Optimal Relay Node Selection in Two-Hop Routing for Intermittently Connected MANETs

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Abstract

Recently, many researchers have been attracted to intermittently connected mobile ad-hoc networks (MANETs), which are a type of DTN (delay/disruption/disconnect tolerant network). To achieve end-to-end communication between a source node and a destination node in the networks, store-carry-forward routing has been considered as a promising solution. In this paper, we propose an algorithm for optimal relay node selection in two-hop store-carry-forward routing schemes, where only the source node can generate relay nodes (nodes with a copy of the message). When the routing scheme restricts the maximum number of relay nodes, its performance is highly dependent on the selection of relay nodes so that the algorithm is important. The routing scheme according to our method of relay node selection can minimize the mean delivery delay. In this paper, we first straightforwardly formulate a system dynamics model from generating an original message to its destination, and then show that it is difficult to derive the optimal relay node selection for the system dynamics model. To construct the algorithm, we consider an system model equivalent to the original system model, and show that the relay node selection can be obtained easily for the equivalent system model. Through numerical experiments, we evaluate the performance of the routing scheme according to our method of relay node selection.

Keywords: delay/disruption tolerant networking, store-carry-forward routing, two-hop routing, relay node selection, dynamic programming

1 Introduction

Recently, many researchers have been attracted to intermittently connected mobile ad-hoc networks (MANETs), which are a type of DTN (delay/disruption/disconnect tolerant network) [1, 2, 3]. In intermittently connected MANETs, mobile nodes can be established chronically at any moment. Therefore, conventional MANET routing algorithms, such as AODV [4] for MANETs, do not work well. Owing to their mobility, however, nodes occasionally happen to establish a connection to other nodes. Store-carry-forward routing, whereby a node receiving a message stores it in the buffer, carries it while moving, and forwards it to other nodes when they are encountered, has been considered as a promising alternative in such situations [5].

To date, many store-carry-forward routing schemes have been proposed (see [6, 7] for a survey of such routing schemes). According to the taxonomy described in [7], those routing schemes can be categorized as either *single-copy routing* or *multi-copy routing*. In single-copy routing, there is only one *relay node* (a node with a copy of the message). Once the relay node forwards its copy to another node, the former deletes the message copy from the buffer. Under multi-copy routing, several copies of the message are distributed over the network. In general, multi-copy routing has a lower undelivered ratio

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(the number of messages undelivered to destination nodes) than single-copy routing, though it imposes a heavier load on the network.

The performance of single-copy routing is highly dependent on the relay node selection method. When the relay node encounters another node, the relay node selection method determines whether or not the message copy is forwarded to the latter node. If the relay node forwards the message to a node that frequently meets the destination, the message can easily be delivered to the destination node. However, if the relay node forwards the message to a node that rarely meets the destination node, it is difficult to deliver the message. Hence, methods of selecting relay nodes in single-copy routing have been actively discussed in the literature. Conan et al. [8] proposed an optimal relay node selection scheme based on the meeting rates among nodes. If every node containing the message knows the rate at which the other nodes meet the destination node, then this routing scheme minimizes the mean delivery delay, i.e., the time interval from message generation in the source node to delivery at the destination node. Throughout simulation experiments with real traces, it was shown that this scheme significantly improves delivery performance compared with primitive routing schemes.

In multi-copy routing schemes, the relay node selection also affects the system performance [9, 10], especially when the number of nodes with a copy of the message is restricted. One of the most representative of those routing schemes is two-hop routing [11, 9, 12]. In two-hop routing, whenever the source node encounters another node that does not have a copy of the message, the former passes on a message copy to the latter. Relay nodes can only forward the message to its destination node. The message thus reaches its destination node in at most two hops.

Spray and wait (SW) is another representative multi-copy routing scheme [13], that places a restriction on the maximum number of relay nodes. Therefore, only some of the nodes in the network can possess copies of the message. Spyropoulos et al. [13] proposed two variants of SW, source SW and binary SW. In source SW, only the source node can forward copies of the message to other nodes. Therefore, when the maximum number of message copies is set to be infinity, the behavior is equivalent to a two-hop routing scheme. In binary SW, however, all nodes with a copy of the message can forward the message. When the maximum number of message copies is set to be an appropriate value, the performance of SW is excellent, meaning that SW is a promising solution for intermittently connected MANETs.

In the literature, many variants of binary SW have been considered [14, 15, 16, 17], whereas there are few variants of source SW [18]. Encounter-based routing (EBR) [16] is one variant of binary SW. Similar to SW, EBR restricts the maximum number of nodes that can have a copy of the message. The difference is that in EBR determines the number of forwarded message copies is determined based on the meeting rates. The more frequently a node encounters other nodes, the more message copies it can generate.

Although variants of binary SW can achieve better performance in a cooperative environment as shown in [19, 13, 17], they may not work well when there are selfish nodes in the network. In general, variants of binary SW need the assistance of relay nodes to prevent their performance level from decreasing. An example is that when selfish nodes prioritize their own generated messages. In this case, even if the selfish node with the message copy encounters another node, the former may not forward its copy to the latter. This selfishness severely affects the performance of families of binary SW schemes.

In contrast, source SW can reduce the influence of selfish nodes in the network. Because source SW is a variant of two-hop routing, the source node can negotiate whether encountered nodes obtain a message copy. For example, when a source node encounters another node, the former node may be able to forward other message copies to the latter in compensation for receiving messages from the latter node.

In this paper, we focus on two-hop routing schemes, i.e., variants of source SW. Despite their advantages, as described above, there are relatively few studies on variants of source SW. Specifically, the optimal relay node selection in variants of source SW has not been considered so far. As we will show, the performance of variants of source SW is highly dependent on the relay node selection. We thus propose an algorithm for the optimal relay node selection that is based on the set of relay nodes containing the message copy when making a forwarding decision. The routing scheme according to our method of relay node selection can minimize the mean delivery delay.

We first straightforwardly formulate a system dynamics model from generating an original message to its destination, and then show that it is difficult to optimally select relay nodes for the system dynamics model. To construct the algorithm, we consider an equivalent system model to the original system model, and show that the relay node selection can be obtained easily for the equivalent system. Through numerical experiments, we evaluate the performance of the routing scheme according to our method of relay node selection. Numerical experiments show that relay node selection dynamically changes the candidate node for message forwarding.

The remainder of this paper is organized as follows. In Section 2, we first presents the system model. In Section 3, we describe the selection of optimal relay nodes in a two-hop routing scheme, and propose a calculation method for optimal relay node selection. In Section 4, we evaluate the performance of the routing scheme according to our method of relay node selection. Finally, some conclusions are provided in Section 5.

2 System Model

We let $\mathscr{N}$ denote the set of nodes in the network, and $|\mathscr{N}| = N+1$ denote the cardinality of this set. We assume that the mobility patterns of all nodes are independent and identically distributed, and that any two nodes can communicate with each other when they are encountered, i.e., they are within transmission ranges of one another. Further, we assume that inter-meeting times between the pairwise nodes i, j ($i, j \in \mathscr{N}, i \neq j$) are distributed according to an exponential distribution with parameter $\lambda_{i,j}$. Note that in [20, 21], the exponential inter-meeting time assumption was examined in depth and validated in random mobility models such as Random Waypoint and Random Direction models.

In this paper, we focus on unicast communication. Specifically, there are a particular source node s ($s \in \mathscr{N}$) and a particular destination node d ($d \in \mathscr{N}$) in the network. At time 0, an original message is generated by the source node s and is delivered to the destination node d according to a variant of the two-hop routing scheme. In the routing scheme, only the source node s can forward message copies to at most $N_M - 1$ ($1 \leq N_M \leq N$) nodes. When the source node s encounters another node i ($i \in \mathscr{N} \setminus \{s\}$), node s can choose whether to forward the message copy is forwarded to node i based on the meeting rate $\lambda_{i,d}$ for the destination node d. When N_M is set to be 1, the routing scheme corresponds to the *Direct Delivery* scheme [9, 10]. Moreover, if the source node forwards the message copy regardless of the meeting rate, the routing scheme corresponds to source SW. Note that for each node i ($i \in \mathscr{N}$), we can easily obtain $\lambda_{i,j}$ ($j \in \mathscr{N} \setminus \{i\}$) by using statistics based on historical encounter information. Therefore when nodes s and j encounter one another, the source node s can also easily obtain $\lambda_{j,d}$ for $j \in \mathscr{N} \setminus \{s\}$ because node j passes $\lambda_{j,d}$ to node s.

3 Optimal Relay Node Selection Rule

In this section, we consider an algorithm for selecting the optimal relay node selection rule in variants of the two-hop routing scheme. First we formulate a system dynamics model from generating an original message to its delivery at the destination. We then formulate the mean delivery delay for an arbitrary relay node selection rule. Finally, we derive the optimal relay node selection rule. Table 1 summarizes mathematical symbols used in this paper.

Table 1: List of mathematical symbols.

Symbol	Definition
$\mathscr{A}(x)$	The set of active nodes (relay nodes without the message copy) for the state x.
$M(x)$	The total number of message copies for the state x.
$\mathscr{N}$	The set of nodes in the network.
N_M	The maximum number of message copies.
$\mathscr{R}$	The set of relay nodes.
T_D	The delivery delay.
$X(t)$	The system state at time t.
$\mathscr{X}_B$	The set of feasible states before message delivery.
$\mathscr{X}_D$	The set of system states immediately after the message delivery.
$\mathscr{V}(x)$	The set of vacant nodes (relay nodes with the message copy) for the state x.
$\lambda_{i,j}$	The meeting rate between node i and node j.
π	The selection rule.
π^*	The optimal selection rule.

3.1 Formulation of system dynamics

The system state can be represented by a $1\times(N+1)$ vector $X(t) = (X_1(t), X_2(t), \ldots, X_{N+1}(t))$ where $t \geq 0$. The ith ($i \in \{1,2,\ldots,N+1\}$) element $X_i(t) \in \{0,1\}$ represents whether node i stores the message copy at time t. When node i stores the message copy, $X_i(t) = 1$; otherwise, $X_i(t) = 0$. Without loss of generality, $X_1(t)$ and X_{N+1} can represent the state of the source node s and the destination node d, respectively. At time 0, the system state $X(0)$ is equal to e_1, where e_j ($j = 1,2,\ldots,N+1$) denotes the $1\times(N+1)$ unit vector whose jth element is equal to 1.

We let T_D denote the delivery delay, i.e., the time interval from the generation of the original message to its delivery at the destination node. The system state $X(T_D)$ at time T_D can be represented as $(1, X_2(T_D), X_3(T_D), \ldots, X_N(T_D), 1)$. We also let $\mathscr{X}_D$ denote the feasible system states immediately after the message delivery. Formally, $\mathscr{X}_D = \{(1, X_2(T_D), \ldots, X_N(T_D), 1) \mid X_i(T_D) \in \{0,1\}\ (i = 2, 3, \ldots, N), \sum_{j=1}^{N} X_j(T_D) \leq N_M\}$.

For the sake of convenience, we introduce the following definitions. $\mathscr{R}$ denotes the set of relay nodes. Formally, $\mathscr{R} = \mathscr{N} \setminus \{1, N+1\} = \{2,3,\ldots,N\}$. Furthermore, we let denote $\mathscr{X}_B = \{(1, x_2, x_3, \ldots, x_N, 0) \mid x_i \in \{0,1\}\ (i \in \mathscr{R})\}$ as the set of feasible system states before the message delivery. When $X(t) = x$ ($x \in \mathscr{X}_B$), we define a function M by $M(x) = \sum_{i=1}^{N} x_i$, where $M(x)$ indicates the total number of message copies (including the original) for x. We let $\mathscr{X}_B(m) = \{x \mid x \in \mathscr{X}_B,\ M(x) = m\}$ denote the set of feasible system states with $M(x) = m$ before the message delivery.

3.2 Relay node selection rule

We define a function $\pi : \mathscr{X}_B \to 2^{\mathscr{R}}$, where $2^{\mathscr{R}}$ indicates the power set of $\mathscr{R}$. For $x \in \mathscr{X}_B$, $\pi(x)$ indicates the set of candidate nodes to which message copies may be forwarded when the system state is x. In the following, we refer to the function π as *the selection rule*.

We now define some symbols when the selection rule π is adopted. $X^\pi(t)$ denotes the system state in the routing scheme with the selection rule π at time t, where the ith element $X_i^\pi(t)$ indicates whether node i has the message copy under rule π at time t. $\mathscr{X}_B^\pi$ also denotes a set of feasible states before message delivery with the selection rule π. The subset $\mathscr{X}_B^\pi(m) \subseteq \mathscr{X}_B^\pi$ ($1 \leq m \leq N_M$) represents the set of feasible system states before its delivery with the selection rule π for $M(x) = m$ ($x \in \mathscr{X}_B^\pi$). By definition, $\mathscr{X}_B^\pi(1) = \{e_1\}$. For $2 \leq m \leq N_M$, $\mathscr{X}_B^\pi(m) = \{x + e_i \mid x \in \mathscr{X}_B^\pi(m-1),\ i \in \pi(x)\}$. $\mathscr{X}_B^\pi = \cup_{m=1}^{N_M} \mathscr{X}_B^\pi(m)$

and $\mathscr{X}_B^\pi \subseteq \mathscr{X}_B$. We let $\mathscr{X}_D^\pi = \{x + e_{N+1} \mid x \in \mathscr{X}_B^\pi\}$ denote the set of system states immediately after the message delivery.

Moreover, for $x \in \mathscr{X}_B^\pi$, let $\mathscr{A}(x) = \{i \mid x_i = 1, i \in \mathscr{R}\}$ and $\mathscr{V}(x) = \{i \mid x_i = 0, i \in \mathscr{R}\}$ denote sets of relay nodes with and without the message copy, respectively. In the following, for simplicity of description, we refer to nodes in $\mathscr{A}(x)$ and nodes in $\mathscr{V}(x)$ as *active nodes* and *vacant nodes*, respectively.

3.3 Delivery delay with relay node selection rule

The system dynamics under the selection rule π from the generation of the original message to its delivery at the destination node can be formulated as a continuous-time Markov chain $\{X^\pi(t) \mid t \geq 0\}$. Let T_D^π denote the message delivery delay under selection rule π. By definition, the message delivery delay under selection rule π is equivalent to the first passage time T_D^π to any states in $\mathscr{X}_D^\pi$ of the Markov chain $\{X^\pi(t);\ t \geq 0\}$, given that $X^\pi(0) = e_1$. T_D^π is defined formally as

$$T_D^\pi = \inf\{t \geq 0 \mid X^\pi(t) \in \mathscr{X}_D^\pi\},$$

where inf indicates the infimum of a set. In order to obtain a recursion to compute the mean message delivery delay $\mathrm{E}[T_D^\pi] := \mathrm{E}[T_D^\pi \mid X^\pi(0) = e_1]$, we define $T_D^\pi(x)$ as

$$T_D^\pi(x) = \mathrm{E}[T_D^\pi \mid X^\pi(0) = x], \qquad x \in \mathscr{X}_B^\pi.$$

Here, we consider the system transitions from the system state $x \in \mathscr{X}_B^\pi$. Figure 1(b) shows the meeting rates among nodes for x, where meetings that cannot change the system states are omitted. In this system, there are four types of meetings that change the system state. Compared with the single-copy routing considered in [8] (see Fig. 1(a)), the difference is that system transitions occur when active nodes encounter the destination node (see Figs. 1(a) and 1(b)). Therefore the algorithm proposed in [8] cannot be immediately adopted to calculate the mean delivery delay $\mathrm{E}[T_D^\pi]$ with the selection rule π in the system.

To calculate the mean delivery delay $\mathrm{E}[T_D^\pi]$ in this system, we consider a system equivalent to that stated above. As we will show, $\mathrm{E}[T_D]$ in the equivalent system can be calculated using the algorithm proposed in [8]. In the equivalent system, we integrates the source node into the active nodes. More specifically, we consider an integrated node $s(x)$, where the meeting rate of node $s(x)$ is set to be as follows:

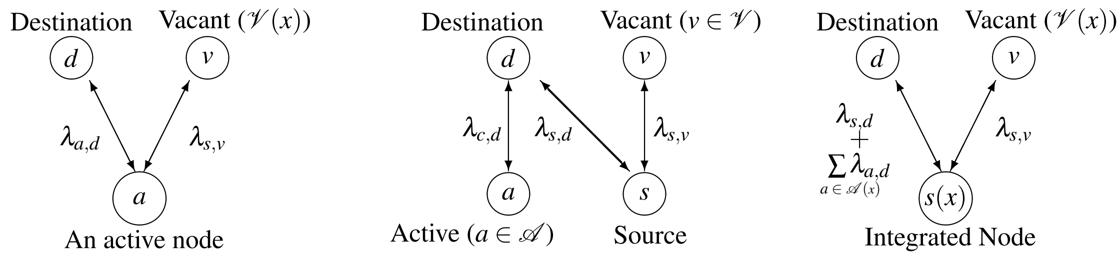
$$\lambda_{s(x),j} = \begin{cases} \lambda_{s,d} + \sum_{i \in \mathscr{A}(x)} \lambda_{i,d} & j = d \\ 0 & j \in \mathscr{A}(x) \\ \lambda_{s,j} & j \in \mathscr{V}(x) \end{cases}$$

Note that the meeting rate $\lambda_{s(x),d}$ depends on the system state x. This integration means that, in the equivalent system, there are three types of nodes: the integrated node $s(x)$, the destination node d, and the vacant nodes $v \in \mathscr{V}(x)$. Figure 1(c) shows the meeting rates among nodes in the equivalent system for $x \in \mathscr{X}_B^\pi$. The meeting rates in the equivalent system are similar to those in the system for the single-copy routing scheme, so that the algorithm proposed in [8] can be adopted to determine the optimal selection rule π when the system state is equal to $x \in \mathscr{X}_B^\pi$.

In the equivalent system, $T_D^\pi(x)$ can be written as follows (see Appendix A).

$$T_D^\pi(x) = \frac{1}{\Lambda^\pi(x)} + \sum_{j \in \pi(x)} \frac{\lambda_{s(x),j}}{\Lambda^\pi(x)} T_D^\pi(x + e_j), \tag{1}$$

where $\Lambda^\pi(x) = \sum_{j \in \pi(x) \cup \{d\}} \lambda_{s(x),j}$.



(a) Single-copy case. (b) Original system. (c) Equivalent system.

Figure 1: Meeting rates among nodes.

3.4 Calculation method for optimal relay selection rule

We consider the minimization of Eq. (1) and denote the selection rule that minimizes the mean delivery delay by π^*. Moreover we call the selection rule π^* the *optimal selection rule* and denote the minimum delivery delay by $T_D^{\pi^*}(x)$, which is formally given as follows.

$$T_D^{\pi^*}(x) = \min_{\pi(x) \subset \mathscr{V}(x)} \left\{ \frac{1}{\Lambda^{\pi}(x)} + \sum_{j \in \pi(x)} \frac{\lambda_{s(x),j}}{\Lambda^{\pi}(x)} T_D^{\pi^*}(x + e_j) \right\}. \tag{2}$$

We refer to Eq. (2) as the optimality equation of dynamic programming [22]. The optimality equation possesses useful properties for solving the minimization problem. One such property is that a solution of Eq. (2) can achieve the minimum mean delivery delay for any states following from the state x. Therefore, the optimal selection rule $\pi^*(x)$ can be given as follows:

$$\pi^*(x) = \operatorname*{argmin}_{\pi(x) \subset \mathscr{R}(x)} \left\{ \frac{1}{\Lambda^{\pi}(x)} + \sum_{j \in \pi(x)} \frac{\lambda_{s(x),j}}{\Lambda^{\pi}(x)} T_D^{\pi^*}(x + e_j) \right\}.$$

As described in [8], the above equation implies that, when the optimal selection set $\pi^*(x)$ includes node v ($v \in \mathscr{V}(x)$), $T_D^{\pi^*}(x + e_v) \le T_D^{\pi^*}(x)$. Otherwise, $T_D^{\pi^*}(x + e_v) > T_D^{\pi^*}(x)$. In the latter case, forwarding message copies to node v does not contribute to improving the mean delivery delay. Therefore, when the source node s encounters node v, it should wait to encounter other nodes without forwarding the message copy to node v. Note that, for each state $x \in \mathscr{X}_B^{\pi^*}$, $\pi^*(x)$ and $T_D^{\pi^*}(x)$ can be calculated by using the algorithm proposed in [8]. Note that the algorithm also has the advantage that brute-force searches are not needed.

Based on the above observations, we propose a method for calculating the mean delivery delay $\mathrm{E}[T_D^{\pi^*}]$ with the optimal relay selection rule π^*. $\mathrm{E}[T_D^{\pi^*}]$ can be calculated by a backward recursive procedure. Figure 2 illustrates this backward recursive procedure, where for a set $\mathscr{L} \subset \mathscr{R}$, we define $\Lambda(x, \mathscr{L}) = \sum_{j \in \mathscr{L} \cup \{d\}} \lambda_{s(x),j}$ and

$$T_D(x, \mathscr{L}) = \frac{1}{\Lambda(x, \mathscr{L})} + \sum_{j \in \pi(x)} \frac{\lambda_{s(x),j}}{\Lambda(x, \mathscr{L})} T_D(x + e_j, \mathscr{L}). \tag{3}$$

In this procedure, the mean delivery delay $T_D^{\pi^*}(x)$ for $x \in \mathscr{X}_B(N_M)$ is calculated first (lines 7 to 8), and then $T_D^{\pi^*}(x)$ for $x \in \mathscr{X}(N_M - 1)$ is calculated (lines 9 to 21). Line 14 determines whether or not the inclusion of node i improves the mean delivery delay. If so, lines 18 to 19 are executed, and otherwise lines 15 to 17 are executed. Next, $T_D^{\pi^*}(x)$ for $x \in \mathscr{X}(N_M - 2)$ is calculated, and so on. Eventually,

Input: $\mathscr{X}_B(m)$ $(m = 1,2,\ldots,N_M)$, $\lambda_{s,j}, \lambda_{j,d}$ $(j \in \mathscr{N})$
Output: $\pi^*(x)$, $T_D^{\pi^*}(x)$ $(x \in \mathscr{X}_B)$

1: Let $m := N_M$.
2: WHILE $m \neq 0$ DO
3: Let $\mathscr{J} := \emptyset$.
4: WHILE $\mathscr{X}_B(m) \neq \mathscr{J}$ DO
5: Choose an arbitrary element x in $\mathscr{X}_B(m) \setminus \mathscr{J}$
6: and let $\mathscr{J} := \mathscr{J} \cup \{x\}$.
7: IF $m = N_M$ THEN
8: $T_D^{\pi^*}(x) := 1/\lambda_{s(x),d}$
9: ELSE
10: Let $\mathscr{L} = \emptyset$.
11: WHILE $\mathscr{V}(x) \neq \mathscr{L}$ DO
12: Let $i = \min_{i \in \mathscr{V}(x) \setminus \mathscr{L}} \{T_D(x+e_i)\}$.
13: Compute $T_D(x, \mathscr{L} \cup \{i\})$ by Eq. (3).
14: IF $T_D(x, \mathscr{L} \cup \{i\}) > T_D(x, \mathscr{L})$ THEN
15: $\pi^*(x) := \mathscr{L}$;
16: $T_D^{\pi^*}(x) := T_D(x, \mathscr{L})$
17: Go to line 5.
18: ELSE
19: $\mathscr{L} := \mathscr{L} \cup \{i\}$
20: ENDIF
21: ENDWHILE
22: ENDIF
23: ENDWHILE
24: $m := m - 1$
25: ENDWHILE

Figure 2: Procedure for relay node selection.

$\mathrm{E}[T_D^{\pi^*}] = T_D(e_1)$ can be calculated. Note that the optimal selection rule π^* can also be obtained by calculating $T_D^{\pi^*}(e_1)$ using this procedure.

Finally, we describe the qualitative characteristics of the optimal selection rule π^*. Under π^*, the candidate node set depends on system state x. Even if a node is not contained in previous candidate node sets, it may be contained in future sets as the system state changes. More specifically, we consider two states $x+e_i$ and $x+e_j$ $(i, j \in \mathscr{V}(x),\ i \neq j)$ that transition from the system state x. In general, if $\lambda_{i,d} \neq \lambda_{j,d}$, for $k \in \mathscr{V}(x) \setminus \{i, j\}$, $\Lambda^{\pi^*}(x+e_i+e_k) \neq \Lambda^{\pi^*}(x+e_j+e_k)$ so that $T_D^{\pi^*}(x+e_i+e_k) \neq T_D^{\pi^*}(x+e_j+e_k)$. The values $T_D^{\pi^*}(x+e_i+e_k)$ and $T_D^{\pi^*}(x+e_j+e_k)$ determine whether $\pi^*(x+e_i)$ and $\pi^*(x+e_j)$ contain node k or not, respectively. This observation indicates that the inclusion of node k in the optimal set is highly dependent on the system state.

4 Performance Evaluation

In this section, we evaluates the performance of the routing scheme according to the optimal selection rule π^*. In the following, we refer to the routing scheme as the *optimal relay routing*. First, we exemplify the qualitative characteristics of the optimal relay routing. Specifically, we show that the optimal set of candidate nodes changes according to the system state in the optimal relay routing. Next, we demonstrate the effectiveness of the optimal relay routing.

Table 2: Setting of meeting rates $\lambda_{1,i}$ and $\lambda_{i,8}$.

	1	2	3	4	5	6	7	8
$\lambda_{1,i}$	0	10^{-4}	10^{-3}	10^{-2}	10^{-1}	1	10	10^{-2}
$\lambda_{i,8}$	10^{-2}	1	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	0

In the performance evaluation, we consider situations where nodes in the network encounter according to Poisson processes. Moreover, we assume that message copies can be forwarded instantly with sufficiently large bandwidth. We also assume that the buffer size is sufficiently large, and thus message loss never happens. We leave the effects of the limited bandwidth and buffering for the future work.

4.1 Dynamic change to optimal relay set

To reveal the property of the optimal relay routing, we consider a network consisting of $N+1=8$ nodes. By definition, $\lambda_{1,i}$ and $\lambda_{i,8}$ indicate the meeting rates for node i ($i \in \mathscr{N}$) encountering the source node $s=1$ and the destination node $d=8$, respectively. Note that $\lambda_{1,1}=\lambda_{8,8}=0$. Table 2 presents the parameter settings for the meeting rates $\lambda_{1,i}$ and $\lambda_{i,8}$ ($i \in \mathscr{N}$). In this situation, we consider that a message to be delivered to the destination node according to the optimal relay routing.

Figure 3 shows the state transitions according to the optimal relay routing, where the state transitions from each state to states after the message delivery are omitted. First, we compare states e_1+e_2 and e_1+e_3. When the system states are e_1+e_2 and e_1+e_3, the optimal candidate node sets are $\pi^*(e_1+e_2)=\{3,4,5,6\}$ and $\pi^*(e_1+e_3)=\{2,4,5\}$, respectively. When the system state x is e_1+e_2, the system condition is good, as node 2 contains a message copy and frequently meets the destination node. Under these system conditions, the optimal candidate node set $\pi^*(x)$ contains node 6, which frequently meets the source node but rarely encounters the destination node. In contrast, when the system state $x$is e_1+e_3, node 3 (whose rate $\lambda_{3,8}$ is smaller than $\lambda_{2,8}$) has a message copy, and the system condition is worse than in the state e_1+e_2. In this situation, the relay node selection was such that node 6 was not selected among the candidate nodes.

Next, we compare $\pi^*(e_1+e_2)$ and $\pi^*(e_1+e_2+e_3)$. Note that $\pi^*(e_1+e_2)=\{3,4,5,6\}$, whereas $\pi^*(e_1+e_2+e_3)=\{3,4,5\}$, and node 6 is not included. Therefore, when the system state transitions from e_1+e_2 to $e_1+e_2+e_3$, the system condition becomes worse, so that the selection of forwarding nodes must be conducted carefully. These results also show that the optimal candidate node set changes dynamically depending on the system state. The mean delivery delay cannot be minimized using static relay node selection rules, and relay node selection rules based on the system state are needed for efficient message delivery.

4.2 Effectiveness of optimal relay selection scheme

To investigate the effectiveness of the optimal relay selection scheme, we consider a network of $N+1=18$ nodes. By definition, note that $\lambda_{1,i}$ and $\lambda_{i,18}$ indicate the meeting rates where node i ($i \in \mathscr{N}$) encounters the source node $s=1$ and the destination node $d=18$, respectively. Depending on the meeting rates of the source node and the destination node, relay nodes i ($i \in \mathscr{R}$) can be classified into the four groups as shown in Table 3. Without relay selection rules, we can infer that the nodes in Group 1 should be selected as forwarders. The reason is that the nodes in Group 1 frequently encounter both the source node and the destination node, and forwarding a message copy to them is more likely to improve the system performance. We can also infer that nodes in Group 4 should not be selected as forwarders. Note that the nodes in Group 4 rarely encounter both the source node and the destination

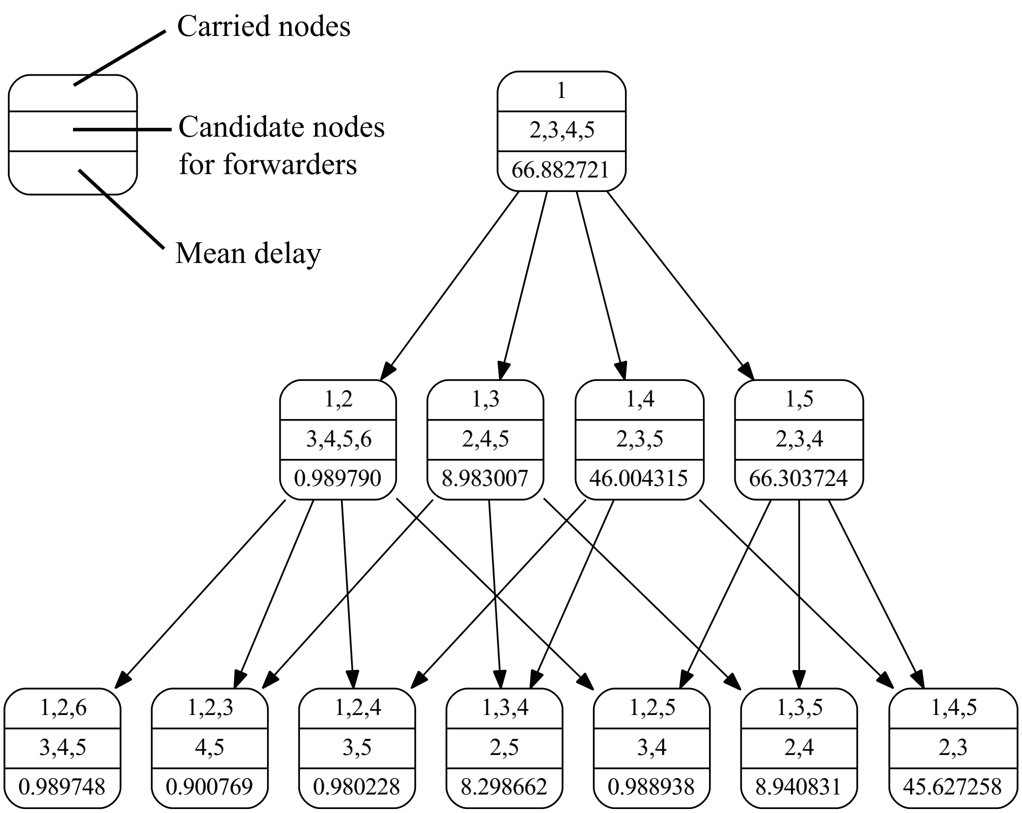


Figure 3: State transitions in the optimal relay routing.

Table 3: Classification of relay nodes.

	Large $\lambda_{1,i}$	Small $\lambda_{1,i}$
Large $\lambda_{i,18}$	Group 1	Group 2
Small $\lambda_{i,18}$	Group 3	Group 4

node. These inferences indicate that we can easily determine whether or not nodes in Groups 1 and 4 should be contained in the optimal candidate node set without the relay node selection. In the following, we consider a situation in which the optimal candidate node set is not obvious. Specifically, we consider the situation where Groups 2 and 3 are present in the network. Let $\mathscr{G}_2$ and $\mathscr{G}_3$ represent the sets of nodes in Groups 2 and 3, respectively, and let $|\mathscr{G}_2|$ and $|\mathscr{G}_3|$ denote the number of nodes in $\mathscr{G}_2$ and $\mathscr{G}_3$.

Unless otherwise noted, the meeting rates $\lambda_{1,i}$ and $\lambda_{i,18}$ ($i \in \mathscr{N}$) of the source node and the destination node are set as shown in Table 4. Moreover, we set $|\mathscr{G}_2| + |\mathscr{G}_3| = 16$ ($0 \leq |\mathscr{G}_2|, |\mathscr{G}_3| \leq 16$). For $|\mathscr{G}_2| \geq 1$, $\mathscr{G}_2 = \{2, 3, \ldots, |\mathscr{G}_2| + 1\}$ and $\mathscr{G}_3 = \mathscr{R} \setminus \mathscr{G}_2$, and for $|\mathscr{G}_2| = 0$, $\mathscr{G}_2 = \emptyset$ and $\mathscr{G}_3 = \mathscr{R}$.

First, we consider the case in which Groups 2 and 3 contain equal numbers of nodes, i.e., $|\mathscr{G}_2| = |\mathscr{G}_3| = 8$. We consider two scenarios: *the non-cooperation scenario* and *the cooperation scenario*. In the non-cooperation scenario, relay nodes are selfish so that they do not generate other relay nodes. In this situation, $\lambda_{i,j} = 0$ ($i, j \in \mathscr{G}_2 \cup \mathscr{G}_3$). On the other hand, in the cooperation scenario, relay nodes are cooperative so that they can generate relay nodes when multi-hop routing schemes are adopted. In this scenario, we set the meeting rates $\lambda_{i,j}$ ($i, j \in \mathscr{G}_2 \cup \mathscr{G}_2$) as shown in Table 5, where nodes in the same group are encountered frequently. We compare the mean delivery delay $\mathrm{E}[T_D]$ given by the optimal relay routing, source SW, binary SW and Epidemic Routing. Note that Epidemic Routing can achieve the

Table 4: Meeting rates $\lambda_{1,i}$, $\lambda_{i,18}$.

	$i = 1$	$i \in \mathscr{G}_2$	$i \in \mathscr{G}_3$	$i = 18$
$\lambda_{1,i}$	0	0.002	0.2	0.02
$\lambda_{i,18}$	0.02	0.2	0.002	0

Table 5: Meeting rates $\lambda_{i,j}$ $(i, j \in \mathscr{G}_2 \cup \mathscr{G}_3)$ in the cooperation scenario.

	$i \in \mathscr{G}_2$	$i \in \mathscr{G}_3$
$j \in \mathscr{G}_2$	0.2	0.002
$j \in \mathscr{G}_3$	0.002	0.2

minimum delivery delay because of broadcasting message copies, but incurs the heaviest network load.

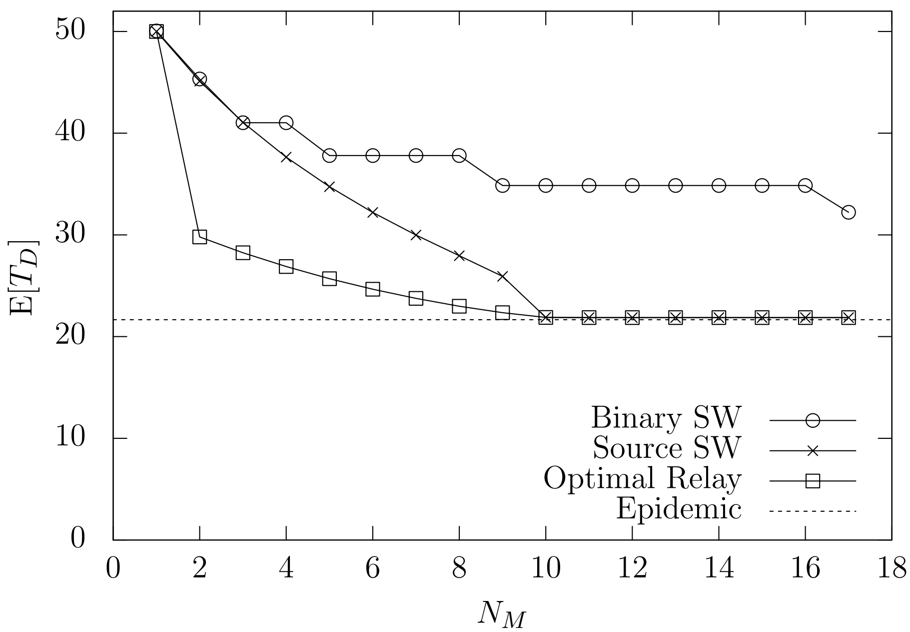
Figure 4 shows $\mathrm{E}[T_D]$ as a function of the maximum number N_M of forwarded message copies. In both scenarios, as N_M increases, $\mathrm{E}[T_D]$ in the optimal relay routing decreases monotonically. In particular, at around $N_M = 2$, $\mathrm{E}[T_D]$ decreases significantly. When all relay nodes can receive a copy of the message, that is, $N_M = 17$, $\mathrm{E}[T_D]$ in the optimal relay routing is comparable to that in source SW. For $N_M < 10$, $\mathrm{E}[T_D]$ in the optimal relay routing is less than that in source SW, and there is a significant difference between these schemes. For $N_M \geq 10$, there is a little difference between the delay in the optimal relay routing and source SW. These results indicate that, for a small maximum number N_M of message copies, relay node selection has a significant effect on system performance, which implies that the relay nodes should be selected carefully.

In the non-cooperation scenario, the optimal relay routing outperforms binary SW. The reason is that in binary SW, relay nodes do not forward message copies even though they have the right to. Moreover, $\mathrm{E}[T_D]$ in the optimal relay routing is comparable to that in Epidemic Routing. The number of forwarding message copies in the optimal relay routing is also smaller than that in Epidemic Routing. These results indicates that the optimal relay routing is effective when there are selfish nodes in the network.

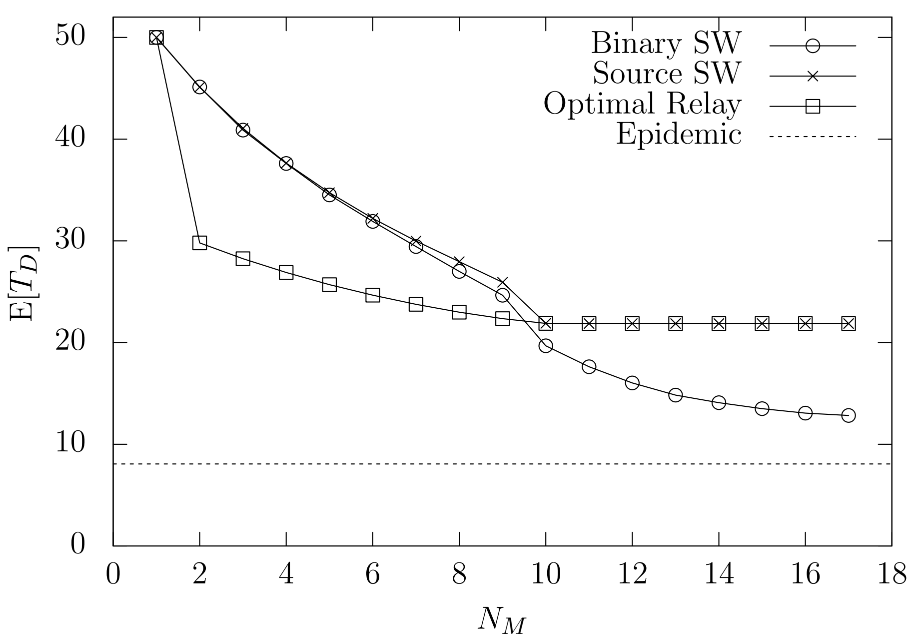
In the cooperation scenario, for $N_M < 10$, $\mathrm{E}[T_D]$ in the optimal relay routing is less than that in binary SW, while for $N_M \geq 10$ binary SW outperforms the optimal relay routing. For small N_M in binary SW, message copies are distributed to nodes in $\mathscr{G}_3$, and thus the improvement of $\mathrm{E}[T_D]$ is small. For large N_M in binary SW, nodes in $\mathscr{G}_2$ can receive the message copy so that $\mathrm{E}[T_D]$ becomes small. This result indicates that binary SW is effective in the cooperation scenario when N_M is set appropriately. However, it is difficult to set an appropriate value for N_M because binary SW is sensitive to N_M.

Next, we investigate how the cardinality of Group 2 $|\mathscr{G}_2|$, affects the mean delivery delay $\mathrm{E}[T_D]$. Figure 5 shows $\mathrm{E}[T_D]$ as a function of $|\mathscr{G}_2|$. For $|\mathscr{G}_2| = 0, 16$, there is only one group in the network, thus all nodes in the network belong to either $\mathscr{G}_2$ or $\mathscr{G}_3$. Therefore, all nodes encounter the destination node at the same rate, so that $\mathrm{E}[T_D]$ cannot be improved by relay node selection. It is apparent that relay node selection is useless in a homogeneous environment.

For $1 \leq |\mathscr{G}_2| \leq 15$, as $|\mathscr{G}_2|$ increases, $\mathrm{E}[T_D]$ decreases monotonically in both routing schemes. The reason is that the possibility of the source node encountering a node in Group 2 increases with $|\mathscr{G}_2|$. However, the rate of decrease of $\mathrm{E}[T_D]$ is different in each scheme. In source SW, $\mathrm{E}[T_D]$ decreases moderately quickly for small $|\mathscr{G}_2|$. For larger $|\mathscr{G}_2|$, $\mathrm{E}[T_D]$ decreases more quickly, and $\mathrm{E}[T_D]$ then equals that under the optimal relay routing scheme. The reason is that, for small $|\mathscr{G}_2|$, all message copies are more likely to be forwarded to nodes in Group 3, whereas the carrier nodes rarely encounter the destination nodes. For large $|\mathscr{G}_2|$, at least one message copy can be forwarded to the nodes in Group 2. However, under the optimal relay routing, as $|\mathscr{G}_2|$ increases, $\mathrm{E}[T_D]$ decreases moderately quickly. For $1 \leq |\mathscr{G}_2| \leq 15$, $\mathrm{E}[T_D]$ in the optimal relay routing is less than that for source SW. This result indicates



(a) Non-cooperation scenario.



(b) Cooperation scenario.

Figure 4: Mean delivery delay $\mathrm{E}[T_D]$ as a function of the maximum number N_M of message copies.

that the relay node selection is very important in situations where the source node frequently encounters strangers of the destination node.

We next investigate the effect of varying with meeting rates for Group 2. Figure 6 shows the mean delivery delay $\mathrm{E}[T_D]$ as a function of $\lambda_{1,i}$ ($i \in \mathscr{G}_2$). For extremely small $\lambda_{1,i}$, the difference between $\mathrm{E}[T_D]$ for the optimal relay routing and for source SW is small. For small $\lambda_{1,i}$, $\mathrm{E}[T_D]$ in the optimal relay routing decreases sharply, whereas that in source SW decreases moderately. For large $\lambda_{1,i}$, the difference is again

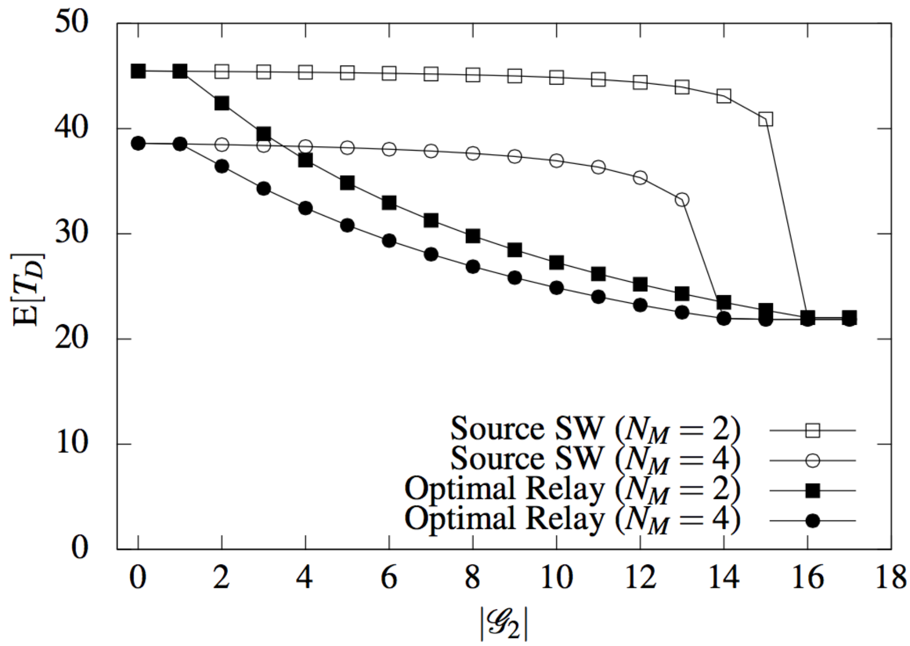


Figure 5: Mean delivery delay $\mathrm{E}[T_D]$ as a function of the number $|\mathscr{G}_2|$ of nodes in Group 2.

small. These results indicate that the relay node selection is effective when the meeting rates of nodes in Group 2 are moderately small.

Finally, we evaluate the effect of the network size $|\mathscr{N}|$. To do so, we set $|\mathscr{G}_2| = |\mathscr{G}_3| = (|\mathscr{N}| - 2)/2$. Figure 7 shows the mean delivery delay $\mathrm{E}[T_D]$ as a function of the number $|\mathscr{N}|$ of nodes in the network. $\mathrm{E}[T_D]$ in the optimal relay routing decreases as $|\mathscr{N}|$ increases, while $\mathrm{E}[T_D]$ in source SW is almost the same regardless of $|\mathscr{N}|$. In source SW, all copies of the message are distributed to nodes in $\mathscr{G}_2$, and thus the distribution cannot improve $\mathrm{E}[T_D]$. Moreover, for large $\mathscr{N}$, the performance difference between the optimal relay routing and source SW is large. Therefore, relay nodes should be carefully selected when the network size is large.

5 Conclusion

This paper considers the optimal relay node selection in two-hop routing. The proposed scheme selects candidate nodes for message forwarding to improve the delay performance from relay nodes. Through a series of numerical experiments, we showed that when messages are delivered to the destination node according to the optimal relay selection scheme, which depends on the set of relay nodes containing message copies, the candidate nodes for further message forwarding change dynamically. Moreover, we demonstrated that relay node selection affects system performance and that the optimal relay selection scheme is effective.

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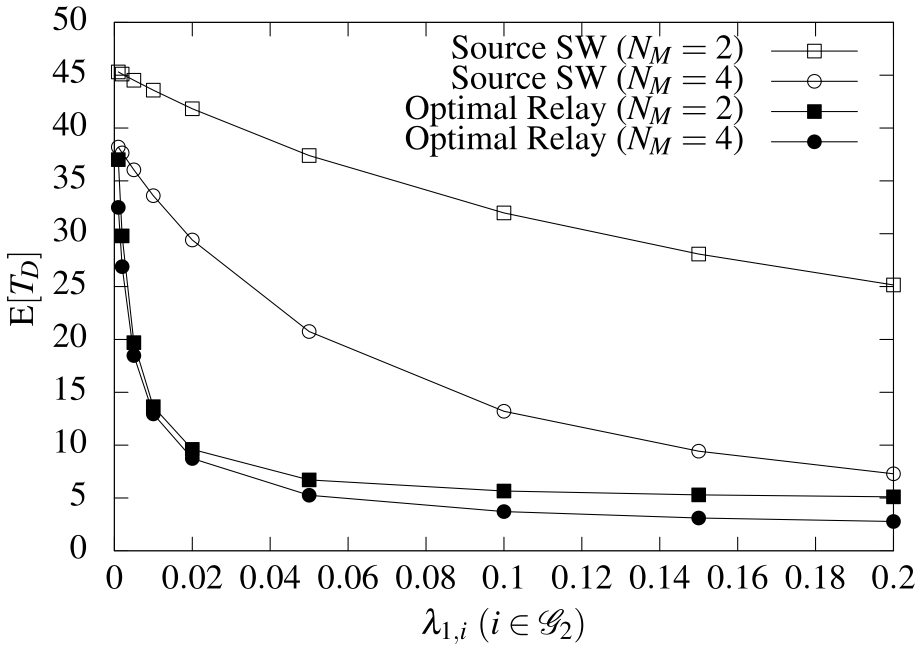

Figure 6: Mean delivery delay E[T_D] as a function of meeting rates $\lambda_{1,i}$ ($i \in \mathscr{G}_2$).

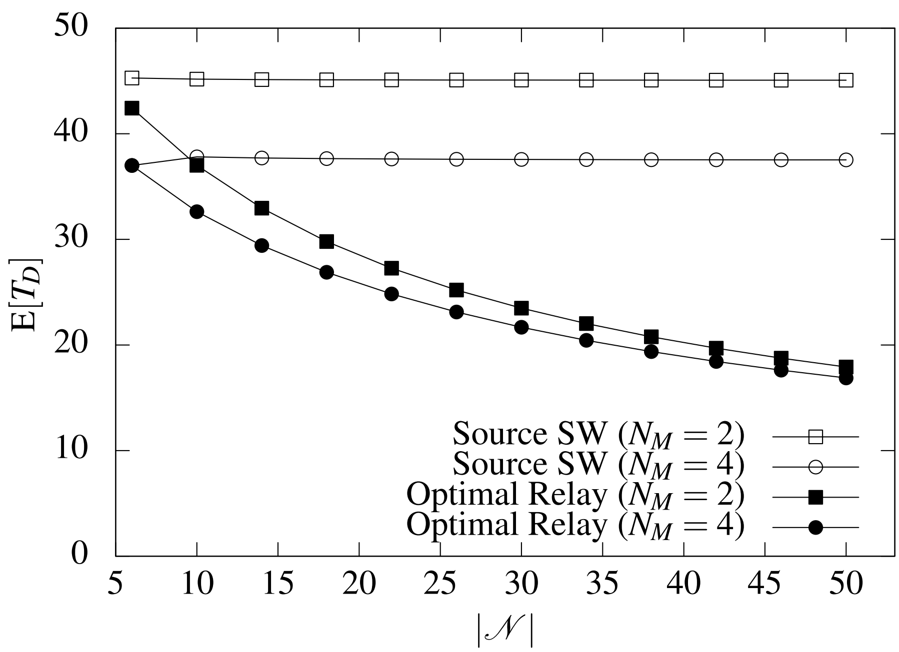

Figure 7: Mean delivery delay E[T_D] as a function of the number $|\mathscr{N}|$ of nodes in the network.

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Appendix

A Mean Delivery Delay in The Equivalent System

We derive Eq. 1 for the mean delivery delay $T_D(x)$ of $x \in \mathscr{X}_B^\pi$ as described in Section 3.4. In our target system, system state transitions occur when the node $s(x)$ encounters vacant nodes in $\mathscr{V}(x)$ or the destination node (see Fig. 1(c)). When the node $s(x)$ encounters a vacant node $v \in \mathscr{V}(x)$, it decides whether to forward a message to the node v according to the rule π. Depending on which nodes encounter the integrated node $s(x)$, the system states after transition will change. These observations indicate that system state transitions from the state x can be classified into the following three categories.

1. the destination node $j = d$
2. candidates for the forwarder $j \in \pi(x)$
3. non-candidates for the forwarder $j \in \mathscr{V}(x) \setminus \pi(x)$

The meeting rates between $s(x)$ and nodes of these three types are equivalent to $\lambda_{s(x),d}$, $\sum_{j\in\pi(x)} \lambda_{s(x),j}$, and $\sum_{j\in\mathscr{V}(x)\setminus\pi(x)} \lambda_{s(x),j}$, respectively. Suppose that $\mathrm{E}[T_D^\pi \mid X^\pi(0) \in \mathscr{X}_D^\pi] = 0$, and the mean delay $T_D^\pi(x)$ is given as follows:

$$T_D^\pi(x) = \frac{1}{\Lambda(x)} + \sum_{j\in\pi(x)} \frac{\lambda_{s(x),j}}{\Lambda(x)} T_D^\pi(x+e_j) + \sum_{j\in\mathscr{V}(x)\setminus\pi(x)} \frac{\lambda_{s(x),j}}{\Lambda(x)} T_D^\pi(x) \tag{4}$$

where $\Lambda(x) = \sum_{j\in\mathscr{V}(x)\cup\{d\}} \lambda_{s(x),j}$. Equation (4) can then be reduced to the below form:

$$\left(\frac{\Lambda(x) - \sum_{j\in\mathscr{V}(x)\setminus\pi(x)} \lambda_{s(x),j}}{\Lambda(x)}\right) T_D^\pi(x) = \frac{1}{\Lambda(x)} + \sum_{j\in\pi(x)} \frac{\lambda_{s(x),j}}{\Lambda(x)} T_D^\pi(x+e_j).$$

To determine $T_D^{\pi}(x)$, we use Eq. (1), which indicates that system state transitions occur when the node $s(x)$ encounters node $j \in \pi(x)$ or the destination node. When node $s(x)$ encounters a non-candidate node $j \in \mathscr{V}(x) \setminus \pi(x)$, no system state transition occurs. Moreover, from a system state $x \in \mathscr{X}_B$, the mean occurrence duration of state transitions is distributed according to an exponential distribution with the parameter $\Lambda^{\pi}(x)$. When system state transitions from x occur, the encounter probability of nodes $s(x)$ and i ($i \in \pi(x) \cup \{d\}$) is $\lambda_{s(x),i}/\Lambda^{\pi}(x)$.