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A General Model for Store-carry-forward Routing Schemes with Multicast in Delay Tolerant Networks

(Invited Paper)

Jiajia Liu
Tohoku University
Sendai, Japan 980-8579
Email: liu-jia@it.ecei.tohoku.ac.jp

Xiaohong Jiang
Future University Hakodate
Hokkaido, Japan 041-8655
Email: jiang@fun.ac.jp

Hiroki Nishiyama and Nei Kato
Tohoku University
Sendai, Japan 980-8579
Email: {bigtree,kato}@it.ecei.tohoku.ac.jp

***Abstract*—Delay tolerant networks (DTNs) are sparse and highly mobile wireless ad hoc networks, where no contemporaneous end-to-end path may ever exist at any given time instant, and thus the "store-carry-forward" kind of schemes becomes a natural routing option. A lot of models have been proposed to analyze the unicast performance of such routing schemes in the DTNs, while few works consider the multicast scenario. In this paper, we develop a general continuous time Markov chain-based theoretical framework to characterize the complicated message delivery process of the DTN multicast scenarios, based on which analytical expressions are further derived for both the expected delivery delay and expected delivery cost. The developed theoretical framework is general in the sense that: 1) it can be used to analyze the DTN multicast performance under the common "store-carry-forward" routing schemes; 2) it can also be used for the common mobility models; 3) it covers some available models developed for the DTN unicast as special cases. We then apply the theoretical framework to explore the delivery performance of two popular routing schemes, the epidemic routing and the two-hop relaying.**

I. Introduction

Delay tolerant networks (DTNs) are sparse and highly mobile wireless ad hoc networks without infrastructure, where two mobile nodes can transmit with each other only when they are within reciprocal transmission range. Since the transmission opportunities between nodes come up and down from time to time, no contemporaneous end-to-end path may ever exist at any given time instant [1]–[3]. The traditional route-based routing schemes fail in the DTNs, as they need to establish a route path from the source to the destination and require the simultaneous availability of a number of links.

The "store-carry-forward" kind of routing schemes, which relies on the mobility of nodes and sequences of their contacts to compensate for lack of continuous connectivity and thus enables messages to be delivered from end to end, becomes a natural option for the DTN [4]–[6]. One common feature of these routing schemes is to employ multiple relay nodes and disseminate a message copy to each relay [3], [7]. Since multiple relay nodes in the network will carry the copies of a message and the destination node can receive the message from any of them, the overall delivery performance is improved.

Among the "store-carry-forward" class of routing schemes, the epidemic routing [8], [9] and two-hop relaying routing [10]–[12] are two typical routing choices. The message delivery process under the epidemic routing is similar to the spread of infectious diseases [13], [14], where a mobile node carrying the message keeps on infecting any other node it meets by sending out a message copy, and the newly infected node will also behave similarly to infect other nodes. Finally, the destination node receives the message when it encounters an infected node. In the two-hop relaying algorithm [10]–[12], the message delivery process is divided into two phases. In the phase 1, the source node delivers a message copy to each relay node it meets; in the phase 2, one of the relay nodes carrying the message copies delivers the message to the destination. Since the source node will directly transmit the message to the destination once such transmission opportunity arises up, the message travels at most two hops to reach its destination.

Currently, a lot of models have been proposed to analyze the routing performance of the DTNs, like the ODE (ordinary differential equation) model developed for the epidemic routing [9], and the Markov chain models developed for the two-hop relaying [15]–[19]. One common limitation of these models is that they are developed for the unicast scenario, so we can not apply them to analyze the DTN routing performance under multicast scenario. Since the multicast is also an important traffic pattern for the future DTNs [20], in this paper we develop a general theoretical framework to analyze the DTN routing performance under the multicast scenarios.

The main contributions of this paper are summarized as follows.

- We develop a general and continuous time Markov chain-based theoretical framework to characterize the complicated message delivery process of the DTN multicast scenario. The developed framework is general in the sense that: it can be used to analyze the DTN multicast performance under the common "store-carry-forward" routing schemes, and can also be used for the common mobility models. Our framework can also cover the available models developed for the DTN unicast under the two-hop relaying [15]–[18] as special cases.
- Based on the Markov chain theoretical framework, analytical expressions of both the expected message delivery delay and expected message delivery cost are then derived for the packet delivery performance analysis under the

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multicast scenario.

- We further adopt the epidemic routing and the two-hop relaying as examples to illustrate how the packet delivery performance analysis of a specified routing algorithm can be performed based on our theoretical framework. Extensive numerical results are also provided to explore how the number of relay nodes n and the number of destination nodes k will affect packet the delivery performance there.

The rest of this paper is outlined as follows. Section II introduces the system models. In Section III, we develop the continuous time Markov chain-based theoretical framework and derive analytical expressions for both the expected delivery delay and the expected delivery cost under the epidemic routing and the two-hop relaying. We provide extensive numerical results in Section IV and conclude this paper in Section V.

II. System Models

Throughout this paper, we consider a DTN with one source node, k destination nodes, and other $n-1$ relay nodes. In such a network, only the source node has traffic to deliver to the k destination nodes, and a destination node will not help forward its received traffic; the relay nodes have no traffic to deliver or receive and thus will act as pure relays.

We assume that all the $n+k$ nodes move within a closed region according to the commonly adopted mobility models such as Random Walk model, Random Direction model or Random Waypoint model. Each node has limited transmission range r such that the network is sparse and disconnected. For any two nodes, they can communicate to each other only when they are within reciprocal transmission range, and the number of bits that can be successfully transmitted during each contact duration between them is fixed as $w\ bits$ there.

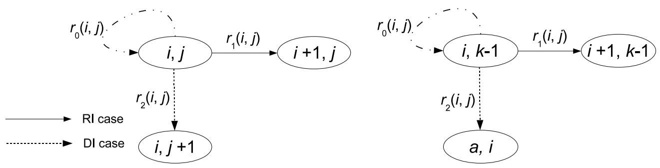
We further assume that the occurrence of the contacts between any node pair follows Poisson distribution, i.e., the node inter-meeting times (the time elapsed between two consecutive contacts of a given node pair) are exponentially distributed with inter-meeting intensity λ. This assumption has been validated in [21] and demonstrated to be fairly accurate for a number of mobility models, like the Random Walk, Random Direction and Random Waypoint, and it has also been widely adopted in the literature, like the [15]–[19], [22]–[25].

As shown in the [21], the inter-meeting intensity λ between any node pair can be determined as

$$\lambda = c \cdot \frac{\nu \cdot r}{A} \tag{1}$$

where r refers to the transmission range of each node and is small enough with respect to the network area A, ν is the mean relative velocity between nodes and the constant $c = 1$ (resp. 1.368) for the Random Direction (resp. Random Waypoint) mobility model.

In order to simplify the analysis, similar to the [15]–[18], [22], [23], we assume that the source has only a single message of size $w\ bits$ to deliver to the k destinations, and thus the message can be successfully transmitted during a contact duration.



(a) Transition diagram with $0 \leq j < k-1$ (b) Transition diagram with $j = k-1$

Fig. 1. Transition diagram of a general transient state (i,j), where the $r_0(i,j)$ denotes the transition rate back to state (i,j), and the $r_1(i,j)$ and $r_2(i,j)$ denote the transition rates of state (i,j) under the RI case and the DI case, respectively.

III. Markovian Analysis

In this section, we first develop a general Markov chain-based theoretical framework to characterize the complicated message delivery process for the multicast in DTNs, then apply it to derive the expected delivery time and the expected delivery cost for both the epidemic routing and the two-hop relaying.

A. A Markov Chain-based Theoretical Framework

It is observed that one common feature of the "store-carry-forward" routing schemes is to employ intermediate relay nodes for message delivery. Based on this observation, we can denote by (i,j) a transient state during the message delivery process, where the i and j denote the number of infected nodes (including the source node but excluding the destination nodes) and the number of infected destination nodes at the current time instant, respectively. Then we can see that, $1 \leq i \leq n$ and $0 \leq j \leq k-1$. Notice that since state $(t, k-1)$ denotes that there are already $k-1$ infected destination nodes, we can further denote by (a,t) an absorbing state that the last destination node gets infected from state $(t, k-1)$, $1 \leq t \leq n$, i.e., the last transient state before absorption is state $(t, k-1)$.

For each transient state (i,j), it may transit into different neighboring states, which depend not only on the number of infected destination nodes, i.e., the value of j, but also on the transmission cases, which are defined as follows.

- (RI Case) Relay node Infected, i.e., a new relay node gets the message in the transmission either from the source node or from some other relay node.
- (DI Case) Destination node Infected, i.e., a new destination node gets the message in the transmission either from the source node or from some relay node.

As shown in the Fig. 1, for a general transient state (i,j) there, it may transit to state $(i+1,j)$ with transition rate $r_1(i,j)$ under the RI case, and transit to state $(i,j+1)$ (resp. (a,i)) with transition rate $r_2(i,j)$ under the DI case when $0 \leq j < k-1$ (resp. when $j = k-1$), and transit back to itself with rate $r_0(i,j)$. Thus, it is easy to see that

$$r_0(i,j) = -r_1(i,j) - r_2(i,j) \tag{2}$$

Based on the above definitions of transient states and absorbing states, and the transition diagram of a general transient state (i,j) illustrated in the Fig. 1, the complicated message

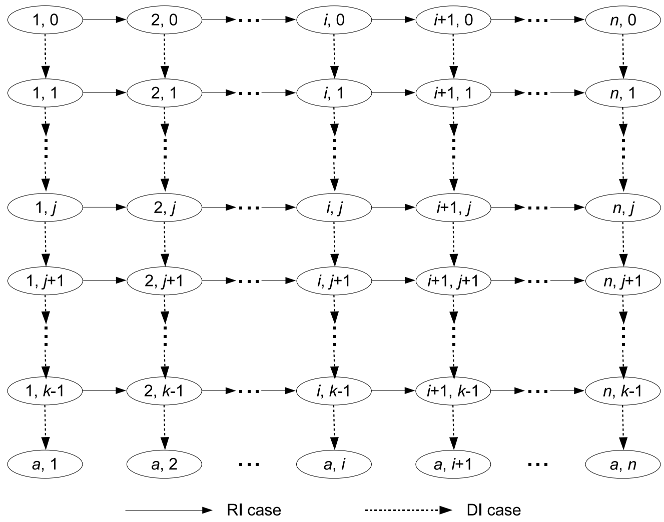


Fig. 2. Illustration of the finite-state absorbing CTMC. For each transient state, only the transitions under the RI case and DI case are included, and the transition back to itself is not shown for simplicity.

delivery process can be characterized by a two-dimensional Continuous Time Markov Chain (CTMC) with a finite number of transient states and absorbing states. We illustrate the finite-state absorbing CTMC in the Fig. 2.

For the CTMC shown in the Fig. 2, there are in total β transient states where

$$\beta = n \cdot k \tag{3}$$

and n absorbing states. All these $\beta + n$ states are arranged into $k+1$ rows, with k rows of transient states (n states per row) plus one row of absorbing states. For the convenience of reference in the following derivations, we now number these β transient states sequentially as $1, 2, \ldots, \beta$, in a left-to-right and top-to-down way, and also number these n absorbing states sequentially as $1, 2, \ldots, n$, in a left-to-right way.

From the chain structure illustrated in the Fig. 2, we can see that a transient state with index (sequence number) t ($1 \leq t \leq \beta$), corresponds to transient state (i, j), where

$$i = (t-1)\%n + 1 \tag{4}$$

$$j = \lfloor \frac{t-1}{n} \rfloor \tag{5}$$

In the following sections, we will base on these sequence numbers to index a transient state or an absorbing state. For a general transient state (i, j) with index t, without incurring any ambiguity, we will also adopt the notations of $r_1(t)$, $r_2(t)$ and $r_0(t)$ to represent the $r_1(i,j)$, $r_2(i,j)$ and $r_0(i,j)$, respectively.

B. Expected Message Delivery Delay

Before deriving the expected message delivery delay, we first formally define the message delivery delay as follows.

Definition 1: For a message at the source node, the message delivery delay is defined as the time elapsed between the time instant when the source starts to transmit this message and the time instant when the last destination node among the k destination nodes receives the message.

We denote by T_d the message delivery delay. Now we proceed to derive the expected message delivery delay $\mathbb{E}\{T_d\}$ based on the above Markov chain theoretical framework.

If we further denote by matrix $\mathbf{P} = (p_{ij})_{(\beta+n)\times(\beta+n)}$ the one-step transition matrix of the finite-state absorbing discrete-time Markov chain (referred to as DTMC from now on) *embedded* just before the jump times of the CTMC in the Fig. 2, according to the absorbing Markov chain theory [26], then we have

$$\mathbf{P} = \begin{pmatrix} \mathbf{Q} & \mathbf{R} \\ \mathbf{0} & \mathbf{I} \end{pmatrix} \tag{6}$$

where matrix $\mathbf{Q} = (p_{ij})_{\beta\times\beta}$ ($i, j \in [1, \beta]$) defines the one-step transition probabilities among transient states in the DTMC, matrix $\mathbf{R} = (p_{s,t})_{\beta\times n}$ ($s \in [1, \beta]$, $t \in [1, n]$) defines the one-step transition probabilities from transient states to absorbing states in the DTMC, and matrix $\mathbf{I}$ is the identity matrix of size $n \times n$.

For the DTMC embedded in the CTMC of Fig. 2, we further denote by matrix $\mathbf{N} = (\mathbf{N}(i,j))_{\beta\times\beta}$ the fundamental matrix of the DTMC. Notice that based on the Markov chain theoretical framework, the expected message delivery delay $\mathbb{E}\{T_d\}$ can be regarded as the mean time it takes the chain in Fig. 2 to become absorbed when the chain starts from state 1 (i.e., state $(1, 0)$). If we denote by t_{1i} the number of visits to state i before absorption given that the chain starts from state 1, and denote by s_{ij} the sojourn time in state i during the j_{th} visit to state i. According to the Markov chain theory [26], then we have

$$\begin{aligned} \mathbb{E}\{T_d\} &= \sum_{i=1}^{\beta} \mathbb{E}\{\sum_{j=1}^{t_{1i}} s_{ij}\} \\ &= \sum_{i=1}^{\beta} \mathbb{E}\{t_{1i}\} \cdot \mathbb{E}\{s_{ij}\} \qquad (7) \\ &= \sum_{i=1}^{\beta} -N(1,i) \cdot \frac{1}{r_0(i)} \qquad (8) \end{aligned}$$

where the (7) follows after applying the Wald's identity since the t_{1i} is independent from the $\{s_{ij}\}$, the (8) follows after substituting $\mathbb{E}\{t_{1i}\} = N(1,i)$ and $\mathbb{E}\{s_{ij}\} = -\frac{1}{r_0(i)}$.

If we further denote by $\mathbf{e}$ (of size $1\times\beta$) the initial probability vector with all entries equal to zero except the first entry, then the (8) can be reorganized as

$$\mathbb{E}\{T_d\} = -\mathbf{e} \cdot \mathbf{N} \cdot \mathbf{r_0} \tag{9}$$

where $\mathbf{r_0} = (1/r_0(1), 1/r_0(2), \ldots, 1/r_0(\beta))^T$.

According to the Markov chain theory [26], the fundamental matrix $\mathbf{N}$ can be further determined as

$$\mathbf{N} = (\mathbf{I} - \mathbf{Q})^{-1} \tag{10}$$

Combining the (9) and the (10), we can see that in order to derive the $\mathbb{E}\{T_d\}$, the only remaining issue is to derive the matrix $\mathbf{Q}$ of size $\beta \times \beta$ which defines the one-step transition probabilities among neighboring transient states in the (6).

C. Expected Message Delivery Cost

Before deriving the expected message delivery cost, we first formally define the message delivery cost.

Definition 2: For a message at the source node, the message delivery cost is defined as the total number of transmissions it takes the message to be received by all the k destination nodes.

We denote by C_d the message delivery cost, and now we are ready to derive the expected message delivery cost $\mathbb{E}\{C_d\}$. Recall that the absorbing state (a, i) ($i \in [1, n]$) denotes that the last destination node receives the message from state $(i, k-1)$. It is further noticed that every time a new node (a relay node or a destination node) gets infected, i.e., receives the message either from some relay node or from the source node, one transmission is consumed. Thus, it is easy to see that when the network is under the state $(i, k-1)$, there are in total $i + k - 2$ transmissions consumed. Together with the transmission taken to deliver the message to the last destination node, we can see that if the Markov chain becomes absorbed in state (a, i), the corresponding message delivery cost is $i+k-1$.

Let b_{ij} be the probability that the DTMC will be absorbed in the absorbing state with index (sequence number) j ($1 \le j \le n$), i.e, state (a, j), given that the chain starts in the transient state with index i ($1 \le i \le \beta$), i.e., state $((i-1)\%n+1, \lfloor \frac{i-1}{n} \rfloor)$, and let matrix $\mathbf{B} = (b_{ij})_{\beta \times n}$, then according to the Markov chain theory [26], we have

$$\mathbf{B} = \mathbf{N} \cdot \mathbf{R} \tag{11}$$

where $\mathbf{N}$ is the fundamental matrix of the DTMC and the $\mathbf{R}$ is the matrix of size $\beta \times n$ defined for the one-step transition probabilities from transient states to absorbing states in the (6).

Based on the (11) and given that the Markov chain start from state $(1, 0)$, the $\mathbb{E}\{C_d\}$ can be determined as

$$\mathbb{E}\{C_d\} = \sum_{i=1}^{n} (i + k - 1) \cdot b_{1i} \tag{12}$$

Combining the (10), (11) and the (12), we can see that in order to derive the $\mathbb{E}\{C_d\}$, the only remaining issue is to derive the matrix $\mathbf{Q}$ and $\mathbf{R}$.

Remark 1: Notice that the Markov chain-based theoretical framework is general in the sense that: 1) it can be used for the common mobility models, like the Random Waypoint, the Random Walk and the Random Direction; 2) the theoretical framework and the corresponding derivations of the $\mathbb{E}\{T_d\}$ and $\mathbb{E}\{C_d\}$ can be used for the common "store-carry-forward" routing protocols in the DTNs, where the transition rates of state (i, j) under the RI case and the DI case, i.e., the $r_1(i, j)$ and $r_2(i, j)$, should be set accordingly.

Remark 2: Our theoretical model covers the available models developed for the two-hop relay with unicast [15]–[18] as special cases by setting $k = 1$.

D. Derivations of the Matrix $\mathbf{Q}$ and Matrix $\mathbf{R}$

According to the (3), it is challenging to directly derive the matrix $\mathbf{Q}$ and $\mathbf{R}$ for the general settings of n and k. Similar to the [12], we derive the matrix $\mathbf{Q}$ and $\mathbf{R}$ in a blocking way.

Notice that for the Markov chain in the Fig. 2, the transitions happen only among the transient states of the same row or neighboring rows. Based on this observation, the matrix $\mathbf{Q}$ can be defined as

$$\mathbf{Q} = \begin{bmatrix} \mathbf{Q}_0 & \mathbf{Q}_0^{'} & & & & & \\ & \mathbf{Q}_1 & \mathbf{Q}_1^{'} & & & & \\ & & \ddots & \ddots & & & \\ & & & \mathbf{Q}_t & \mathbf{Q}_t^{'} & & \\ & & & & \ddots & \ddots & \\ & & & & & \mathbf{Q}_{k-2} & \mathbf{Q}_{k-2}^{'} \\ & & & & & & \mathbf{Q}_{k-1} \end{bmatrix} \tag{13}$$

here the block (sub-matrix) $\mathbf{Q}_t$ ($t \in [0, k-1]$) of size $n \times n$ corresponds to the one-step transition probabilities among transient states of the t_{th} row of the DTMC, while the block $\mathbf{Q}_t^{'}$ of size $n \times n$ corresponds to the one-step transition probabilities from transient states of the t_{th} row to transients states of the $(t+1)_{th}$ row of the DTMC. The (13) indicates that in order to derive the matrix $\mathbf{Q}$, we just need to derive the blocks $\mathbf{Q}_t$ and $\mathbf{Q}_t^{'}$ there.

Derivation of sub-matrix $\mathbf{Q}_t$: Let $\mathbf{Q}_t(i, j)$ denote the ij-entry of the sub-matrix $\mathbf{Q}_t$, $i, j \in [1, n]$, then the non-zero entry of $\mathbf{Q}_t$ can be given by

$$\mathbf{Q}_t(i, i+1) = \frac{r_1(i, t)}{r_1(i, t) + r_2(i, t)} \qquad \text{if } 1 \le i \le n-1 \tag{14}$$

Derivation of sub-matrix $\mathbf{Q}_t^{'}$: Let $\mathbf{Q}_t^{'}(i, j)$ denote the ij-entry of the sub-matrix $\mathbf{Q}_t^{'}$, $i, j \in [1, n]$, then the non-zero entry of $\mathbf{Q}_t^{'}$ can be given by

$$\mathbf{Q}_t^{'}(i, i) = \begin{cases} \frac{r_2(i,t)}{r_1(i,t)+r_2(i,t)} & \text{if } 1 \le i \le n-1, \\ 1 & \text{if } i = n. \end{cases} \tag{15}$$

Now we proceed to derive the matrix $\mathbf{R}$. Similar to the block-partition of matrix $\mathbf{Q}$, the matrix $\mathbf{R}$ can be defined as

$$\mathbf{R} = \left[\mathbf{R}_0,\ \mathbf{R}_1,\ \ldots,\ \mathbf{R}_{k-1}\right]^T \tag{16}$$

here the block (sub-matrix) $\mathbf{R}_t$ (of size $n \times n$) corresponds to the one-step transition probabilities from transient states of the t_{th} row to the absorbing states in the last row, $t \in [0, k-1]$. The (16) indicates that in order to derive the $\mathbf{R}$, we just need to derive the blocks $\mathbf{R}_t$ there.

Derivation of sub-matrix $\mathbf{R}_t$: Let $\mathbf{R}_t(i, j)$ denote the ij-entry of sub-matrix $\mathbf{R}_t$, $i, j \in [1, n]$, then the non-zero entry of $\mathbf{R}_t$ can be given by

$$\mathbf{R}_{k-1}(i, i) = \begin{cases} \frac{r_2(i,k-1)}{r_1(i,k-1)+r_2(i,k-1)} & \text{if } 1 \le i \le n-1, \\ 1 & \text{if } i = n. \end{cases} \tag{17}$$

Notice that from the Markov chain in the Fig. 2, we have $\mathbf{R}_t = \mathbf{0}$ when $0 \le t \le k-2$.

E. Derivations of the Matrix $\mathbf{N}$

If we denote the matrix $\mathbf{I}-\mathbf{Q}$ as $\mathbf{G}$, so we have $\mathbf{N} = \mathbf{G}^{-1}$. Based on the structure $\mathbf{Q}$ in the (13), the matrix $\mathbf{G}$ can also be defined in a similar block-partition structure. Let $\{\mathbf{G}_t\}$ and $\{\mathbf{G}_t^{'}\}$ denote the main diagonal blocks and the upper diagonal blocks of the matrix $\mathbf{G}$, respectively, then we have

$$\mathbf{G}_t(i,j) = \begin{cases} 1-\mathbf{Q}_t(i,j) & \text{if } i=j, \\ -\mathbf{Q}_t(i,j) & \text{otherwise.} \end{cases} \tag{18}$$

$$\mathbf{G}_t^{'}(i,j) = -\mathbf{Q}_t^{'}(i,j) \tag{19}$$

The following two lemmas indicate that the matrix $\mathbf{N}$ can be calculated based on sub-matrices $\{\mathbf{G}_t^{-1}\}$ and $\{\mathbf{G}_t^{'}\}$.

Lemma 1: Each main diagonal block $\mathbf{G}_t$ of matrix $\mathbf{G}$ has an inverse matrix $\mathbf{G}_t^{-1}$, where the ij-entry $\mathbf{G}_t^{-1}(i,j)$ of the $\mathbf{G}_t^{-1}$ can be given by

$$\mathbf{G}_t^{-1}(i,j) = \begin{cases} 0 & \text{if } i>j, \\ 1 & \text{if } i=j, \\ \prod_{s=i}^{j-1} \mathbf{Q}_t(s,s+1) & \text{otherwise.} \end{cases} \tag{20}$$

where $t \in [0, k-1]$ and $i,j \in [1,n]$.

Proof: As indicated in the (18), for each $\mathbf{G}_t$, we have $\mathbf{G}_t = \mathbf{I}_t - \mathbf{Q}_t$. Obviously, the $\mathbf{G}_t$ is a square matrix of size $n \times n$. Combining with the definitions of $\mathbf{Q}_t$ in the (14), and that $0 < \mathbf{Q}_t(i,i+1) < 1$, we can see that the main diagonal entries $\mathbf{G}_t(i,i) = 1$, and all of the off-diagonal entries are zero except for the upper diagonal entries where $\mathbf{G}_t(i,i+1) < 0$. It's easy to see that the $\mathbf{G}_t$ is invertible and its inverse matrix $\mathbf{G}_t^{-1}$ is an upper triangular matrix. After some basic row operations, it follows the (20). ■

Similar to the [27], we have the following lemma regarding the fundamental matrix $\mathbf{N}$.

Lemma 2: The fundamental matrix $\mathbf{N} = (\mathbf{N}_{i,j})_{k\times k}$ of the DTMC can be determined as

$$\mathbf{N}_{ij} = \begin{cases} \mathbf{0} & \text{if } i>j, \\ \mathbf{G}_{i-1}^{-1} & \text{if } i=j, \\ (-1)^{j-i}\big(\prod_{s=i-1}^{j-2} \mathbf{G}_s^{-1}\mathbf{G}_s^{'}\big)\mathbf{G}_{j-1}^{-1} & \text{otherwise.} \end{cases} \tag{21}$$

where $i,j \in [1,k]$.

Proof: The proof of Lemma 2 is omitted here, and please refer to the [27] for details. ■

F. Instantiations for the Epidemic Routing and the Two-hop Relaying

We now apply the above general theoretical framework to derive the expected message delivery delay and expected message delivery cost for the epidemic routing and the two-hop relaying. We denote by $\mathbb{E}\{T_d^{ur}\}$ and $\mathbb{E}\{C_d^{ur}\}$ the expected delivery delay and the expected delivery cost under the epidemic routing, respectively, and denote by $\mathbb{E}\{T_d^{2hr}\}$ and $\mathbb{E}\{C_d^{2hr}\}$ the expected delivery delay and the expected delivery cost under the two-hop relaying, respectively.

Recall that in the Fig. 1, for a general transient state (i,j) there, we denote by $r_1(i,j)$ and $r_2(i,j)$ the general transition rates of state (i,j) under the RI case and the DI case, respectively. All we need to do is to define the specific transition rates $r_1(i,j)$ and $r_2(i,j)$ for the two routing schemes.

We first consider the epidemic routing. For a general state (i,j), if we denote by $r_1^{ur}(i,j)$ its transition rate under the RI case, denote by $r_2^{ur}(i,j)$ its transition rate under the DI case and denote by $r_0^{ur}(i,j)$ its transition rate back to itself, then the $r_1^{ur}(i,j)$, $r_2^{ur}(i,j)$ and $r_0^{ur}(i,j)$ can be determined as

$$r_1^{ur}(i,j) = (n-i)i\lambda \tag{22}$$

$$r_2^{ur}(i,j) = (k-j)i\lambda \tag{23}$$

$$r_0^{ur}(i,j) = -(n+k-i-j)i\lambda \tag{24}$$

After substituting the (22), (23) and (24) into the (9), (14), (15) and (17) instead of the general $r_1(i,j)$, $r_2(i,j)$ and $r_0(i,j)$, it then follows the $\mathbb{E}\{T_d^{ur}\}$ and $\mathbb{E}\{C_d^{ur}\}$.

Similarly, for a general transient state (i,j) under the two-hop relaying, if we denote by $r_1^{2hr}(i,j)$ its transition rate under the RI case, denote by $r_2^{2hr}(i,j)$ its transition rate under the DI case and denote by $r_0^{2hr}(i,j)$ its transition rate back to itself, then the $r_1^{2hr}(i,j)$, $r_2^{2hr}(i,j)$ and $r_0^{2hr}(i,j)$ can be determined as

$$r_1^{2hr}(i,j) = (n-i)\lambda \tag{25}$$

$$r_2^{2hr}(i,j) = (k-j)i\lambda \tag{26}$$

$$r_0^{2hr}(i,j) = -(n+ki-i-ij)\lambda \tag{27}$$

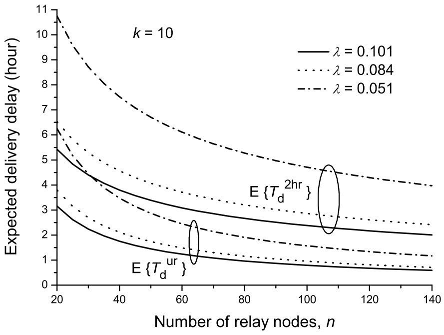
After substituting the (25), (26) and (27) into the (9), (14), (15) and (17) instead of the general $r_1(i,j)$, $r_2(i,j)$ and $r_0(i,j)$, it then follows the $\mathbb{E}\{T_d^{2hr}\}$ and $\mathbb{E}\{C_d^{2hr}\}$.

IV. Numerical Results

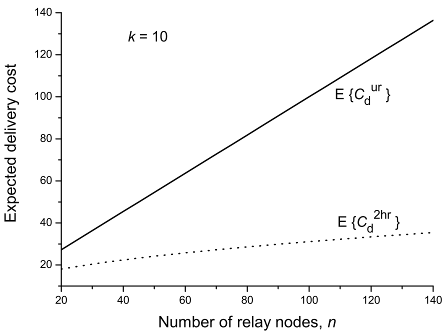
Based on the Markov chain theoretical framework developed in the Section III, in this section, we proceed to analytically evaluate the delivery performance of the epidemic routing and two-hop relaying.

A. Parameter Settings

In order to evaluate the delivery performance of the considered two routing schemes in a wide range of network scenarios, we considered in total three different mobility patterns, where the meeting intensity λ $(contacts/hr)$ is selected as $\lambda = 0.101$, 0.084 and 0.051. Notice that the settings of $\lambda = 0.101$, 0.084 and 0.051 are obtained by average statistics of the *Cambridge* trace dataset [28] using the calculation method introduced in [20]. As indicated in the (1), the parameter λ which corresponds to network scenarios with other mobility patterns can also be easily calculated.

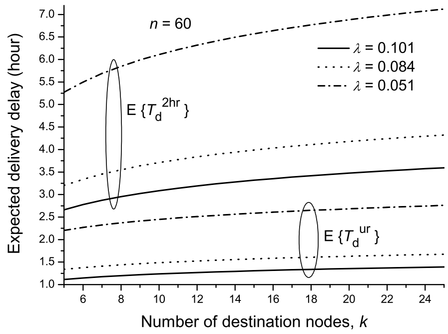


(a) $\mathbb{E}\{T_d^{ur}\}$ and $\mathbb{E}\{T_d^{2hr}\}$ vs. n

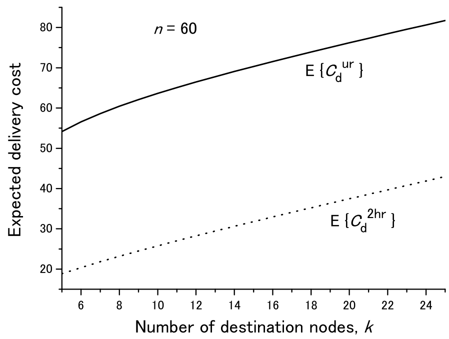


(b) $\mathbb{E}\{C_d^{ur}\}$ and $\mathbb{E}\{C_d^{2hr}\}$ vs. n

Fig. 3. Delivery performance vs. number of relay nodes n



(a) $\mathbb{E}\{T_d^{ur}\}$ and $\mathbb{E}\{T_d^{2hr}\}$ vs. k



(b) $\mathbb{E}\{C_d^{ur}\}$ and $\mathbb{E}\{C_d^{2hr}\}$ vs. k

Fig. 4. Delivery performance vs. number of destination nodes k

B. Performance Analysis

We first explore how the expected delivery delay under the epidemic routing and the two-hop relaying, i.e., the $\mathbb{E}\{T_d^{ur}\}$ and $\mathbb{E}\{T_d^{2hr}\}$ vary with the number of relay nodes n. With the k fixed as $k = 10$, we let the n vary from 20 to 140, and summarize the corresponding theoretical results in the Fig. 3a. As shown in the Fig. 3a, under all the settings of λ there, both the $\mathbb{E}\{T_d^{ur}\}$ and $\mathbb{E}\{T_d^{2hr}\}$ monotonically decrease with the n. This can be interpreted as that as the n increases up, there are more available relay nodes helping forward the message, which will improve the message spreading speed and thus shorten the message delivery delay. It is also observed that for any given n there, a bigger λ (and thus a higher meeting intensity between any node pair) can always lead to a smaller $\mathbb{E}\{T_d^{ur}\}$ (or $\mathbb{E}\{T_d^{2hr}\}$). A further careful observation of the Fig. 3a indicates that under the same network setting, the epidemic routing can always achieve a smaller expected delivery delay than the two-hop relaying. This can be attributed to the reason that under the two-hop relaying, only the source node is allowed to infect a new relay node, which will necessarily slow down the message delivery speed.

The Fig. 3b illustrates the relationship between the expected delivery cost and the n. It is observed that, both the $\mathbb{E}\{C_d^{ur}\}$ and $\mathbb{E}\{C_d^{2hr}\}$ rise up almost linearly with the n, but the $\mathbb{E}\{C_d^{ur}\}$ is much more sensitive to the variation of n than the $\mathbb{E}\{C_d^{2hr}\}$ (and thus the gap between the $\mathbb{E}\{C_d^{ur}\}$ and the $\mathbb{E}\{C_d^{2hr}\}$ increases with the n). Combining with the Fig. 3a, we can see that for the epidemic routing, the delivery delay performance advantage over the two-hop relaying comes with the sacrifice of delivery cost performance. Since in the real-world DTNs each mobile is usually power-limited, a careful trade-off between the delivery delay performance and the delivery cost performance should be made when deciding the routing schemes. Also, a further performance comparison between the epidemic routing and the two-hop relaying is needed. For example, for the case of $\lambda = 0.051$ in the Fig. 3a, the $\mathbb{E}\{T_d^{2hr}\}$ of $n = 120$ is 4.30 hr, which is 3.21 times the $\mathbb{E}\{T_d^{ur}\}$ of $n = 120$ (1.34 hr); while in the Fig. 3b, the $\mathbb{E}\{C_d^{ur}\}$ of $n = 120$ is 118.18, which is 3.54 times the $\mathbb{E}\{C_d^{2hr}\}$ of $n = 120$ (33.36).

We proceed to explore how the k will affect the $\mathbb{E}\{T_d^{ur}\}$ and $\mathbb{E}\{T_d^{2hr}\}$. With the n fixed as $n = 60$, we let the k vary from 5 to 25, and summarize the corresponding results in the Fig. 4a. As shown in the Fig. 4a, under all the settings of λ there, both the $\mathbb{E}\{T_d^{ur}\}$ and $\mathbb{E}\{T_d^{2hr}\}$ monotonically increase with the k. A further careful observation of the Fig. 4a indicates that, the $\mathbb{E}\{T_d^{2hr}\}$ is much more sensitive to the variation of k than the $\mathbb{E}\{T_d^{ur}\}$. For example, when $\lambda = 0.101$, the $\mathbb{E}\{T_d^{2hr}\}$ of $k = 15$ is 3.32 hr, which is nearly 1.25 times that of $k = 5$ (2.66 hr there); while the $\mathbb{E}\{T_d^{ur}\}$ of $k = 15$ (1.31 hr) is only

1.18 times that of $k = 5$ (1.11 hr).

The Fig. 4b shows the impact of the k on the $\mathbb{E}\{C_d^{ur}\}$ and $\mathbb{E}\{C_d^{2hr}\}$. It is easy to observe that, similar to the Fig. 3b, both the $\mathbb{E}\{C_d^{ur}\}$ and $\mathbb{E}\{C_d^{2hr}\}$ also increase up almost linearly with the k. A further careful comparison between the Fig. 4b and the Fig. 3b indicates that, however, the behavior of $\mathbb{E}\{C_d^{ur}\}$ and $\mathbb{E}\{C_d^{2hr}\}$ with the k is totally different from that with the n. As indicated in the Fig. 4b, the curve of the $\mathbb{E}\{C_d^{ur}\}$ shares almost the same slope with that of the $\mathbb{E}\{C_d^{2hr}\}$ and the gap between the $\mathbb{E}\{C_d^{ur}\}$ and the $\mathbb{E}\{C_d^{2hr}\}$ almost remains 39 since $k = 15$.

V. Conclusion

In this paper, we developed a general continuous time Markov chain based theoretical framework for the DTN multicast performance modeling, based on which analytical expressions were further derived for the expected message delivery delay and the expected message delivery cost. We then applied this framework to analytically explore the delivery performance under the epidemic routing and the two-hop relaying. Our results indicate that the delivery cost of both routing schemes rises almost linearly with the number of relay nodes n (or the number of destination nodes k), and the meeting intensity λ will affect only the message delivery speed but the message delivery cost.

References

[1] S. Burleigh, A. Hooke, L. Torgerson, K. Fall, V. Cerf, B. Durst, K. Scott, and H. Weiss, "Delay-tolerant networking: an approach to interplanetary internet," *IEEE Communications Magazine*, vol. 41, no. 6, pp. 128–136, June 2003.

[2] A. Chaintreau, P. Hui, J. Crowcroft, C. Diot, R. Gass, and J. Scott, "Impact of human mobility on opportunistic forwarding algorithms," *IEEE Transactions on Mobile Computing*, vol. 6, no. 6, pp. 606–620, June 2007.

[3] 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.

[4] S. Jain, K. Fall, and R. Patra, "Routing in a delay tolerant network," in *SIGCOMM*, 2004.

[5] Z. Zhang, "Routing in intermittently connected mobile ad hoc networks and delay tolerant networks: overview and challenges," *IEEE Communications Surveys & Tutorials*, vol. 8, no. 1, pp. 24–37, March 2006.

[6] K. Fall and S. Farrell, "Dtn: an architectural retrospective," *IEEE Journal on Selected Areas in Communications*, vol. 26, no. 5, pp. 828–836, June 2008.

[7] 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.

[8] A. Vahdat and D. Becker, "Epidemic routing for partially connected ad hoc networks," in *Duke Univ., Durham, NC, Tech.Rep.CS-200006*, April 2000.

[9] X. Zhang, G. Neglia, J. Kurose, and D. Towsley, "Performance modeling of epidemic routing," in *Proc. IFIP Networking*, 2006.

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

[11] 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.

[12] J. Liu, X. Jiang, H. Nishiyama, and N. Kato, "Group-based two-hop relay with redundancy in manets," in *HPSR*, 2011.

[13] C. Singh, A. Kumar, and R. Sundaresan, "Delay and energy optimal two-hop relaying in delay tolerant networks," in *WiOpt*, May 2010.

[14] Z. J. Haas and T. Small, "A new networking model for biological applications of ad hoc sensor networks," *IEEE/ACM Transactions on Networking*, vol. 14, no. 1, pp. 27–40, February 2006.

[15] R. Groenevelt, P. Nain, and G. Koole, "The message delay in mobile ad hoc networks," *Performance Evaluation*, vol. 62, no. 1-4, pp. 210–228, October 2005.

[16] 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.

[17] 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.

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

[19] X. Zhang, H. Zhang, and Y. Gu, "Impact of source counter on dtn routing control under resource constraints," in *MobiOpp*, February 2010.

[20] W. Gao, Q. Li, B. Zhao, and G. Cao, "Multicasting in delay tolerant networks: a social network perspective," in *MobiHoc*, 2009.

[21] R. Groenevelt, "Stochastic models in mobile ad hoc networks," Ph.D. dissertation, University of Nice Sophia Antipolis, April 2005.

[22] M. Karaliopoulos, "Assessing the vulnerability of dtn data relaying schemes to node selfishness," *IEEE Communications Letters*, vol. 13, no. 12, pp. 923–925, December 2009.

[23] Y. Li, P. Hui, D. Jin, L. Su, and L. Zeng, "Evaluating the impact of social selfishness on the epidemic routing in delay tolerant networks," *IEEE Communications Letters*, vol. 14, no. 11, pp. 1026–1028, November 2010.

[24] E. Altman and F. D. Pellegrini, "Forward correction and fountain codes in delay tolerant networks," in *INFOCOM*, 2009.

[25] E. Altman, F. D. Pellegrini, and L. Sassatelli, "Dynamic control of coding in delay tolerant networks," in *INFOCOM*, 2010.

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

[27] J. Liu, X. Jiang, H. Nishiyama, and N. Kato, "Two-hop relay with erasure coding in manets," 2011, technical report 201103.01. [Online]. Available: http://distplat.blogspot.com

[28] P. Hui, J. Crowcroft, and E. Yoneki, "Bubble rap: social-based forwarding in delay tolerant networks," in *MobiHoc*, 2008.