

On the Delivery Probability of Two-Hop Relay MANETs with Erasure Coding

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On the Delivery Probability of Two-Hop Relay MANETs with Erasure Coding

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Abstract—This paper focuses on the delivery probability performance in a two-hop relay mobile ad hoc network (MANET) with erasure coding. Available works in this line either considered a simple extreme case of achieving the delivery probability 1, or assumed a simple traffic pattern with only one source-destination pair, or studied a very special MANET scenario (i.e., the sparsely distributed MANET) by assuming that whenever two nodes meet together they can transmit to each other. Obviously, such models cannot be applied for an accurate delivery probability analysis in the general MANETs where the interference, medium contention and traffic contention issues are of significant importance. In this paper, a general finite-state absorbing Markov chain theoretical framework is first developed to model the complicated message spreading process in the challenging MANETs. Based on the theoretical framework, closed-form expressions are further derived for the corresponding message delivery probability under any given message lifetime and message size, where all the above important issues in MANETs are carefully incorporated into analysis. As verified through extensive simulation studies, the new framework can be used to accurately predict the message delivery probability behavior and characterize its relationship with the message size, replication factor and node density there.

Index Terms—Mobile ad hoc networks, delivery probability, two-hop relay, erasure coding.

I. INTRODUCTION

A mobile ad hoc network (MANET) is a peer-to-peer network without any pre-existing infrastructure or centralized administration, which consists of fully self-organized mobile nodes. As it can be rapidly deployed and flexibly reconfigured, the MANET has found many promising applications, such as the disaster relief, emergency response, daily information exchange, etc., and thus becomes an indispensable component among the next generation networks [1], [2].

Since their seminal work in [3], a significant amount of work has been done for a thorough understanding of the delivery delay performance of various routing protocols in MANETs. Zhang *et al.* in [4] developed an ODE (ordinary differential equations) based framework to analyze the delivery delay of epidemic routing and its variants. Later, Hanbali *et al.* focused on a multicopy two-hop relay algorithm and explored the impact of packet lifetime (time-to-live TTL) on the packet delivery delay in [5], [6]. Recently, Liu *et al.* derived closed-form expressions for the packet delivery delay of erasure

coding enhanced two-hop relay in [7] and that of group-based two-hop relay in [8].

The delivery delay study [3]–[8], although important and meaningful, can only tell the expected time it takes a routing protocol to deliver a message (or packet) from the source to the destination, i.e., the mean time required to achieve the delivery probability 1, which is actually a simple extreme case of the delivery probability study. Obviously, it is of more interest for network designers to know the corresponding delivery probability under any given message lifetime (or permitted delivery delay). Further notice that in the challenging MANET environment, multiple message replicas are often propagated to improve the delivery performance, where a relay node receiving a message may forward it or carry it for long periods of time, even after its arrival at the destination. Such combination of message replication and long-term storage imposes a severe overhead on the mobile nodes which are usually not only power energy-constrained but also buffer storage-limited. Thus, the message lifetime should be carefully tuned so as to reduce the network resource consumption in terms of buffer occupation and power consumption while simultaneously satisfy the specified delivery performance requirement.

It is noticed that there have been some efforts in literature focusing on the delivery probability study. Panagakis *et al.* in [9] analytically derived the message delivery probability of two-hop relay under a given time limit by approximating the cumulative distributed function (CDF) of message delivery delay, with the assumption that for any node pair the message can be successfully transmitted whenever they meet each other. In [10], Whitbeck *et al.* explored the impact of message size, message lifetime and link lifetime on the message delivery ratio (probability) of epidemic routing by treating the intermittently connected mobile networks (ICMNs) as edge-Markovian graphs, where each link (edge) is considered independent and has the same transition probabilities between “up” and “down” status. Later, Krifa *et al.* in [11] explored the impact of message scheduling and drop policies on the delivery probability performance of epidemic routing, and proposed a distributed scheduling and drop policy based on statistical learning to approximate the optimal performance. More recently, the optimization issue of message delivery probability under specific energy constraints and message lifetime requirement has also been intensively addressed in the context of delay tolerant networks (DTNs) [12]–[20], in which the basic two-hop relay was adopted for packet routing and a wireless link becomes available whenever two nodes

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meet each other.

A common limitation of the available models in [9], [10], [12]–[20] is that, all these works assumed a single flow (source-destination pair) in their analysis such that all other nodes act as pure relays for this flow. Such models, although simple and easy to use, may neglect an important fact that for the general MANET scenarios, multiple traffic flows may co-exist and a relay node may simultaneously carry messages belonging to multiple flows. Moreover, all these models (no matter for the ICMNs or for the DTNs) focus on a very special MANET scenario, i.e., the sparsely distributed MANET, by assuming that whenever two nodes meet together they can transmit with each other. Obviously, the available models cannot be applied for delivery probability analysis in the general MANETs where the interference and medium contention issues are of significant importance. In this paper, we study the delivery probability performance of two-hop relay MANETs with a careful consideration of the above important issues. The main contributions of this paper are summarized as follows.

- We focus on the two-hop relay algorithm in MANETs with erasure coding and more general traffic pattern, where the message at each source node is erasure coded into multiple frames (coded blocks). We develop a general finite-state absorbing Markov chain theoretical framework to model the complicated message spreading process in the challenging MANETs, which can also be used to analyze the delivery probability performances under other popular routing protocols, like the epidemic routing [3], [4], [21], the two-hop relay with f -cast [22], [23] and the group-based two-hop relay [8], etc.
- Based on the Markov chain framework, we further derive closed-form expressions for the corresponding message delivery probability under any given message lifetime and message size by adopting the blocking matrix technique, where the important issues of interference, medium contention and traffic contention in MANETs are carefully incorporated into the analysis.
- Extensive simulation studies are conducted to validate our theoretical framework, which indicates that the new framework can be used to accurately predict the message delivery probability in MANETs with two-hop relay and erasure coding, and characterizes how the delivery probability varies with the parameters of message size, replication factor and node density there.

The rest of this paper is outlined as follows. Section II introduces the system models, the routing protocol and the scheduling scheme considered in the paper. In Section III, we develop a Markov chain theoretical model for the delivery probability analysis under any given message lifetime and message size. In Section IV, we present numerical results to validate the new theoretical framework and explore the minimum message lifetime required to achieve a specified delivery probability. Finally, we conclude the whole paper in Section V.

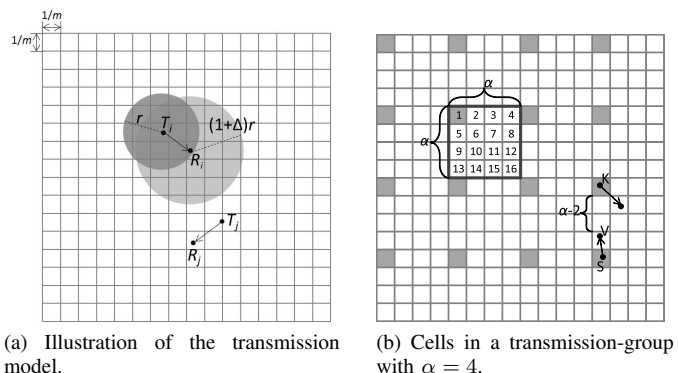


Fig. 1. Illustration of a cell-partitioned network with $m = 16$.

II. PRELIMINARIES

A. System Models

The considered mobile ad hoc network is a unit torus with n mobile nodes. The torus is evenly divided into $m \times m$ equal cells (or squares), each cell of side length $1/m$ as shown in Fig. 1a. Time is slotted and nodes randomly roam from cell to cell according to the i.i.d. mobility model [24], which is defined as follows: at time slot $t = 0$, a node is initially placed in one of the m^2 cells according to the uniform distribution. The node randomly selects a cell from the m^2 cells with equal probability of $1/m^2$ independent of other nodes, and moves to the selected cell at time slot $t = 1$. The node then repeats this process in every subsequent time slot. One can see that at each time slot, the n nodes are uniformly and randomly distributed in the m^2 cells. Since the node movements are also independent from time slot to time slot, the nodes are totally reshuffled at each time slot.

We employ the protocol model in [25] to address the interference among simultaneous link transmissions. Similar to [23], we assume that each time slot will be allocated only for data transmissions in one hop range. The data transmission model is defined as follows: suppose node T_i is transmitting to node R_i at time slot t as shown in Fig. 1a, and denote by T_i^t and R_i^t the positions of T_i and R_i , respectively. According to the protocol model, the data transmission from T_i to R_i can be successful if and only if the following two conditions hold for any other simultaneous transmitting node T_j :

- (1) $|T_i^t - R_i^t| \leq r$
- (2) $|T_j^t - R_i^t| \geq (1 + \Delta)|T_i^t - R_i^t|$

Here r is the transmission range adopted by each node, and $\Delta > 0$ is a protocol specified factor to represent the guard zone around each receiver.

In order to fully characterize the traffic contention issue in MANETs, we consider here the permutation traffic pattern [7], [23], [26], where each node has a locally generated traffic flow to deliver to its destination and also needs to receive a traffic flow originated from another node. Since there are n mobile nodes in the network, it is easy to see that there exist in total n distinct traffic flows. To simplify the analysis, similar to previous works [9], [10], [12]–[20], we assume that the local traffic flow at each node has only a single message. Without loss of generality, we focus on a tagged flow hereafter and

denote its source and destination by S and D , respectively.

For the tagged flow, the message generated at the source S is assumed to have in total ω blocks ($\omega \geq 1$), where a single block can be successfully transmitted during a time slot (or meeting duration). We further assume that the message is relevant during τ time slots, i.e., the message is labeled with a lifetime of τ time slots, and will be dropped from the network if it fails to make itself to the destination D within τ time slots.

Remark 1: Note that the node mobility is homogeneous under the i.i.d. model, where during each time slot all node pairs have the same probability to encounter and the n nodes are uniformly and randomly distributed in the m^2 cells. Such features of homogeneous node meeting and uniform node distribution, although simple and easy to use, are different from other more practical node distributions, like the correlated distribution, the clustered distribution, the home-point distribution, etc., where nodes exhibit significant inhomogeneities in spatial distribution over the network area.

Remark 2: The main difficulties in extending the i.i.d. model to take into account more complex mobility, such as the random walk model, random waypoint model, random direction model, correlated mobility model, reference point group mobility, etc., are two folds: the first difficulty is to characterize the node meeting process which depends solely on the node mobility, and the second one is to derive the data transmission probability during each node meeting which is related to both the spatial distribution and data transmissions of other nodes. It is notable that in MANETs, even though a node pair meet together in a time slot they may fail to transmit data due to the interference caused by other simultaneous data transmissions in the network. These two difficulties combined together make the analytical modeling of delivery performance in MANETs much more challenging. Actually, the main reason behind adopting the simple i.i.d. model is that it is very helpful to keep the theoretical analysis tractable and thus enables closed-form analytical results to be developed for the message delivery probability in the challenging MANETs.

B. Two-Hop Relay with Erasure Coding

The two-hop relay, since first proposed by Grossglauser and Tse (2001) in [27], has been extensively explored in literature and proved to be a popular and efficient routing protocol for DTNs. However, its delivery performance remains largely unknown in the general MANET environment, where the interference may create extra delay in the delivery of packets. It is further noticed that extensive simulation studies have been conducted in [28] to show that the delay performance of two-hop relay in DTNs can be improved via incorporating the erasure coding technique. Therefore, we focus on the two-hop relay with erasure coding in this paper and develop a theoretical framework to analytically study its delivery performance.

According to the two-hop relay algorithm with erasure coding [22], [28], for the tagged flow, the message is first erasure coded into $\omega \cdot \beta$ equal sized frames (or code blocks) after it is locally generated at S , where β is the replication

factor. Since each frame is almost the same size as the original block, we assume that it can also be successfully transmitted during a time slot. Any $(1 + \epsilon) \cdot \omega$ frames can be used to successfully reconstruct the message, where ϵ is a small constant and it varies with the adopted erasure coding algorithm. Similar to [22], [28], we ignore the constant ϵ here and thus the message can be successfully recovered at the destination D with no less than ω frames collected before it expires (i.e., within τ time slots).

After erasure coding the message into $\omega \cdot \beta$ frames, the source node S starts to deliver out these frames according to the two-hop relay algorithm [23], [24], [27]. Every time S is selected as the transmitter via the transmission scheduling scheme introduced in Section II-C, it operates as follows:

Step 1: S first checks whether D is in the transmission range. If so, S conducts with D the “source-to-destination” transmission, where a frame is sent directly to D .

Step 2: For the case that D is not in the transmission range of S , if there is no other node in the one-hop neighborhood of S , S remains idle for the time slot; otherwise, S randomly selects a node, say R , from the one-hop neighborhood as the receiver, and flips an unbiased coin;

- If it is the head, S chooses to perform the “source-to-relay” transmission with R . S initiates a handshake with R to check whether R is carrying a frame received from S . If so, S remains idle for the time slot; otherwise, S sends to R a frame destined for D .
- Otherwise, S chooses to perform with R the “relay-to-destination” transmission. S first checks whether it is carrying a frame destined for R . If so, S forwards the frame to R ; otherwise, S stays idle for the time slot.

It is noticed that distinguished from available works which assumed a simple scenario of single traffic flow, we consider in this paper the permutation traffic pattern to fully characterize the traffic contention issue in MANETs. Under such traffic pattern, each node may not only carry the frames of its own message, but also simultaneously carry multiple frames originated from other nodes in the network. To simplify the analysis and thus keep the theoretical framework tractable, we assume that each frame will be delivered to at most one relay node and each relay node will carry at most one frame from S .

We consider a single-copy version of the two-hop relay with erasure coding, where S either delivers a frame to D or sends it to a relay node. After sending a frame to a relay node, S retains a copy of the frame as backup; while the relay node will delete the frame from the buffer after forwarding it to D . Therefore, before arriving at D , each frame may have at most two copies in the network, one in the relay node and the other one in S .

C. Transmission Scheduling

Similar to previous studies [7], [23], [29], we consider a local transmission scenario where a transmitter in a cell can only transmit to receivers in the same cell or other eight adjacent cells (two cells are called adjacent cells if they share a common point). Thus, the transmission range can

be accordingly determined as $r = \sqrt{8}/m$. It is easy to see that two links can transmit simultaneously if and only if they are sufficiently far away from each other. To avoid collisions among simultaneous transmitting links and support as many simultaneous link transmissions as possible, we adopt here the transmission-group based scheduling scheme [7], [23], [29]–[31].

Transmission-group: A transmission-group is a subset of cells where any two of them have a vertical and horizontal distance of some multiple of α cells and all the cells there could transmit simultaneously without interfering with each other.

With such a transmission-group definition, all m^2 cells are actually divided into α^2 distinct transmission-groups. If each transmission-group becomes active (i.e., has link transmissions) alternatively, then each cell will also become active every α^2 time slots. As illustrated in Fig. 1b for the case $\alpha = 4$, there are in total 16 transmission-groups, and all shaded cells belong to the same transmission-group.

Setting of Parameter α : As shown in Fig. 1b, suppose node S in an active cell is transmitting to node V in a time slot. It is easy to see that another transmitter, say K , in another active cell is at least $\alpha - 2$ cells away from V . According to the protocol interference model [25], we should have $(\alpha - 2) \cdot \frac{1}{m} \geq (1 + \Delta) \cdot r$ to ensure the successful data reception at V . Notice that $\alpha \leq m$ and $r = \sqrt{8}/m$, then the parameter α can be determined as

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

It is noticed that with the setting of $\alpha = m$, all network cells are divided into m^2 distinct transmission-groups, with each transmission-group containing a single cell. Therefore, the network can support only one active transmitter-receiver pair during each time slot.

For the transmission-group based scheduling scheme, a node is assumed to be able to obtain the cell id where it resides at the beginning of each time slot. Actually, for a given network cell partition, such hypotheses can be satisfied by adopting the global positioning system (GPS) or some node localization schemes [32], [33]. Therefore, after obtaining the cell id, a node can easily judge whether it is inside an active cell or not for the current time slot, and then the nodes in an active cell can compete to become the transmitter via a distributed coordination function (DCF)-style mechanism [34].

Remark 3: The transmission-group based scheduling scheme has the following two advantageous features: firstly, it is fully distributed and thus it can be implemented without any centralized management; secondly, it enables closed-form expressions to be derived for the transmission probability under the two-hop relay during each time slot. It is also noticed that in (1) we derive α according to the possible maximum distance (i.e., $r = \sqrt{8}/m$) between a transmitter-receiver pair in two adjacent cells. However, one can see that the distance between a transmitter-receiver pair selected for each active cell may be less than $\sqrt{8}/m$ with high probability during each time slot. Consequently, the scheduling scheme may unavoidably result in an inefficient spatial reuse due to the fixed setting of α .

III. MESSAGE DELIVERY PROBABILITY

In this section, we first introduce some basic probabilities under the two-hop relay with erasure coding, develop the Markov chain-based theoretical framework, and then proceed to derive the message delivery probability.

A. Some Basic Probabilities

Lemma 1: For a time slot and the tagged flow, if we denote by p_1 the probability that S conducts a “source-to-destination” transmission with the destination node D and denote by p_2 the probability that S conducts a “source-to-relay” transmission or “relay-to-destination” transmission with some other node, then we have

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

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

Lemma 2: For a time slot and the tagged flow, given that there are t_1 relay nodes each carrying a frame from the source node S and t_2 relay nodes carrying no frames from S , we denote by $p_r(t_1)$, $p_d(t_2)$ and $p_s(t_1, t_2)$ the probability that the destination node D will receive a frame, the probability that S will successfully deliver out a frame to a new relay node (if $t_1 < \omega \cdot \beta$), and the probability of simultaneous “relay-to-destination” transmission (where D obtains a frame from the t_1 relay nodes) and “source-to-relay” transmission (where S delivers out a frame to the t_2 relay nodes) in the next time slot. Then we have

$$p_r(t_1) = p_1 + \frac{t_1}{2(n-2)} p_2 \quad (4)$$

$$p_d(t_2) = \frac{t_2}{2(n-2)} p_2 \quad (5)$$

$$p_s(t_1, t_2) = \frac{t_1 t_2 (m^2 - \alpha^2)}{4m^2 \alpha^4} \sum_{k=0}^{n-5} \binom{n-5}{k} h(k) \cdot \left\{ \sum_{t=0}^{n-4-k} \binom{n-4-k}{t} h(t) \left(1 - \frac{18}{m^2}\right)^{n-4-k-t} \right\} \quad (6)$$

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 derivations of (2), (3), (4), (5) and (6) are similar to that in [35], and please refer to [35] for details. From Lemma 1, one can see that the notation $p_1 + p_2$ actually denotes the probability that S conducts a data transmission in a time slot. It is noticed that in Lemma 2, since t_1 denotes the number of relay nodes each carrying a frame from S and t_2 denotes the number of relays carrying no frames from S , we have $t_1 + t_2 = n - 2$. For the special setting that $t_1 = n - 2 < \omega \cdot \beta$, we have $t_2 = 0$ and thus $p_d(t_2) = 0$, which means that S cannot deliver out a frame in the current time slot. Note that in order to simplify the analysis, we assume that each relay can carry at most one frame from S . Therefore, for the case

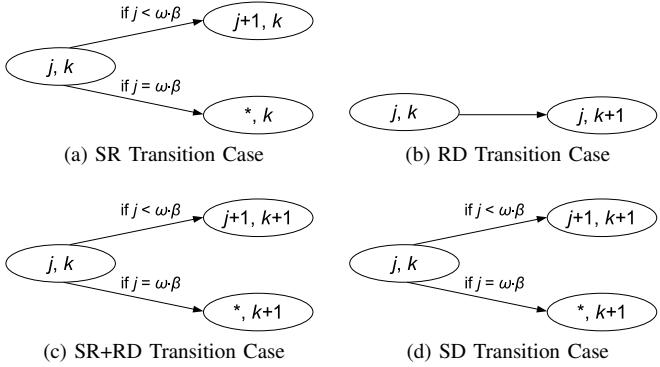


Fig. 2. Transition cases of a general transient state (j, k) , where $1 \leq j \leq \omega \cdot \beta$, $0 \leq k < \omega$, $k < j$.

that $t_1 = n - 2 < \omega \cdot \beta$, S can deliver out a frame only after a relay has forwarded its frame to the destination D .

Remark 4: It is noticed that in Step 2 of the two-hop relay scheme, S may choose to perform with R “source-to-relay” transmission with any probability $\rho \in [0, 1]$ and perform with R “relay-to-destination” transmission with probability $1 - \rho$. In “source-to-relay” transmission, S acts as a source and tries to send a frame of its own message (destined for D); while in “relay-to-destination” transmission, S acts as a relay and tries to send a frame destined for R . Therefore, ρ can be regarded as the willingness that a node would prefer to send a frame for its own message; the bigger the ρ is, the more incentive to deliver its own message. As our main focus is to develop a theoretical framework to study the delivery performance of two-hop relay in mobile ad hoc networks with erasure coding, similar to previous works [24], [36], [37], we consider a simple setting of $\rho = 1/2$ in this paper. Actually, one can see that the general setting of ρ will affect the details of delivering and receiving a frame, i.e., the probability that S will deliver out a frame to a relay and the probability that D will receive a frame in each time slot; while it will never change the basic Markovian property of message delivery process under the two-hop relay with erasure coding. Therefore, our framework can be readily applied to the general settings of ρ after the probability results in (4), (5) and (6) are accordingly updated.

B. Markov Chain Framework

For the tagged flow, as the message generated at the source node S is erasure coded into $\omega \cdot \beta$ frames and is relevant only in τ time slots, the destination node D needs to collect at least ω frames within τ time slots so as to successfully recover the message. If we denote by (j, k) a general transient state during the message delivery process that S is delivering the j_{th} frame and D has already received k distinct frames, and further denote by $(*, k)$ a transient state that S has already finished dispatching all $\omega \cdot \beta$ frames while D has only received k of them, $1 \leq j \leq \omega \cdot \beta$, $0 \leq k < \omega$, then we can characterize the message delivery process with a finite-state absorbing Markov chain. Specifically, if the tagged flow is in state (j, k) at the current time slot, only one of the following four transition cases illustrated in Fig. 2 may happen in the next time slot.

- SR Case: “source-to-relay” transmission only, i.e., S

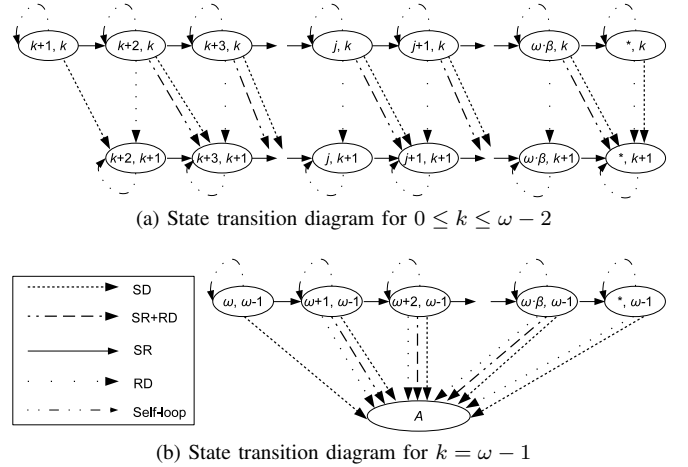


Fig. 3. Transition diagram of the Markov chain for the message delivery process.

successfully delivers the j_{th} frame to a new relay node while none of the relays delivers a frame to D . As shown in Fig. 2a that under such a transition case, the state (j, k) may transit to two different neighboring states depending on the current frame index j .

- RD Case: “relay-to-destination” transmission only, i.e., some relay node successfully delivers a frame to D while S fails to deliver out the j_{th} frame to a new relay node. As shown in Fig. 2b that there is only one target state $(j, k + 1)$ under the RD case.
- SR+RD Case: both “source-to-relay” and “relay-to-destination” transmissions, i.e., these two transmissions happen simultaneously. We can see from Fig. 2c that depending on the value of j there are two possible target states under the SR+RD case.
- SD Case: “source-to-destination” transmission only, i.e., S successfully delivers a frame to D . As shown in Fig. 2d that under the SD case, the state (j, k) may transit to $(j + 1, k + 1)$ or $(*, k + 1)$, similar to that under the SR+RD case.

If we denote by A the absorbing state that the destination node D has collected ω distinct frames, then the transition diagrams in Fig. 2 indicate that the message delivery process can be modeled as a discrete-time finite-state absorbing Markov chain illustrated in Fig. 3, where Figs. 3a and 3b each represents some cases of the full chain. Specifically, Fig. 3a represents the cases that D may receive at most one more frame given that it has already received k frames, $0 \leq k \leq \omega - 2$; Fig. 3b shows the transition diagrams of how D may receive the last frame. The transitions of SR, RD, SD and SR+RD in Fig. 3 correspond to two-hop transmissions of “source-to-relay”, “relay-to-destination”, “source-to-destination” and both “source-to-relay” and “relay-to-destination”, respectively. For each transient state, the transition of Self-loop corresponds to the transition back to itself.

As shown in Fig. 3, there are in total ω rows of transient states, with L_k transient states in the k_{th} ($0 \leq k \leq \omega - 1$) row, where

$$L_k = \omega \cdot \beta - k + 1 \quad (8)$$

$$\mathbf{Q}'_k(i, i-1) = \begin{cases} p_r(u_r) - p_1 - p_s(u_r, u_o) & \text{if } 2 \leq i < L_k \\ p_r(u_r) & \text{if } i = L_k \end{cases} \quad (20)$$

Since the fundamental matrix $\mathbf{N} = (\mathbf{I} - \mathbf{Q})^{-1}$, we can derive \mathbf{N} based on the matrix \mathbf{Q} . Please refer to [35] for the details of derivation for matrix \mathbf{N} .

Now we proceed to define the matrix \mathbf{B} . It is easy to see that \mathbf{B} can also be defined as

$$\mathbf{B} = (\mathbf{0}, \mathbf{0}, \dots, \mathbf{B}_{\omega-1})^T \quad (21)$$

where $\mathbf{0}$ is the zero matrix.

Definitions of $\mathbf{B}_{\omega-1}$: The block $\mathbf{B}_{\omega-1}$ is of size $L_{\omega-1} \times 1$, where its non-zero ij -entry $\mathbf{B}_{\omega-1}(i, j)$ can be defined as:

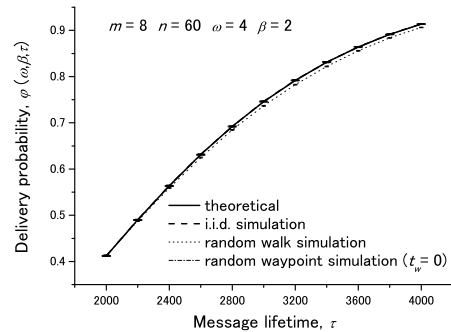
$$\mathbf{B}_{\omega-1}(i, 1) = p_r(u_r) \quad \text{if } 1 \leq i \leq L_{\omega-1} \quad (22)$$

Combining (15), (16), (17), (18), (19), (20), (21) and (22), then we get matrices \mathbf{Q} , \mathbf{N} and \mathbf{B} , and thus the message delivery probability $\varphi(\omega, \beta, \tau)$.

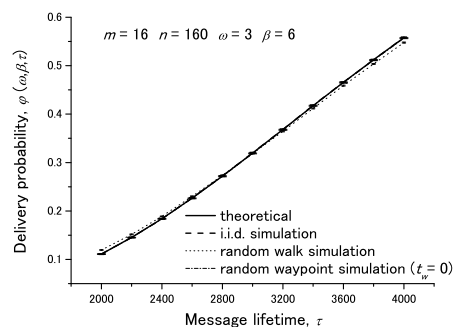
Remark 6: Notice that the Markov chain-based theoretical framework, although developed for the two-hop relay with erasure coding in this paper, can also be used to analyze the delivery probability performances under other popular routing schemes, like the epidemic routing [3], [4], [21], the two-hop relay with f -cast [22], [23] and the group-based two-hop relay [8], etc. It is noticed that under such routing protocols the probability that a node will deliver a packet (or copy) to a relay or the destination in a time slot, depends only on the current network state (in terms of node spatial distribution and copy distribution among nodes), i.e., independent of the network states in previous time slots. Obviously, such feature satisfies the mathematical definition of Markov chain, and thus the message delivery process under these routing protocols can also be modeled by a Markov chain framework. However, it is further noticed that when operating under different routing protocols, the detailed operations that a node may follow can also be different. For example, with the two-hop relay routing, after receiving a packet from the source a relay node can only forward the packet to the destination; while under the epidemic routing, the relay node can further replicate the packet to other relay nodes. Therefore, the transition diagram details of the Markov chain framework, i.e., the transitions and also the corresponding transition probabilities from a transient state to other transient states (and the absorbing state), need to be carefully reexamined according to the specific routing protocol.

IV. NUMERICAL RESULTS

In this section, we first provide simulation studies to verify the Markov chain theoretical framework, then apply it to explore how network parameters would affect the message delivery probability, and also the minimum message lifetime required to achieve a specified delivery probability.



(a) Network scenario ($m = 8, n = 60, \omega = 4, \beta = 2$).



(b) Network scenario ($m = 16, n = 160, \omega = 3, \beta = 6$).

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

A. Simulation Settings

A specific simulator was developed to simulate the message delivery process under the two-hop relay algorithm with erasure coding, which is now available at [39]. Similar to the settings in [40], [41], Δ is fixed as $\Delta = 1$ and thus the transmission-group is defined with $\alpha = \min\{8, m\}$. Besides the i.i.d. mobility model considered in this paper, we also implemented the simulator for the popular random walk model [42], [43] and random waypoint model with waiting time t_w [44]. For each network setting of $(m, n, \omega, \beta, \tau)$, the simulated message delivery probability was calculated as the average value of 10^2 batches of simulation results, where each batch consists of 10^4 random and independent simulations.

B. Model Validation

Extensive simulation studies have been conducted to validate the Markov chain theoretical framework developed for the message delivery probability under a given message lifetime τ . Here only the simulation results of two network scenarios ($m = 8, n = 60, \omega = 4, \beta = 2$) and ($m = 16, n = 160, \omega = 3, \beta = 6$) were presented, and that of other network scenarios can also be easily obtained by our simulator as well [39]. Given that the message lifetime τ varies from 2000 to 4000 (time slots), the comparisons between the simulation results and theoretical ones were summarized in Fig. 4. Notice that all the simulation results of message delivery probability were reported with the 95% confidence intervals.

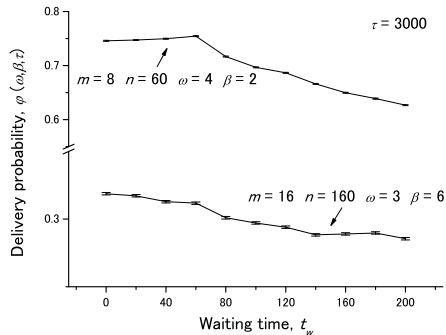
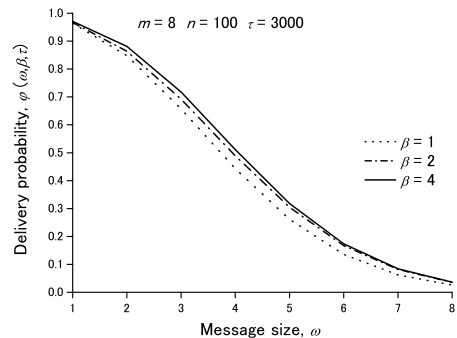


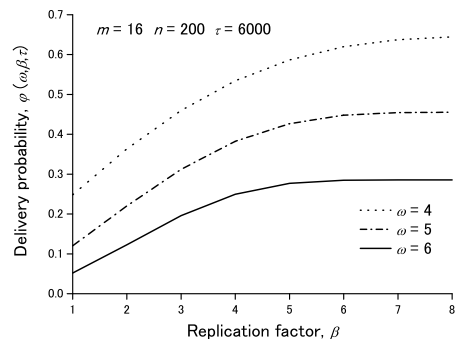
Fig. 5. Delivery probability vs. waiting time in random waypoint model.

Fig. 4 indicates clearly that for both the network scenarios there, the simulated message delivery probabilities under the i.i.d. mobility model match nicely with the theoretical ones, so our framework can be used to efficiently model the message delivery process in MANETs and accurately characterize the message delivery probability there. It is also interesting to observe from Figs. 4a and 4b that for the two network scenarios there, the simulated message delivery probability under the random walk model and random waypoint model (with $t_w = 0$) exhibit very similar behaviors with that under the i.i.d. mobility model, where the three curves almost coincide with each other. Actually, it is related to the cell-partitioned network considered in this paper and the special setting of $t_w = 0$ used for the random waypoint model. One can easily see that in a cell-partitioned network where nodes roam from cell to cell, the steady-state channel distribution under the random waypoint model with $t_w = 0$ is the same as that under the random walk and i.i.d. models, which results in very similar message delivery probability under these three mobility models. As shown in [24], [34], 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 if they follow the same steady-state channel distribution. Therefore, our theoretical models, although were developed for the message delivery probability under the i.i.d. mobility model, can also be used to nicely capture the message delivery probability behaviors in MANETs under the random walk and random waypoint mobility models.

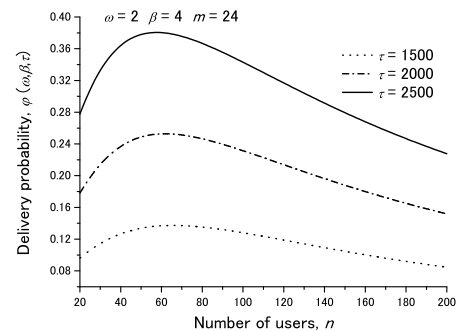
We further conducted simulation studies to explore how the waiting time t_w would affect the message delivery probability in random waypoint mobility. Specifically, for the network scenarios of $(m = 8, n = 60, \omega = 4, \beta = 2)$ and $(m = 16, n = 160, \omega = 3, \beta = 6)$, we fix $\tau = 3000$ and let t_w vary from 0 to 200, and summarize the corresponding simulation results in Fig. 5. One can easily observe from Fig. 5 that for both the network scenarios there, the message delivery probability has a general trend of decreasing as t_w increases from 0 to 200. Actually, such behavior can be interpreted as follows: with the setting of a bigger value of t_w , each node stays for a longer time during a cell and thus the network topology varies less dramatically, which unavoidably results



(a) $\varphi(\omega, \beta, \tau)$ vs. ω



(b) $\varphi(\omega, \beta, \tau)$ vs. β .



(c) $\varphi(\omega, \beta, \tau)$ vs. n .

Fig. 6. Relationship between message delivery probability $\varphi(\omega, \beta, \tau)$ and message size ω , replication factor β and number of users n .

in inefficient dissemination of message frames. It is notable that the impact of t_w on the delivery probability is actually very complicated. For example, the delivery probability of $(m = 8, n = 60, \omega = 4, \beta = 2)$ remains almost unchanged as 0.75 when $t_w \in [0, 60]$ and starts to decrease when $t_w > 60$. However, this is not the case for the scenario of $(m = 16, n = 160, \omega = 3, \beta = 6)$, where the delivery probability monotonically decreases with t_w .

C. Performance Analysis

Based on the Markov chain theoretical framework for the message delivery probability, we now proceed to explore the

impact of message size ω on the message delivery probability $\varphi(\omega, \beta, \tau)$. With $m = 8$, $n = 100$ and $\tau = 3000$, we examined three settings of $\beta = 1, 2$ and 4 , and summarized the corresponding results in Fig. 6a. One can easily observe from Fig. 6a that, the message delivery probability diminishes quickly as ω increases up. For example, for the setting of $\beta = 4$, the message delivery probability at $\omega = 2$ is 0.88, which is almost 5.18 times that of $\omega = 6$ (0.17). A further careful observation of Fig. 6a indicates that under the same setting of ω , a bigger value of β results in a bigger delivery probability. Combining with the results in Fig. 4, we can see that the message lifetime τ , therefore, should be carefully tuned according to the message size ω , replication factor β and node density (i.e., n/m^2) so as to guarantee a specified message delivery.

Fig. 6b illustrates how the message delivery probability $\varphi(\omega, \beta, \tau)$ varies with the replication factor β . It is easy to see that for all the three settings of $\omega = 4$, $\omega = 5$ and $\omega = 6$ there, the message delivery probability $\varphi(\omega, \beta, \tau)$ monotonically increases with the replication factor β . It is interesting to observe from Fig. 6b that, the slope of each curve (i.e., the increasing tendency) decreases as β increases up, and there exists some threshold value of β , beyond which the delivery probability performance has almost no improvement. Specifically, for the setting $\omega = 5$ (resp. $\omega = 6$), the message delivery probability remains nearly unchanged as 0.45 (resp. 0.28) when $\beta \geq 6$ (resp. $\beta \geq 5$). Thus, for a two-hop relay MANET with erasure coding, there exists a limiting (asymptotic) performance for the message delivery probability, which is determined only by the control parameters (ω, τ) .

Actually, the reason why the delivery probability saturates as β is increased is due to the fact that given the node mobility pattern and message lifetime τ , only a limited number of frames (or erasure coded blocks) can be distributed out by the source S before the message becomes expired. Specifically, for a message of ω blocks at S , when β is relatively small (i.e., when all $\omega \cdot \beta$ frames can be distributed out before message expiration), increasing β could increase the number of relay nodes carrying the message frames and thus improve the message delivery probability; however, when β continues to increase up, all $\omega \cdot \beta$ frames cannot be distributed out before message expiration. Since the number of frames that S can distribute out before message expiration depends only on node mobility pattern and message lifetime (i.e., independent of ω and β), increasing β could not increase the message delivery probability any more. Therefore, the message delivery probability becomes saturated as β increases beyond a threshold value. Furthermore, we can see that given the message lifetime, the bigger the message size ω , the smaller the threshold value of β (i.e., the faster the message delivery probability becomes saturated), as shown in Fig. 6b.

Finally, we examine in Fig. 6c how the delivery performance $\varphi(\omega, \beta, \tau)$ varies with the number of users n , given that $\omega = 2, \beta = 4, m = 24$. We can see from Fig. 6c that for each setting of τ there, we can find a most suitable network size n^* to achieve the maximum message delivery probability $\varphi(\omega, \beta, \tau)$. For example, for the setting $\tau = 1500$, $\tau = 2000$ and $\tau = 2500$, the corresponding n^* are 66, 62 and 58,

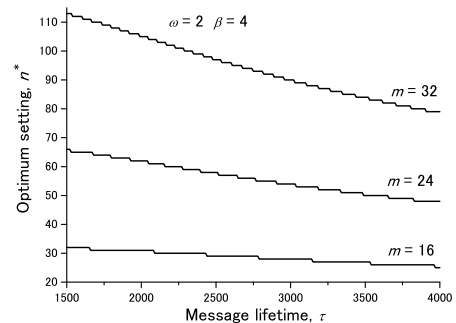


Fig. 7. Optimum setting n^* vs. message lifetime τ .

respectively. Actually, it can be explained as follows: for a given message lifetime τ and relay scheme setting (ω, β) , when $n < n^*$, the network is sparse and the increasing of n could help increase the probability to distribute a frame and thus improve the message delivery speed; while as $n > n^*$, the network users become relatively densely distributed and the negative effects of interference and medium contention issues begin to dominate the delivery performance.

We now apply our framework to further explore how the optimum setting n^* (as observed in Fig. 6c) varies with the message lifetime τ . With $\omega = 2$ and $\beta = 4$, we consider three different cell partitions $m = 16, 24$ and 32 and summarize the corresponding results in Fig. 7. One can observe from Fig. 7 that, n^* monotonically decreases with τ and n^* is actually a piecewise function of τ , i.e., a specific value of n^* can only apply to a small range of τ . A further careful observation of Fig. 7 indicates that under the same setting of τ , a bigger cell partition (i.e., m) could always result in a bigger n^* . Furthermore, one can also see that as m increases up, the n^* in Fig. 7 becomes much more sensitive to the variations of τ (i.e., as m increases up, an optimum setting n^* applies to a narrower range of τ). Therefore, the optimum setting n^* depends much more heavily on the variations of τ in a network with a bigger cell partition m .

The above behaviors of n^* with m and τ observed in Fig. 7 can be intuitively explained as follows. Recall that in this paper we consider a cell-partitioned network where the network area is evenly divided into $m \times m$ equal cells. Since the mobile nodes roam from cell to cell, the nodes become relatively sparsely distributed in the network as m increases up. Furthermore, as shown in Fig. 6c, for a sparsely distributed network increasing the number of nodes could improve the message delivery probability. Therefore, given the message lifetime τ , the optimum setting of the number of nodes (i.e., n^*) increases for a bigger value of m , so as to achieve the maximum delivery probability. We now proceed to justify the monotonically decreasing behavior of n^* with τ . For a given network cell partition m , a relay node carrying a frame will have more chances to deliver the frame to the destination node as the message lifetime τ increases, which results in a higher message delivery probability as shown in Fig. 4. Since each relay node has a higher probability to deliver its frame to

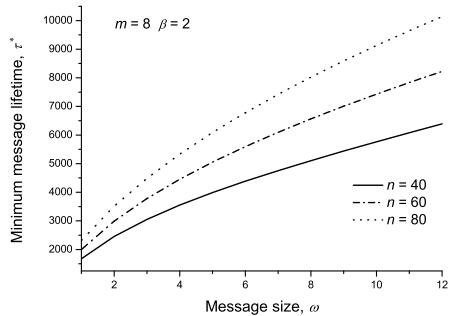
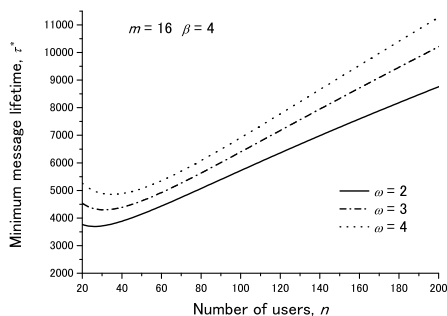
(a) τ^* vs. ω .(b) τ^* vs. n .

Fig. 8. The minimum message lifetime τ^* required to guarantee the 95% delivery probability.

the destination under the setting of a bigger τ , the maximum delivery probability could be achieved via relatively fewer nodes. Thus, the optimal setting n^* decreases with the message lifetime τ .

D. Minimum Message Lifetime τ^*

To see how the message lifetime should be tuned according to a specific delivery probability target, we now apply our framework to network scenarios ($m = 8, \beta = 2$) and ($m = 16, \beta = 4$), and show in Fig. 8 the minimum message lifetime τ^* required to guarantee the 95% delivery probability, i.e., $\tau^* = \min\{\tau | \varphi(\omega, \beta, \tau) \geq 0.95\}$. We let the message size ω vary from 1 to 12 and summarize in Fig. 8a the corresponding τ^* , given that $n = \{40, 60, 80\}$. It is easy to observe from Fig. 8a that the minimum message lifetime τ^* monotonically increases as the message size ω increases. A further careful observation of Fig. 8a indicates that for all the three n settings there, τ^* is much more sensitive to the variations of ω when ω is relatively small, where the slope of each curve gradually decreases as ω increases up. Different from that in Fig. 8a, the minimum message lifetime τ^* illustrated in Fig. 8b, first decreases and then increases as n varies from 20 to 200 for all the three settings $\omega = \{2, 3, 4\}$ there. Specifically, for the settings $\omega = 2$, $\omega = 3$ and $\omega = 4$, a minimum τ^* of 3695, 4299 and 4858 are achieved at the settings $n = 26$, $n = 31$ and $n = 35$, respectively. Actually, such behavior can be attributed to the reason that in a sparsely distributed network, increasing the number of

users n could improve the message delivery speed and thus the message delivery probability, as shown in Fig. 6c. Therefore, our theoretical framework can be very helpful for network designers to determine a suitable message lifetime so as to meet the specified delivery probability requirement.

V. CONCLUSION

In this paper, we have investigated the message delivery probability in two-hop relay MANETs with erasure coding. A general Markov chain theoretical framework was developed to characterize the message delivery process, which can also be used to analyze the delivery probability performances under other popular routing protocols. Based on the new theoretical framework, closed-form expressions were further derived for the delivery probability under any given message lifetime and message size. As verified by extensive simulation studies, our framework can be used to efficiently model the message delivery process and thus accurately characterize the delivery probability performance there. Our results indicate that for a two-hop relay MANET with erasure coding, there exists a limiting performance for the delivery probability, which is determined only by the control parameters of message size ω and message lifetime τ . Another interesting finding of our work is that the considered MANETs actually exhibit very similar behaviors in terms of delivery probability under different node mobility models, like the i.i.d., random walk and random waypoint. It is expected that this paper will contribute to the future network design in terms of determining a suitable message lifetime, so as to minimize the per node buffer occupation and power consumption while simultaneously meet the specified delivery performance requirement.

Note that the theoretical framework and closed-form results developed in this paper only hold for the simple scenario that each node has only a single message to deliver to its destination, and it chooses to conduct a “source-to-relay” or “relay-to-destination” transmission in a probabilistic fashion. Therefore, one future work is to further explore the delivery probability of two-hop relay with erasure coding in a more general scenario, where each node may need to simultaneously deliver k distinct messages, and it conducts the “source-to-relay” or “relay-to-destination” transmission in the best-effort fashion so as to take the full advantage of each transmission opportunity. Another interesting future direction is to extend the theoretical models in this paper to analytically derive the optimum setting of n (i.e., n^*) to achieve the maximum message delivery probability for a given relay scheme setting of (ω, β, τ) , or to formally determine the asymptotic (limiting) delivery probability for any specified control parameters of ω and τ .

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