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Delivery Ratio in Two-Hop Relay MANETs with Limited Message Lifetime and Redundancy

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***Abstract*—A lot of work has been done to model and analyze the performances of two-hop relay algorithm and its variants. However, the delivery ratio, especially under limited message lifetime, has been largely neglected in literature, which is not only of significant importance for delay sensitive applications (where a message beyond some delay limit will typically be dropped) but also of practical interests for general MANET scenarios (where mobile nodes are usually both energy-constrained and buffer storage-limited). In this paper, we study the delivery ratio of a generalized two-hop relay with limited message lifetime and redundancy. In particular, a finite-state absorbing Markov chain-based theoretical framework is first developed to model the complicated message delivery process under the considered relay algorithm. Closed-form expressions are then derived for the message delivery ratio under any given message lifetime, where the important interference, medium contention and traffic contention issues are carefully incorporated into analysis. Finally, extensive simulations are conducted to validate the theoretical framework and corresponding delivery ratio results.**

I. Introduction

Since first proposed by Grossglauser and Tse (2001) in [1], the two-hop relay algorithm has become a class of attractive routing protocols for mobile ad hoc networks (MANETs) due to its efficiency and simplicity [2]. Under such a routing algorithm, the source node replicates a copy of its message to every node (i.e., the relay) it encounters, the intermediate relay node carrying a message copy is allowed to forward the copy only to the destination node, and the destination can receive the message when meeting either the source node or one of the relay nodes. Thus, each message travels at most two hops to reach the destination.

By now, a lot of work has been done to model and analyze the performance of two-hop relay algorithm and its variants. Groenevelt *et al.* [3] derived closed-form expressions for the delivery performances in MANETs, including message delivery delay and the number of message copies at delivery time. Later, Hanbali *et al.* [4] also analyzed the delivery performances where packets at relay nodes are assumed to have an exponentially distributed lifetime. More recently, the delivery delay of two-hop relay algorithm with erasure coding has also been examined in [5]. For a detailed survey, please refer to the [6] and reference therein.

However, the delivery ratio, especially under limited message lifetime, has been largely neglected in literature, which is not only of significant importance for delay sensitive applications (where a message beyond some delay limit will typically be dropped) but also of practical interests for general MANET scenarios (where mobile nodes are usually both energy-constrained and buffer storage-limited). Panagakis *et al.* [7] derived analytical expressions and also an approximation for the message delivery probability (by a given time) in delay tolerant networks (DTNs) where the message has no lifetime limit. More recently, Whitbeck *et al.* [8] examined the relationship between delivery ratio and intermittently connected mobile network (ICMN) parameters such as message size, message lifetime and link lifetime by treating the ICMNs as edge-markovian dynamic graphs.

It is notable, however, that all available works [7], [8] consider a very simple scenario where there is only one source-destination pair and thus no traffic contention. Whereas in general MANET scenarios, multiple traffic flows (source-destination pairs) may co-exist and a relay node may simultaneously carry messages belonging to multiple flows. Also, the important interference and medium contention issues have not been carefully addressed in above models, so they cannot be adopted for an accurate delivery ratio analysis in general MANETs. In this paper, we focus on a generalized two-hop relay MANET where each message is assigned a limited lifetime and delivered to a limited number of relays, and derive closed-form expressions for the message delivery ratio there with a careful consideration of these important issues.

The main contributions of this paper are summarized as follows.

- We develop an absorbing Markov chain-based theoretical framework to model the complicated message delivery process in two-hop relay MANETs where each message is delivered to a limited number of relay nodes.
- Based on the Markov chain framework, we derive closed-form expressions for the message delivery ratio under any given message lifetime, where the important interference, medium contention and traffic contention issues are carefully incorporated into analysis.
- We conduct extensive simulations to validate the theoretical framework and corresponding delivery ratio results, which indicates that our new model can efficiently and accurately characterize the delivery ratio behaviors in two-hop relay MANETs with limited message lifetime

and redundancy.

The remainder of this paper is outlined as follows. Section II introduces the system models, a generalized two-hop relay algorithm with limited redundancy and a transmission-group based MAC scheme. In Section III, we develop a Markov chain-based theoretical framework and derive closed-form expressions for the delivery ratio under any given message lifetime. We provide extensive simulation results in Section IV, and finally conclude this paper in Section V.

II. Preliminaries

A. System Models

Network Model: We assume a cell-partitioned network structure where the network is assumed to be a two-dimensional unit torus and evenly divided into $m \times m$ equal cells. There are in total n users moving randomly and independently among these m^2 cells. Similar to previous works [6], time is slotted into contiguous slots and each slot is of fixed length. We consider a limited bandwidth and the number of data bits that can be successfully transmitted during a time slot between any node pair is assumed to be ω bits.

Mobility Model: The independent and identically distributed (i.i.d.) model in [9] is adopted here as the mobility model. At the beginning of a time slot, each user first randomly selects a cell among the m^2 cells (each cell has the same probability of $1/m^2$ to be selected), then moves to the selected cell and stays in it for a whole time slot. Each user then repeats this process for every subsequent time slot.

Interference Model: The *protocol* model first introduced in [10] is adopted here as the interference model. Suppose at a time slot, node i is transmitting to node j. Then according to the *protocol* model, in order to guarantee the successful reception at node j, we only need to ensure that for node i and any other node k simultaneously transmitting with node i, the following two conditions hold:

(1) $|X(i) - X(j)| \leq r$

(2) $|X(k) - X(j)| \geq (1 + \Delta)|X(i) - X(j)|$

where Δ is the guarding factor representing the guard zone defined in the *protocol* model, $X(\cdot)$ denotes the node physical location and r is the node transmission range.

Traffic Pattern: Similar to previous works [11], we assume the permutation traffic pattern in this paper, where each node has a locally generated message to deliver to its destination node and also needs to receive another message originated from some other node. In order to simplify the analysis, we assume that the message generated at each node is of size less than ω bits and thus can be successfully transmitted during a time slot.

Message Lifetime: After locally generated at its source node, each message is assumed to have a fixed lifetime of τ time slots. Therefore, a message will be dropped and thus fails to reach its destination if none of its redundant copies (including the original one at its source node) reach the destination within τ time slots. Notice that when the message is replicated from its source node to a relay node, the new copy is assigned the same remaining lifetime as the original one at the source node.

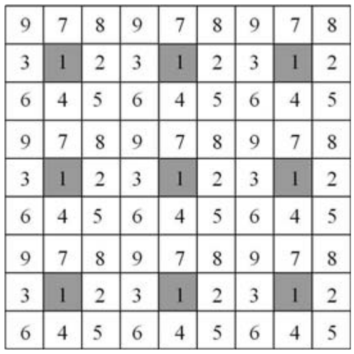


Fig. 1. Illustration of transmission-groups with $\alpha = 3$, where the network cells are divided into 9 distinct transmission-groups and all the shaded cells there belong to the same transmission-group, i.e., the transmission-group 1.

B. Generalized Two-Hop Relay Algorithm with Limited Redundancy

Similar to [4], [6], [9], in this paper, we consider a generalized two-hop relay algorithm with limited redundancy. Under such a relay algorithm, each source node delivers its locally generated message to at most f $(1 \leq f \leq n-2)$ distinct relay nodes before the message becomes expired.

Notice that there are in total n distinct source-destination pairs in the network. Without loss of generality, we focus on a tagged source-destination pair in the remaining sections, and denote by S and D the source node and the destination node, respectively. Every time node S wins a transmission opportunity, it operates as follows:

Step 1: It first checks whether node D is in the one-hop neighborhood. If so, it conducts the "source-to-destination" transmission with D and delivers its locally generated message (if not expired) to D;

Step 2: Otherwise, S randomly selects a node from its one-hop neighbors, say R, and conducts with R the "source-to-relay" transmission or "relay-to-destination" transmission with equal probability.

Notice that in the "source-to-relay" transmission, node S tries to deliver a new copy of its locally generated message to node R, while in the "relay-to-destination" transmission, node S will try to deliver to node R the message destined for node R [6].

C. A Transmission-Group Based MAC Scheme

In this paper, we consider a local transmission scenario where a node in some cell can only transmit to other nodes inside the same cell or eight surrounding adjacent cells [12]. Thus, the node transmission range r can be accordingly determined as $r = \sqrt{8}/m$. According to the interference model, we can see that only cells that are sufficiently far away could simultaneously transmit without interfering with each other. In order to support as many simultaneous transmissions as possible, we adopt here a transmission-group based medium access control (MAC) scheme for transmission scheduling [6], [13]. We first give the following definition of a transmission-group.

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, there are in total 9 distinct transmission-groups when α is fixed as $\alpha = 3$. Given node transmission range r and guard factor Δ, after using derivations similar to that in [6], [12] the parameter α can be given by

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

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

It's easy to see that there are in total α^2 distinct transmission-groups and each cell belongs to a single transmission-group. If we let α^2 transmission-groups become active (i.e., get transmission opportunity) alternatively, then each cell becomes active in every α^2 time slots. If there are more than one node in an active cell, a transmitting node is randomly selected from them (please refer to [6] for the details of selection mechanism). The selected transmitting node (i.e., the node winning the transmission opportunity) follows the generalized two-hop relay algorithm in Section II-B for message transmission.

III. Markov Chain Framework and Delivery Ratio

A. Some Basic Results

Before introducing the Markov chain based theoretical framework and deriving the message delivery ratio under any given message lifetime τ, we first present the following basic results regarding transmission probabilities in the considered MANETs.

Lemma 1: For a given time slot and a tagged source-destination pair, we use p_1 and p_2 to denote the probability that the source node S conducts a "source-to-destination" transmission and the probability that node S conducts a "source-to-relay" or "relay-to-destination" transmission, respectively. Then we have

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

$$p_2 = \frac{1}{\alpha^2}\left\{\frac{m^2-9}{n-1}\left(1-\left(\frac{m^2-1}{m^2}\right)^{n-1}\right) - \left(\frac{m^2-9}{m^2}\right)^{n-1}\right\} \quad (3)$$

Lemma 2: For a tagged source-destination pair, we denote by M the message locally generated at the source node S. Suppose at a time slot there are j $(1 \le j \le f+1)$ copies of M in the network, and the remaining lifetime of M is no smaller than one time slot. If we use $P_r(j)$, $P_d(j)$ and $P_s(j)$ to denote the probability that the destination node D will receive M, the probability that node S will successfully deliver out a new copy of M (if $j \le f$) and the probability of simultaneous source-to-relay and relay-to-destination transmissions in the next time slot, respectively, then we have

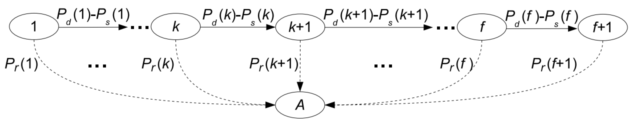


Fig. 2. Finite state absorbing Markov chain for a general message M, where k $(1 \le k \le f+1)$ denotes a state that there are in total k copies of message M in the network (including the original one at the source node S). For each transient state, the transition back to itself is not shown for simplicity.

$$P_r(j) = p_1 + \frac{j-1}{2(n-2)} \cdot p_2 \quad (4)$$

$$P_d(j) = \frac{n-j-1}{2(n-2)} \cdot p_2 \quad (5)$$

$$P_s(j) = \frac{(j-1)(n-j-1)(m^2-\alpha^2)}{4m^2\alpha^4}\sum_{k=0}^{n-5}\binom{n-5}{k}h(k) \cdot\left\{\sum_{t=0}^{n-4-k}\binom{n-4-k}{t}h(t)\left(1-\frac{18}{m^2}\right)^{n-4-k-t}\right\} \quad (6)$$

where

$$h(x) = \frac{9\left(\frac{9}{m^2}\right)^{x+1} - 8\left(\frac{8}{m^2}\right)^{x+1}}{(x+1)(x+2)} \quad (7)$$

The proofs of Lemmas 1 and 2 are omitted here due to space limit, and please kindly refer to the [6], [12] for details.

B. A Markov Chain-Based Theoretical Framework

For a tagged source-destination pair, its message delivery process can be characterized by a finite-state absorbing Markov chain shown in Fig. 2, where A denotes the absorbing state that the destination node D has received the message, and k denotes a transient state that there are in total k copies of the message (including the original one at the source node S) in the network.

It's easy to see that for the Markov chain in Fig. 2, there are in total $f+2$ distinct states, i.e., $f+1$ transient states and one absorbing state. We index these states sequentially as $1, 2, \ldots, f+2$, in a left-to-right and top-to-down way, then each transient state k has an index number k $(1 \le k \le f+1)$ and the absorbing state has an index number $f+2$. If we denote by matrix $\mathbf{P}$ the one-step transition matrix of the absorbing Markov chain, according to the absorbing Markov chain theory [14], then we have

$$\mathbf{P} = \begin{pmatrix} \mathbf{Q} & \mathbf{R} \\ \mathbf{0} & \mathbf{1} \end{pmatrix} \quad (8)$$

where matrix $\mathbf{Q} = (q_{ij})_{(f+1)\times(f+1)}$ $(i, j \in [1, f+1])$ defines the one-step transition probabilities among $f+1$ transient states and matrix $\mathbf{R} = (r_{ij})_{(f+1)\times 1}$ $(i \in [1, f+1], j = 1)$ defines the one-step transition probabilities from $f+1$ transient states to the absorbing state.

Now we proceed to define matrices $\mathbf{Q}$ and $\mathbf{R}$. The non-zero entry of matrix $\mathbf{Q} = (q_{ij})_{(f+1)\times(f+1)}$ $(i, j \in [1, f+1])$ can be determined as

$$q_{ii} = \begin{cases} 1 - p_1 - p_2/2 + P_s(i) & \text{if } 1 \le i \le f, \\ 1 - P_r(f+1) & \text{if } i = f+1. \end{cases} \tag{9}$$

$$q_{i(i+1)} = P_d(i) - P_s(i) \quad \text{if } 1 \le i \le f \tag{10}$$

The non-zero entry of matrix $\mathbf{R} = (r_{ij})_{(f+1)\times 1}$ $(i \in [1, f+1], j = 1)$ can be determined as

$$r_{i,1} = P_r(i) \quad 1 \le i \le f+1 \tag{11}$$

C. Derivations of the Message Delivery Ratio

With the above Markov chain-based theoretical framework, now we are ready to derive the message delivery ratio. If we denote by φ the corresponding message delivery ratio under message lifetime τ, then according to the theory of Markov chain [14], we have

Theorem 1: For a MANET adopting the generalized two-hop relay algorithm and the transmission-group based MAC scheme, under any given message lifetime τ, the corresponding message delivery ratio φ can be determined as

$$\varphi = \mathbf{e} \cdot \mathbf{N} \cdot (\mathbf{I} - \mathbf{Q}^\tau) \cdot \mathbf{R} \tag{12}$$

where $\mathbf{e}$ is the initial probability vector of size $1 \times (f+1)$ with all entries equal to zero except the first entry, matrix $\mathbf{N} = (\mathbf{I} - \mathbf{Q})^{-1}$ is the fundamental matrix of size $(f+1)\times(f+1)$, matrices $\mathbf{Q}$ and $\mathbf{R}$ are as defined in (8).

Proof: Suppose that the Markov chain in Fig. 2 starts from the i_{th} state, $1 \le i \le f+1$. If we denote by ϕ_i the probability that by the end of time slot τ the message has been received by the destination node, then we have

$$\varphi = \phi_1 \tag{13}$$

If we further denote by $q_{ij}^{(t)}$ the probability that the Markov chain is in the j_{th} state at the end of time slot t, then ϕ_i can be given by

$$\begin{aligned} \phi_i &= \sum_{t=0}^{\tau-1} \sum_{j=1}^{f+1} q_{ij}^{(t)} \cdot r_{j1} \\ &= \sum_{j=1}^{f+1} \sum_{t=0}^{\tau-1} q_{ij}^{(t)} \cdot r_{j1} \end{aligned} \tag{14}$$

Since $q_{ij}^{(t)}$ is the ij-entry of matrix $\mathbf{Q}^t$, if we let $\Phi = (\phi_1, \phi_2, \ldots, \phi_{f+1})^T$, then (14) can be reorganized as

$$\Phi = \sum_{t=0}^{\tau-1} \mathbf{Q}^t \cdot \mathbf{R} \tag{15}$$

$$= (\mathbf{I} - \mathbf{Q})^{-1} \cdot (\mathbf{I} - \mathbf{Q}^\tau) \cdot \mathbf{R} \tag{16}$$

$$= \mathbf{N} \cdot (\mathbf{I} - \mathbf{Q}^\tau) \cdot \mathbf{R} \tag{17}$$

Combining (15) with (13), then we have

$$\varphi = \mathbf{e} \cdot \Phi \tag{18}$$

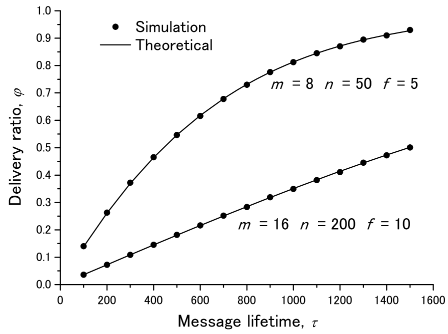


Fig. 3. Comparison between theoretical delivery ratio and simulation ones.

Substituting (17) into (18), we have (12) and then complete the proof for Theorem 1. ■

From (9), (10), (11) and (12), we can see that the only remaining issue for deriving φ is the derivation of the fundamental matrix $\mathbf{N}$. Since $\mathbf{N} = (\mathbf{I} - \mathbf{Q})^{-1}$, we can derive $\mathbf{N}$ based on the definition of matrix $\mathbf{Q}$. Please kindly refer to [12] for details of derivations for matrix $\mathbf{N}$.

IV. Numerical Results

A. Simulation Settings

We developed a network simulator in C++ to simulate the message delivery process in a two-hop relay MANET with limited message lifetime, which is now available at [15]. Similar to the settings adopted in [16], the guard factor Δ here is fixed as $\Delta = 1$, and hence the transmission-group is defined with $\alpha = \min\{8, m\}$.

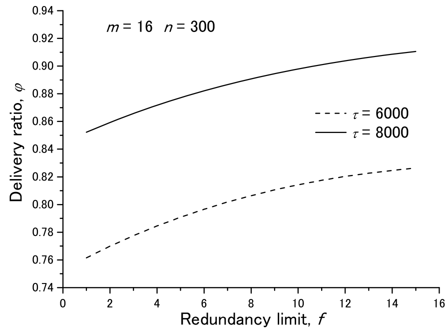
For each simulation scenario, the corresponding message delivery ratio was calculated as the average value of 10^2 batches of simulation results, where each batch consists of 10^3 random and independent simulations.

B. Theoretical vs. Simulation Results

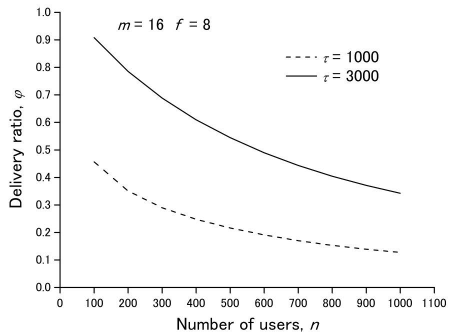
Extensive simulations have been conducted to verify the Markov chain-based theoretical framework. Here the results of two network scenarios $(m = 8, n = 50, f = 5)$ and $(m = 16, n = 200, f = 10)$ are presented (the other scenarios can be easily obtained by our simulator [15] as well). The comparisons between the theoretical and simulation results are summarized in Fig. 3.

As shown in Fig. 3, with message lifetime τ varying from 100 to 1500, the simulation results of delivery ratio φ under both network scenarios match nicely with the theoretical ones there. Therefore, our theoretical framework can be used to efficiently model the message delivery process and thus accurately characterize the corresponding message delivery ratio in two-hop relay mobile ad hoc networks with limited message lifetime.

A further careful observation of Fig. 3 indicates that, the delivery ratio φ may have different varying tendencies with the message lifetime τ. For example, as τ varies from 100



(a) Delivery ratio φ vs. redundancy limit f.



(b) Delivery ratio φ vs. number of users n.

Fig. 4. Illustration of the relationship between φ and network parameters f and n.

to 1500, the delivery ratio of $(m = 16, n = 200, f = 10)$ increases almost linearly with τ. For the case that $(m = 8, n = 50, f = 5)$, however, the delivery ratio first rises quickly with τ, and then becomes insensitive to the variations of τ when approaching 1.

C. Performance Analysis

Based on the above theoretical framework, we further proceed to explore how the message delivery ratio φ varies with other network parameters, such as the redundancy limit f, the number of users n, etc.

Fig. 4a shows the relationship between message delivery ratio φ and redundancy limit f when $m = 16, n = 300$. We can see that for both the settings of $\tau = 6000$ and $\tau = 8000$, the delivery ratios there monotonically increase with f. It's interesting to notice that the delivery ratios of $\tau = 6000$ and $\tau = 8000$ have very similar varying tendencies with f, and thus the gap between these two curves remains almost unchanged as 0.09 as f increases from 1 to 15.

With m and f fixed as $m = 16, f = 8$, Fig. 4b illustrates how the message delivery ratio φ varies with the number of users n. It's easy to see that for the two settings of $\tau = 1000$ and $\tau = 3000$, the delivery ratios there monotonically decreases as n varies from 100 to 1000. For example, for the case of $\tau = 3000$ (resp. $\tau = 1000$), the delivery ratio of $n = 500$ is 0.545 (resp. 0.216), which is nearly 0.6 (resp. 0.47) times that of $n = 100$. It can be attributed to the following reason that, as n increases up, the network becomes crowded and difficult for a user to win a transmitting opportunity and thus results in a lower delivery ratio.

V. Conclusion

In this paper, we have investigated the message delivery ratio in mobile ad hoc networks where each message locally generated at its source node is assigned a fixed lifetime and delivered to a limited number of relays. Specifically, we first developed a Markov chain-based theoretical framework to model the message delivery process in two-hop relay mobile ad hoc networks. We then derived closed-form expressions for the corresponding delivery ratio under any given message lifetime. As verified through extensive simulations, our new model can be used to efficiently model the message delivery process and thus accurately characterize the message delivery ratio there.

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