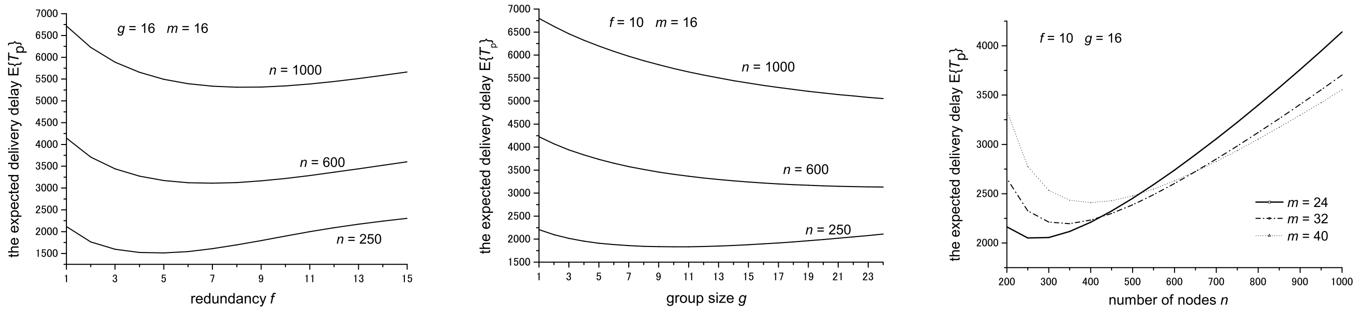
To verify the theoretical framework, extensive simulations were conducted under the setting of ($m = 8$, $n = 100$). Here only four scenarios ($g = 1, 6, 8, 12$) are included, and the results of other scenarios can be easily obtained by our simulator as well [18]. The corresponding simulation and theoretical results are summarized in the Table. I. Notice that the scenarios of $g = 1$ and $g = 12$ correspond to the strict in-order reception and complete out-of-order reception, respectively.

The Table. I indicates clearly that the simulation results match nicely with the theoretical ones, so our framework can be used to efficiently model the packet delivery process. A further careful observation of Table. I shows that there is still a very small gap ($\leq 5\%$) between the simulation results and theoretical ones. This gap is mainly due to the following two reasons. The first one is that the simplification adopted in the Assumption 1 slightly "slows" down the absorbing speed of the Markov chain, and thus results in a higher absorption time (i.e., delivery delay). The other reason is that in the definitions of $\mathbf{Q}_k$ and $\mathbf{Q}_k^{'}$, we applied the lower-bound (3) and (5) (rather than the actual number) of fresh relay nodes and eligible relay candidates, which made the theoretical results shift slightly from simulation ones.

C. Expected Delivery Delay vs. Control Parameters

Based on the theoretical framework, the Fig. 4 illustrates how expected delivery delay $\mathbb{E}\{T_p\}$ varies with f, g and n. It is interesting to note that in the Fig. 4a, for each setting of n, there exists an optimum value of redundancy f which achieves the minimum expected delivery delay $\mathbb{E}\{T_p\}$. For example, when $n = 250$, a minimal $\mathbb{E}\{T_p\}$ of 1511.17 is achieved at $f = 5$; for the case that $n = 600$ (resp. $n = 1000$), a minimal expected delivery delay of 3110.11 (resp. 5311.75) is achieved at $f = 7$ (resp. $f = 8$).

The Fig. 4b shows the relationship between the expected delivery delay $\mathbb{E}\{T_p\}$ and group size g. We can see from the Fig. 4b that when the number of nodes n is much bigger than the $g \cdot f$, the $\mathbb{E}\{T_p\}$ decreases as the g increases up. For example, when $n = 600, 1000$, the $\mathbb{E}\{T_p\}$ monotonically



(a) $\mathbb{E}\{T_p\}$ vs. f (b) $\mathbb{E}\{T_p\}$ vs. g (c) $\mathbb{E}\{T_p\}$ vs. n

Fig. 4. expected delivery delay vs. control parameters

decreases as the g increases from 1 up to 24. However, for the case that $n = 250$, as the g varies from 1 to 24, the $\mathbb{E}\{T_p\}$ first decreases, achieves the minimal value of 1833.77 at $g = 10$, and then gradually increases up to 2109.76 at $g = 24$.

When the parameters f, g are fixed as $f = 10$, $g = 16$, we can see from the Fig. 4c that there exists an optimum value of n which minimizes the $\mathbb{E}\{T_p\}$. For example, when $m = 32$ (resp. $m = 40$), the minimal $\mathbb{E}\{T_p\}$ of 2195.62 (resp. 2408.41) is achieved at $n = 350$ (resp. $n = 400$). The Fig. 4c also indicates that the n and thus the average node density (n/m^2) can significantly affect the $\mathbb{E}\{T_p\}$. For example, when $m = 24$, the $\mathbb{E}\{T_p\}$ of the $n = 1000$ is 4139.83, which is nearly 1.69 times as that of the $n = 500$ (2452.83 there).

V. Conclusion

This paper proposed a general 2HR-(f, g) algorithm for packet transmission in MANETs, which covers the available two-hop relay algorithms as special cases. A Markov chain theoretical framework was further developed for performance modeling of the new relay algorithm, based on which closed-form expressions for the expected packet delivery delay were derived. Extensive simulation and theoretical studies indicate that the theoretical framework is very efficient in performance modeling for the 2HR-(f, g) algorithm, and the new relay algorithm enables a flexible performance trade-off to be made in a large range through a proper setting of parameters f and g.

References

[1] M. Grossglauser and D. N. Tse, "Mobility increases the capacity of ad hoc wireless networks," in *INFOCOM*, 2001.

[2] E. Perevalov and R. S. Blum, "Delay-limited throughput of ad hoc networks," *IEEE Transactions on Communications*, vol. 52, no. 11, pp. 1957–1968, November 2004.

[3] J. Mammen and D. Shah, "Throughput and delay in random wireless networks with restricted mobility," *IEEE Transactions on Information Theory*, vol. 53, no. 3, pp. 1108–1116, 2007.

[4] T. Spyropoulos, K. Psounis, and C. S. Raghavendra, "Efficient routing in intermittently connected mobile networks: The multiple-copy case," *IEEE/ACM Transactions on Networking*, vol. 16, no. 1, pp. 77–90, February 2008.

[5] T. Small and Z. Hass, "Resource and performance tradeoffs in delay-tolerant wireless networks," in *ACM SIGCOMM Workshop on Delay Tolerant Networks (WDTN)*, 2005.

[6] M. J. Neely and E. Modiano, "Capacity and delay tradeoffs for ad-hoc mobile networks," *IEEE Transactions on Information Theory*, vol. 51, no. 6, pp. 1917–1936, June 2005.

[7] G. Sharma and R. Mazumdar, "On achievable delay/capacity trade-offs in mobile ad hoc networks," in *Wiopt*, 2004.

[8] J. Liu, X. Jiang, H. Nishiyama, and N. Kato, "Delay and capacity in ad hoc mobile networks with f-cast relay algorithms," in *ICC*, 2011.

[9] A. A. Hanbali, A. A. Kherani, and P. Nain, "Simple models for the performance evaluation of a class of two-hop relay protocols," in *Proc. IFIP Networking*, 2007.

[10] A. A. Hanbali, P. Nain, and E. Altman, "Performance of ad hoc networks with two-hop relay routing and limited packet lifetime," in *Valuetools*, 2006.

[11] A. Panagakis, A. Vaios, and I. Stavrakakis, "Study of two-hop message spreading in dtns," in *WiOpt*, April 2007.

[12] R. Groenevelt, G. Koole, and P. Nain, "Message delay in manet (extended abstract)," in *ACM Sigmetrics*, 2005.

[13] D. Ciullo, V. Martina, M. Garetto, and E. Leonardi, "Impact of correlated mobility on delay-throughput performance in mobile ad-hoc networks," in *INFOCOM*, 2010.

[14] P. Gupta and P. Kumar, "The capacity of wireless networks," *IEEE Transactions on Information Theory*, vol. 46, no. 2, pp. 388–404, March 2000.

[15] S. R. Kulkarni and P. Viswanath, "A deterministic approach to throughput scaling in wireless networks," *IEEE Transactions on Information Theory*, vol. 50, no. 6, pp. 1041–1049, June 2004.

[16] J. Liu, X. Jiang, H. Nishiyama, and N. Kato, "Group-based two-hop relay with redundancy in manets," Tohoku university, 2011, technical report 201104.01. [Online]. Available: http://distplat.blogspot.com

[17] C. M. Grinstead and J. L. Snell, *Introduction to Probability: Second Revised Edition*. American Mathematical Society, 1997.

[18] "C++ programs for the 2hr-(f, g) manet," http://distplat.blogspot.com.