Performance Modeling for Two-hop Relay with Node Selfishness in Delay Tolerant Networks

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***Abstract*—Delay tolerant networks (DTNs) rely on the mobility of nodes and sequences of their contacts to compensate for lack of continuous connectivity and thus enable messages to be delivered from end to end in a "store-carry-forward" way. Since each node may also need to deliver out its locally generated message, in addition to carrying and forwarding messages for other nodes, the node may become more willing to forward its own message rather than that of others when it encounters some node. This kind of selfish behaviors may become much more significant when the nodes are operating under both QoS requirements (e.g., delivery delay requirements) and energy constraints. In this paper, we analytically explore how this kind of selfish behaviors will influence the delivery performance of the two-hop relay in the challenging DTNs. In particular, a continuous time Markov chain-based theoretical framework is developed to model the complicated message delivery process. With the help of the theoretical framework, closed-form expressions are further derived for both the expected delivery delay and the expected delivery cost, where the important node selfishness issue is carefully incorporated into the analysis.**

I. INTRODUCTION

Delay tolerant networks (DTNs) are sparse and highly mobile wireless ad hoc networks, where the transmission opportunities come up and down from time to time, and no contemporaneous end-to-end path may ever exist at any given time instant [1]–[3]. Therefore, the "store-carry-forward" kind of routing, which relies on the mobility of nodes and sequences of their contacts to compensate for lack of continuous connectivity and thus enable messages to be delivered from end to end, becomes a natural routing option for the DTN routing [4]–[6].

Among these "store-carry-forward" routing protocols, the two-hop relay and its variants [3], [7] have become a class of attractive routing protocols due to its efficiency and simplicity. In the two-hop relay routing, the source transmits copies of its message to all mobiles (relays) it encounters; relays transmit the message only if they come in contact with the destination. Thus, as shown in the Fig. 1, a message travels at most two hops to reach its destination.

The two-hop relay routing requires all nodes to forward messages for each other in a cooperative and altruistic way. Consequently, this kind of cooperation and mutually helping routing inflict significant energy consumption and storage cost on each node. Most studies in the literature have assumed that in the message delivery process, nodes are willing to cooperate

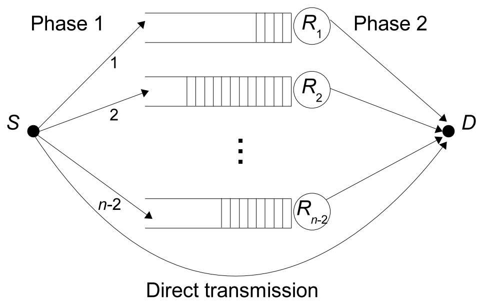


Fig. 1. Illustration of the two-hop relay routing protocol, where the destination D receives a message either directly from the source S or from one of the $n-2$ distinct relays.

with each other in a perfect way, like the [8]–[11]. In the real world, however, nodes may act selfishly, in particular when they are energy and storage resource constrained.

It is noticed that recently, some interesting works have been done to address the important node selfishness issue. Panagakis *et al.* in [12] experimentally examined the effect of node cooperation in DTNs, where a node may choose to probabilistically drop a newly received message or refuse to forward a buffered message. This kind of individual selfishness was further addressed in [13] by Karaliopoulos *et al.*, where a specific group of selfish relay nodes are assumed. It was further extended by Li *et al.* in [14] into the social selfishness scenarios where there are two groups of relay nodes, and a relay node has greater incentive to help forward messages from the nodes in the same group, but less interests to forward the messages from nodes of the other group [15], [16].

These works [12]–[14] suffered from the same limitation that all of them considered a very simple network scenario with only a single source-destination pair. Under such scenario, all the other nodes (except the source and the destination) act as "pure" relays, and have only one kind of selfish behavior, to either carry and forward messages for the source or not. In the DTNs, however, there may simultaneously coexist multiple source-destination pairs (traffic flows). Each node may act not only as a relay carrying and forwarding messages for other nodes, but also as a source trying to deliver out its locally generated message. Thus, a node may become more willing to forward its own message rather than that of others when it encounters some node. This kind of selfish behaviors may become much more significant when the nodes are operating under both QoS requirements (e.g., delivery delay requirements) and energy consumption constraints. In this paper, we focus on this kind of node selfishness and analytically explore how it will influence the delivery performance of the two-hop relay in the challenging DTNs.

The main contributions of this paper are summarized as follows.

- We focus on a network scenario where each node has a locally generated traffic destined for some node and also an incoming traffic originated from some other node, and develop a continuous time Markov chain-based theoretical framework to model the complicated message delivery process.
- With the help of the theoretical framework, we further derive closed-form expressions for both the expected delivery delay and the expected delivery cost, where the node selfishness regarding forwarding messages for itself or for other nodes, is carefully incorporated into the analysis.
- Finally, we provide extensive numerical results to explore how the node selfishness and network size will influence both the expected delivery delay and the expected delivery cost.

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

II. System Model

We consider a delay tolerant network with n mobile nodes. We assume that two nodes are able to communicate with each other only when they are within reciprocal transmission range. We also assume that the number of bits that can be successfully transmitted during each contact duration between any two nodes is fixed as $w\ bits$ there.

We further assume that the node inter-meeting times, i.e., the time elapsed between two consecutive contacts of a given node pair, are exponentially distributed with inter-meeting intensity λ. The validity of this assumption has been discussed in [17], and it has been demonstrated to be fairly accurate for a number of mobility models, like the Random Walker, Random Direction, and Random Waypoint [11], [18], [19]. As shown in the [17], the inter-meeting intensity λ can be determined by

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

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.

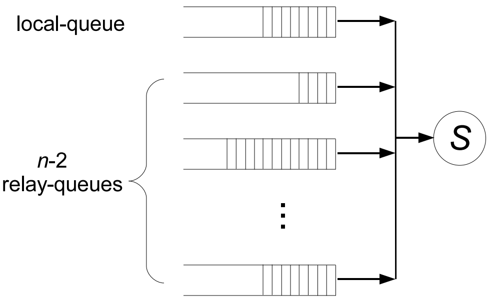


Fig. 2. Illustration of the queue structure at the buffer of node S, which contains one local-queue for its locally generated traffic, and $n-2$ parallel relay-queues for traffic of other flows.

In order to fully capture the node selfishness regarding forwarding traffic for itself or for other nodes, we assume here a permutation traffic pattern [20], where each node has a locally generated traffic destined for some node and also an incoming traffic originated from some other node, i.e., each node is not only the source of its own traffic flow but also the destination of some other traffic flow. Thus, there are in total n distinct flows inside the whole network.

Without loss of generality, we focus on a tagged flow and denote its source and destination by node S and node D, respectively. According to the two-hop relay [7], the node S can also be a potential relay for other $n-2$ flows (except the two flows originated from and destined for itself). As illustrated in the Fig. 2, we assume that the S maintains $n-1$ individual queues at its buffer, one local-queue for storing the messages that are locally generated and destined for the node D, and $n-2$ parallel relay-queues for storing messages destined for other $n-2$ nodes (excluding the node S and D).

For a tagged flow, when the source S encounters some node (say R) (rather than the destination D), the S have two choices: to act either as a source delivering to R copy of messages in its local-queue, or as a relay delivering to R messages in the relay-queue specified for the R. The former choice expedites the delivery process of its own messages (destined for node D), while the latter improves the message delivery process of other flow (destined for node R). It is notable that a node may become more willing to forward its own message rather than that of others when it encounters some node. This kind of selfish behaviors may become much more significant when the nodes are operating under both QoS requirements (e.g., delivery delay requirements) and energy consumption constraints.

To characterize the impact of this kind of node selfishness on the delivery performance, we assume that each time the node S encounters some node R (rather than D), the S will act as a source with probability p (delivering its own messages to node R), and act as a relay with probability $1-p$ (delivering to R messages destined for node R), $0 \leq p \leq 1$. In order to simplify the analysis, similar to the [13], [14], we assume that for each flow, the source has only a single message of size $w\ bits$ to deliver to the destination, and thus each message can be successfully transmitted during a contact duration.

III. Markovian Analysis

In this section, we first develop a Markov chain-based theoretical framework to model the message delivery process and derive some related basic results, then proceed to derive closed-form expressions for the expected delivery delay and expected delivery cost.

A. Markov Chain and Related Basic Results

For a tagged flow, the source node S will deliver out a copy of its message with probability p when encountering a relay node, and a relay node will forward this message with probability $1-p$ when encountering the destination node. If we use the number of message copies in the network (including the one at the source node) to denote a transient state, the whole message delivery process can be modeled with an absorbing CTMC (Continuous Time Markov Chain). Since the source node S can deliver copies of its message to at most $n-2$ distinct relay nodes, the corresponding CTMC is a finite-state absorbing CTMC. We illustrate the transition diagram of the Markov chain in the Fig. 3, where the state A denotes the absorbing state, i.e., the destination node D successfully receives the message.

For a general transient state k, $1 \leq k < n-1$, it may transit to state $k+1$ and state A with a rate of $b_1(k)$ and $b_2(k)$, respectively, where

$$b_1(k) = (n-k-1)p\lambda \tag{2}$$

$$b_2(k) = (k-kp+p)\lambda \tag{3}$$

Thus, for state k, the rate of transiting back to itself $b(k)$ can be given by

$$b(k) = (np-2kp+k)\lambda \tag{4}$$

If we denote by $S(k)$ the overall sojourn time inside a general transient state k, $1 \leq k \leq n-1$, then we have the following lemma.

Lemma 1: For a general transient state k, $1 \leq k \leq n-1$, the sojourn time $S(k)$ follows an exponential distribution with mean $\frac{1}{b(k)}$, i.e.,

$$P_r(S(k) < x) = 1 - \mathrm{e}^{-(np-2kp+k)\lambda x} \tag{5}$$

Proof: Since there are two outgoing transitions from state k, $1 \leq k < n-1$, i.e., the transitions to state $k+1$ and to state A, we further assume that when in state k, the Markov chain either transits to state $k+1$ after time $S_1(k)$ or transits to state A after time $S_2(k)$. Thus, the overall sojourn time $S(k)$ can be determined as

$$S(k) = \min\{S_1(k), S_2(k)\} \tag{6}$$

As indicated by the (2) and (3), the $S_1(k)$ and $S_2(k)$ follow an exponential distribution with mean $\frac{1}{b_1(k)}$ and $\frac{1}{b_2(k)}$, respectively, i.e.,

$$Pr(S_1(k) < x) = 1 - \mathrm{e}^{-b_1(k)x} \tag{7}$$

$$Pr(S_2(k) < x) = 1 - \mathrm{e}^{-b_2(k)x} \tag{8}$$

Together with the (6), we have

$$\begin{aligned} Pr(S(k) < x) &= Pr(S_1(k) < x \mid S_1(k) < S_2(k)) \\ &= \frac{P_r(S_1(k) < x, S_1(k) < S_2(k))}{P_r(S_1(k) < S_2(k))} \end{aligned} \tag{9}$$

Since

$$\begin{aligned} & P_r(S_1(k) < x, S_1(k) < S_2(k)) \\ &= \int_0^x b_1(k)\mathrm{e}^{-b_1(k)t}\mathrm{d}t \int_t^\infty b_2(k)\mathrm{e}^{-b_2(k)u}\mathrm{d}u \\ &= \int_0^x b_1(k)\mathrm{e}^{-(b_1(k)+b_2(k))t}\mathrm{d}t \\ &= \frac{b_1(k)}{b_1(k)+b_2(k)}\left(1 - \mathrm{e}^{-(b_1(k)+b_2(k))x}\right) \end{aligned} \tag{10}$$

and

$$P_r(S_1(k) < S_2(k)) = \frac{b_1(k)}{b_1(k)+b_2(k)} \tag{11}$$

Substituting the (10) and (11) into the (9), it follows the (5). It's easy to further verify that the (5) also holds for the case that $k = n-1$. ■

If we denote by $p_1(k)$ and $p_2(k)$ the transition probability from state k to $k+1$ and that from state k to A, respectively, from the (2), (3) and (4), we can see that

$$p_1(k) = \frac{b_1(k)}{b(k)} = \frac{(n-k-1)p}{np-2kp+k} \tag{12}$$

$$p_2(k) = \frac{b_2(k)}{b(k)} = \frac{k-kp+p}{np-2kp+k} \tag{13}$$

We further assume that when the Markov chain in the Fig. 3 enters the absorbing state A, there are in total N_d message copies in the network. Notice that the N_d message copies include (resp. exclude) the copy at the source (resp. destination) node. Thus, we have the following lemma.

Lemma 2: The pdf (probability distribution function) of N_d can be given by

$$P_r(N_d = k) = \frac{(n-2)! \cdot p^{k-1}(k-kp+p)}{(n-k-1)! \cdot \prod_{j=1}^{k}(np-2jp+j)} \tag{14}$$

where $1 \leq k \leq n-1$.

Proof: Given $N_d = k$, we can see that the last transient state before the Markov chain gets absorbed is the state k, i.e, the Markov chain becomes absorbed along the path $1 \to 2 \to 3 \to \cdots \to k \to A$. Thus, we have

$$P_r(N_d = k) = \prod_{j=1}^{k-1} p_1(j) \cdot p_2(k) \tag{15}$$

Substituting the (12) and (13) into the (15), it follows the (14) after some basic algebraic operations. ■

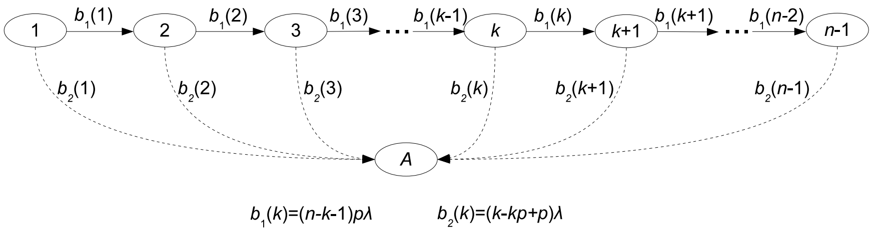


Fig. 3. Transition diagram of the Markov chain for the two-hop relay with node selfishness. For a general transient state k, the corresponding transition rates are listed at the bottom part of the figure.

B. Expected Delivery Delay and Expected Delivery Cost

With the help of the Markov chain framework and the related basic results, we proceed to derive closed-form expressions for the expected delivery delay and the expected delivery cost in this subsection. We first introduce here the following definitions for the delivery delay and delivery cost.

Definition 1: For a message at some source node S, the delivery delay of this message is the time elapsed between the time when the S starts to transmit this message and the time when the destination node D receives this message.

Definition 2: For a message at some source node S, the delivery cost of this message here is regarded as the total number of transmissions this message takes to arrive at the destination node D.

Notice that delivery cost includes the last transmission from the source S (or some relay) to the destination D. We denote by T_d and C_d the delivery delay and delivery cost, respectively. Thus, we have the following theorems about the $\mathbb{E}\{T_d\}$ and $\mathbb{E}\{C_d\}$.

Theorem 1: The expected delivery delay $\mathbb{E}\{T_d\}$ can be determined as

$$\mathbb{E}\{T_d\} = \sum_{k=1}^{n-1} P_r(N_d = k) \cdot \sum_{j=1}^{k} \frac{1}{b(j)} \tag{16}$$

where the $P_r(N_d = k)$ and $b(j)$ are given by the (14) and (4), respectively.

Proof: We denote by $L_d(s)$ the Laplace-Stieltjes transform of T_d, $s \geq 0$, thus we have

$$\mathbb{E}\{T_d\} = -\frac{\mathrm{d}L_d(s)}{\mathrm{d}s}\Big|_{s=0} \tag{17}$$

Since

$$\begin{aligned} L_d(s) &= \mathbb{E}\{\mathrm{e}^{-T_d \cdot s}\} \\ &= \sum_{k=1}^{n-1} \mathbb{E}\{\mathrm{e}^{-T_d \cdot s} \mid N_d = k\} \cdot P_r(N_d = k) \quad (18) \\ &= \sum_{k=1}^{n-1} \mathbb{E}\{\mathrm{e}^{-\sum_{j=1}^{k} S(j)\cdot s} \mid N_d = k\} \cdot P_r(N_d = k) \quad (19) \\ &= \sum_{k=1}^{n-1} f(s,k) \cdot P_r(N_d = k) \quad (20) \end{aligned}$$

where

$$f(s,k) = \mathbb{E}\{\mathrm{e}^{-\sum_{j=1}^{k} S(j)\cdot s} \mid N_d = k\} \tag{21}$$

the (18) follows by conditioning on the N_d, and the (19) follows after substituting the $(T_d \mid_{N_d=k}) = \sum_{j=1}^{k} S(j)$.

Notice that in the (20), as the $P_r(N_d = k)$ is given by the (14), the only remaining issue for derivation of the $L_d(s)$ is to derive the $f(s,k)$.

Since the $S(1)$, $S(2)$, …, $S(k)$ in the (21) are mutually independent, we have

$$f(s,k) = \prod_{j=1}^{k} \mathbb{E}\{\mathrm{e}^{-S(j)\cdot s}\} \tag{22}$$

where

$$\begin{aligned} &\mathbb{E}\{\mathrm{e}^{-S(j)\cdot s}\} \\ &= \int_0^{\infty} \mathrm{e}^{-s\cdot x} \cdot b(j)\mathrm{e}^{-b(j)x}\mathrm{d}x \quad (23) \\ &= \frac{b(j)}{s + b(j)} \quad (24) \end{aligned}$$

and the (23) follows after substituting the (5). Substituting the (24) into the (22), we have

$$f(s,k) = \prod_{j=1}^{k} \Big(1 + \frac{s}{b(j)}\Big)^{-1} \tag{25}$$

From the (17) and (20), we can see that

$$\mathbb{E}\{T_d\} = \sum_{k=1}^{n-1} P_r(N_d = k) \cdot \Big(-\frac{\mathrm{d}f(s,k)}{\mathrm{d}s}\Big|_{s=0}\Big) \tag{26}$$

where

$$\begin{aligned} &\Big(-\frac{\mathrm{d}f(s,k)}{\mathrm{d}s}\Big|_{s=0}\Big) \\ &= \Big(\sum_{j=1}^{k} \Big(1 + \frac{s}{b(j)}\Big)^{-2} \frac{1}{b(j)} \cdot \prod_{i=1, i\neq j}^{k} \Big(1 + \frac{s}{b(i)}\Big)^{-1} \Big)\Big|_{s=0} \quad (27) \\ &= \sum_{j=1}^{k} \frac{1}{b(j)} \quad (28) \end{aligned}$$

and the (27) follows after substituting the (25).

Substituting the (28) into the (26), it follows the (16). ■

Theorem 2: The expected delivery cost $\mathbb{E}\{C_d\}$ can be determined as

$$\mathbb{E}\{C_d\} = \sum_{k=1}^{n-1} \frac{(n-2)! \cdot p^{k-1}(k^2 - k^2 p + kp)}{(n-k-1)! \cdot \prod_{j=1}^{k}(np - 2jp + j)} \quad (29)$$

Proof: As indicated by the Lemma 2, the Markov chain will become absorbed from state k with probability $P_r(N_d = k)$. Notice that when the chain arrives at the state k, $k-1$ transmissions in total are taken. Plus the last transmission from state k to A, we can see that when the Markov chain gets absorbed from state k, the corresponding delivery cost is also k. Thus, the $\mathbb{E}\{C_d\}$ can be given by

$$\mathbb{E}\{C_d\} = \sum_{k=1}^{n-1} k \cdot P_r(N_d = k) \quad (30)$$

after substituting the (14), it follows the (29) after some basic algebraic operations. ■

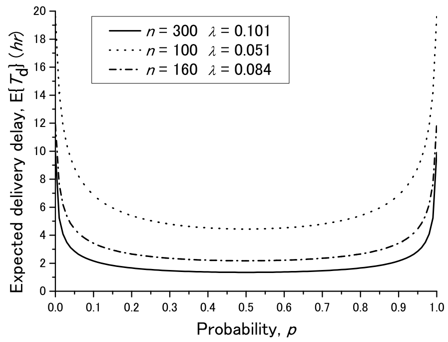
IV. Numerical Results

In this section, based on the Markov chain-based theoretical framework, we proceed to quantify the delivery performance of the two-hop relay with node selfishness, and explore how the probability p will affect both the $\mathbb{E}\{T_d\}$ and the $\mathbb{E}\{C_d\}$.

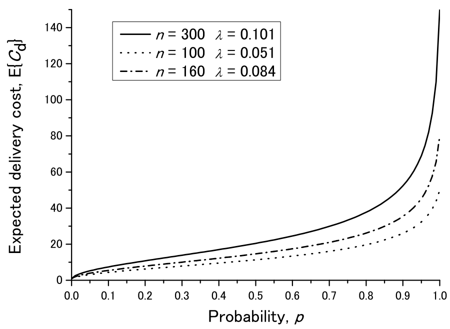
As indicated in the (1), the parameter λ corresponds to the contact rate between any two mobile nodes. In order to examine the delivery performance under a wide range of network scenarios, we adopted in total four different settings of λ ($contacts/hr$) here, i.e., $\lambda = 0.37$, 0.101, 0.051 and 0.084. The setting that $\lambda = 0.37$ practically corresponds to nodes with transmission range equal to $50m$ moving at a speed uniformly spread in $[0.5, 2.5]$ m/sec according to the random direction (random waypoint) model in a square area of 1 km side length (circle of radius $\frac{1}{\pi}$ km) [13]. The settings that $\lambda = 0.101$, 0.051 and 0.084 [14] are obtained by average statistics of the *Cambridge* trace dataset [21] using the calculation method introduced in [22].

We first explore how the $\mathbb{E}\{T_d\}$ and $\mathbb{E}\{C_d\}$ vary with the probability p and summarize the corresponding results in the Fig. 4. As shown in the Fig. 4a, for all the three network settings there, as the p varies from 0 to 1, the $\mathbb{E}\{T_d\}$ first monotonically decreases down from the $\frac{1}{\lambda}$, achieves the minimum value at $p = 0.50$, and then monotonically increases up to the $\frac{1}{\lambda}$. For the settings that $\lambda = 0.101$, 0.051 and 0.084, when $p = 0$ ($p = 1$) we have a $\mathbb{E}\{T_d\}$ of 9.901 hr, 19.608 hr and 11.905 hr, respectively; when $p = 0.50$, a minimum $\mathbb{E}\{T_d\}$ of 1.350 hr, 4.440 hr and 2.175 hr is achieved, respectively. A further careful observation of the Fig. 4a indicates that the $\mathbb{E}\{T_d\}$ is symmetric with the line $p = 0.50$, i.e., the $\mathbb{E}\{T_d\}$ achieved at the value p is the same as that of the value $1 - p$.

The Fig. 4b illustrates the relationship between the $\mathbb{E}\{C_d\}$ and the probability p. It's easy to observe that, the $\mathbb{E}\{C_d\}$ monotonically increases from 1 to $\frac{n}{2}$ as the p varies from 0 to 1. A further careful observation of the Fig. 4b indicates that the sensitivity (increasing tendency) of the $\mathbb{E}\{C_d\}$ also varies with the p. Specifically, when $0 \le p \le 0.5$, the $\mathbb{E}\{C_d\}$ increases up slowly; while as p varies beyond 0.5, the $\mathbb{E}\{C_d\}$ rises up sharply. Combining with the symmetric property of $\mathbb{E}\{T_d\}$ observed from the Fig. 4a, we can see that when $p \in [0, 0.5]$, a higher p value achieves a smaller delivery delay but unavoidably results in a higher delivery cost.



(a) $\mathbb{E}\{T_d\}$ vs. p

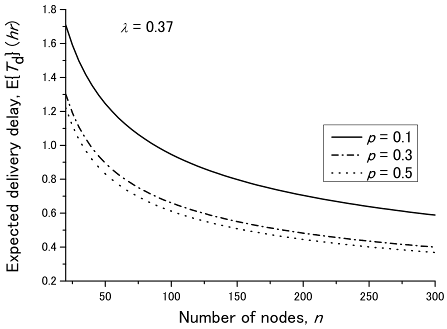


(b) $\mathbb{E}\{C_d\}$ vs. p

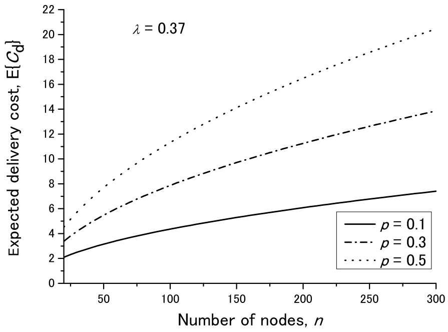
Fig. 4. Delivery delay and delivery cost vs. probability p

We further proceed to study how the number of nodes n, will affect the $\mathbb{E}\{T_d\}$ and $\mathbb{E}\{C_d\}$. With the λ fixed as $\lambda = 0.37$, we consider three settings of p ($p = 0.1$, 0.3 and 0.5) and let the n varies from 20 to 300. As shown in the Fig. 5a, the $\mathbb{E}\{T_d\}$ decreases quickly with the n. For example, when $p = 0.1$, the $\mathbb{E}\{T_d\}$ of $n = 200$ is 0.705 hr, which is nearly 0.57 times that of the $n = 50$ (1.245 hr); regarding the setting that $p = 0.3$, the $\mathbb{E}\{T_d\}$ of $n = 200$ is 0.483 hr, which is nearly 0.54 times that of the $n = 50$ (0.895 hr). This property can be interpreted as that the increasing of n provides more chances for the source node S to deliver out copies for its message and thus results in a smaller delivery delay.

We can see from the Fig. 5b that, for all the settings of p ($p = 0.1$, 0.3 and 0.5) there, the $\mathbb{E}\{C_d\}$ monotonically increases up with the n. It is further noticed that the sensitivity of the $\mathbb{E}\{C_d\}$ also varies with the p, i.e., the $\mathbb{E}\{C_d\}$ of a bigger p value is much more sensitive to the variations of n. For example, as the n varies from 20 to 300, the $\mathbb{E}\{C_d\}$ of $p = 0.1$ increases from 2.098 to 7.404 by a factor of nearly 3.53 times; while for the setting $p = 0.5$, the $\mathbb{E}\{C_d\}$ increases



(a) $\mathbb{E}\{T_d\}$ vs. n



(b) $\mathbb{E}\{C_d\}$ vs. n

Fig. 5. Delivery delay and delivery cost vs. number of nodes n

from 4.52 to 20.449 by a factor of nearly 4.52 times.

V. Conclusion

In this paper, we analytically evaluated the impact of node selfishness on the delivery performance of the two hop relay in DTNs. A continuous time Markov chain-based theoretical framework was developed, based on which closed-form expressions were further derived for both the expected delivery delay and the expected delivery cost. Our numerical results indicate that the simple rule of $p = 0.50$ achieves the minimum expected delivery delay, and when $p \in [0, 0.5]$, a bigger p could achieve a better delivery delay performance but unavoidably result in a higher delivery cost.

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