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Research Article

Improving the Dominating-Set Routing over Delay-Tolerant Mobile Ad-Hoc Networks via Estimating Node Intermeeting Times

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With limited coverage of wireless networks and frequent roaming of mobile users, providing a seamless communication service poses a technical challenge. In our previous research, we presented a supernode system architecture that employs the delay-tolerant network (DTN) concept to provide seamless communications for roaming users over interconnected heterogeneous wireless networks. Mobile ad hoc networks (MANETs) are considered a key component of the supernode system for services over an area not covered by other wireless networks. Within the super node system, a dominating-set routing technique is proposed to improve message delivery over MANETs and to achieve better resource utilization. The performance of the dominating-set routing technique depends on estimation accuracy of the probability of a future contact between nodes. This paper studies how node mobility can be modeled and used to better estimate the probability of a contact. We derive a distribution for the node-to-node intermeeting time and present numerical results to demonstrate that the distribution can be used to improve the dominating-set routing technique performance. Moreover, we investigate how the distribution can be employed to relax the constraints of selecting the dominating-set members in order to improve the system resource utilization.

1. Introduction

The supernode system is introduced in [1] to achieve end-to-end information delivery for users roaming over heterogeneous wireless networks. Considering a set of heterogeneous wireless networks interconnected over an Internet backbone, a roaming user can encounter an intermittent connection to wireless access networks due to many factors such as user mobility, link failure, vertical handoff between heterogeneous networks, power off, and limited wireless network coverage. The supernode system adopts the delay-tolerant network (DTN) architecture [2] to achieve message delivery over intermittent connections. The message delivery is accomplished through the store and forward mechanism where intermediate nodes store a received message and then forward it to its destination node or to another intermediate node that is likely to meet the destination.

The delay-tolerant network architecture has been proposed to achieve reliable communication (using the store and forward mechanism) over challenged networks. Challenged networks [2] are networks where the communications path between a data source and its destination may never exist and/or the time to send a message from a source to the destination is excessive. There are a broad range of networks that can be considered as challenged networks such as deep space networks [3], sensor networks [4], vehicular networks [5], and sparse mobile ad hoc networks [6–10]. Within the problem domain under consideration, sparse mobile ad hoc networks are the focus of our research. Mobile ad hoc networks (MANETs) are considered an essential component of wireless access networks in the supernode system. It can provide service coverage over areas where there is no network infrastructure to provide communication services. Integrating MANETs as part of the supernode system introduces many challenges such as preventing unauthorized use of the networks [11] and achieving end-to-end message security [12]. One main challenge is how to route messages successfully over a sparse MANET. There exist various regular routing techniques such as AODV [13], DSR [14], and DSDV [15]. The main limitation of the regular MANET routing schemes is the need for an end-to-end path between the source and the destination, which makes them unsuitable for the system under consideration.

Research efforts have been devoted to routing in a sparse mobile ad hoc network (e.g., [8, 10]), which depends on known routes and movements of some nodes to deliver messages. Moreover, a moving node may be required to change its movement trajectory to deliver a message [9]. Other techniques assume totally scheduled contacts among nodes [16, 17]. These techniques make routing decisions based on *a prior* information of moving schedule of the mobile nodes. Such schemes are not suitable to the MANETs of interest where mobile nodes move randomly (freely) without known schedule. On the other hand, epidemic routing [18] assumes no knowledge about the network topology. It uses flooding to deliver messages, each node forwarding its received message to all its neighbor nodes. The message delivery mainly depends on node mobility, taking advantage that one of the message carriers may meet the message's destination node. Therefore, it is inefficient in terms of resources utilization, but sometimes necessary. A compromise between the two extremes is routing based on prediction of the future movement of a node using the knowledge of its previous location and movement pattern [6, 19].

Dominating-set-based routing for DTNs, first introduced in [20] for MANETs within the supernode system, is based on the concept of virtual network topology. Unlike regular network topology where graph links represent physical connections among nodes, the virtual network topology defines a link between two mobile nodes by the probability of future contacts (i.e., meetings) between the two nodes within the network. The routing technique is based on finding a dominating set for the virtual network topology graph. The more accurate the virtual graph is, the better the performance of the routing technique. The accuracy of the virtual network topology is mainly based on how accurate the probability of a contact between each pair of nodes can be estimated. In this paper, we investigate how to exploit node mobility model to better estimate the probability of a contact between nodes. Our contributions are threefold: (i) we derive a node intermeeting time distribution based on the node mobility model used in our previous work [21] and demonstrate the accuracy of the distribution by a simulation study; (ii) we investigate how the proposed estimation of the contact probability can improve the performance of the dominating-set-based routing scheme; (iii) we study how to relax the constraints of selecting the dominating-set members in order to achieve better resource utilization with acceptable performance.

The rest of this paper is organized as follows. Section 2 gives a brief overview of the supernode system and the dominating-set-based routing technique. Section 3 describes the system model for this research. Section 4 presents the proposed estimation of contact probability based on user mobility modeling. Section 5 shows how the proposed estimation can be employed to relax the dominating-set selection constraints. Section 6 gives a detailed example of atypical network scenario, and then Section 7 provides performance evaluation of the dominating-set routing scheme based on user mobility model. Finally, Section 8 presents conclusions of this research.

2. Dominating-Set-Based Routing

The supernode system corresponds to a global information transport platform, which consists of a number of heterogeneous wireless networks (e.g., cellular networks, MANETs, wireless local area networks, etc.) that are interconnected over an Internet backbone [22], as illustrated in Figure 1. Each wireless access network is connected to the Internet backbone through a DTN gateway [2]. Each node is able to connect to the platform through any interconnected wireless network. To achieve seamless communication for mobile nodes, the system has a number of supernodes that are interconnected over the Internet backbone. Each supernode is responsible for a set of users (mobile nodes), and each user has a unique and fixed home supernode, independent of its location changes. The supernodes and the gateways are assumed to communicate reliably over the Internet. Upon connecting through any access network, a node contacts its supernode for registering its current location. To deliver a message, the source node first locates the supernode of the destination using the destination ID. With the latest known location of the destination provided by its supernode, the source tries to establish an end-to-end connection with the destination. If the connection fails, all the messages are sent to and kept at the supernode of the destination for forwarding to the destination upon its availability. More details about the supernode system are given in [21].

A dominating-set-based routing scheme is proposed in [20] for DTN-based MANET routing within the supernode system. It is based on a dominating set for an established virtual network topology graph. A dominating set of a graph is defined as the subset of vertices of the graph where every vertex not in the subset is adjacent to at least one vertex in the subset [23]. The virtual network topology graph is represented as an undirected graph $G = (V, E)$, where V represents the set of mobile nodes currently connected to the network and E represents the set of the estimated contact probabilities for all node pairs. In the dominating set routing scheme, message delivery is done by forwarding a message to the message destination or the dominating set members only. When a dominating-set member encounters the message destination, it forwards the message to the destination. The dominating-set represents the set of nodes that have a high probability to meet every node in the network; the expected number of forwarded messages is proportional to the size of the dominating set.

The main challenge in developing an efficient routing algorithm for the DTN-based MANET is how to accurately estimate the probability of a future contact between a pair

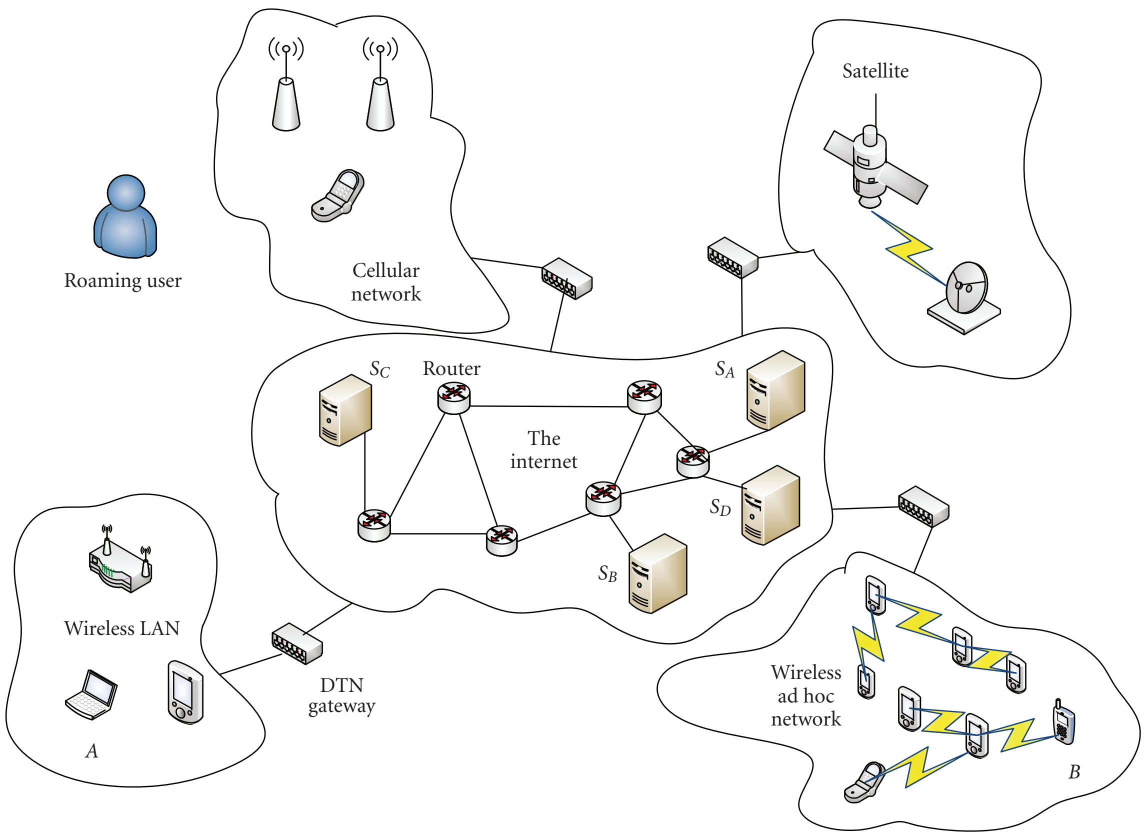

FIGURE 1: An illustration of the supernode system.

of nodes, in order to select the best next hop (i.e., carrier) for the message. In our previous work [20], estimating the probability of future contact is based on the durations of node previous contacts which is proved to be more reliable estimation criterion compared to the criterion of the number of previous contacts. Without loss of generality, consider two nodes, A and B. At any time, let T_{AB} denote the total time during which nodes A and B were in contact up to the moment. Regardless of time synchronization and the time durations during which nodes A and B, respectively, stay connected to the network, $T_{AB} = T_{BA}$. The probability of a future contact between nodes A and B is estimated approximately by

$$P_{AB} = \frac{T_{AB}}{[T_A + T_B]/2}, \qquad (1)$$

where T_A and T_B are the total time durations during which nodes A and B, respectively, are connected to the network up to the moment of estimation.

Using (1), a virtual network topology can be constructed based on network statistics. The topology is represented as an undirected graph $G = (V, E)$, where V represents the set of mobile nodes currently participating in the network and E represents the set of contact probabilities for all node pairs. To determine the dominating set, the basic technique for dominating set calculation proposed in [23] is not suitable to the virtual network topology for two reasons: the first is that the edge weights should be taken into consideration to select the most probable nodes to meet and the other is the fact that the constructed graph may be a fully connected graph where most of the edges have very low weights which make the regular algorithm in [23] useless.

(1) Start with DS contains only the gateway node
(2) **for all** node $i \in V$ and $i \notin$ DS and $NG(i) \notin$ DS **do**
(3) get max P_{ij} where $j \in NG(i)$ and $NG(j) - i \neq \phi$
(4) **if** $j \notin$ DS **then**
(5) add j to DS
(6) **end if**
(7) **end for**
(8) **for all** node $i \in$ DS **do**
(9) **if** $j \notin$ DS, $\forall j \in NG(i)$ **then**
(10) get max P_{ij} where $j \in NG(i)$ and $j \in NG(k)$ where $k \in$ DS
(11) add j to DS
(12) **end if**
(13) **end for**

ALGORITHM 1: Calculation of the dominating set (DS) based on previous contact duration [20].

Algorithm 1 is proposed in [20] to calculate a dominating set for the introduced virtual network topology, where DS represents the dominating set and $NG(i)$ represents the set of neighbors for node i. The procedure for formulating the dominating set contains two phases. In the first phase, nodes are processed one by one in ascending order of their IDs; for each node not already in the set, the node that is most probable to be met is added to the dominating set. The second phase ensures that the dominating set is connected, which is necessary for ensuring the spread of the message within the set. As the gateway connects the MANET to the overall system, it should always be included in the dominating set. A detailed example of how the algorithm can be applied is given in Section 6.

3. System Model

Consider a MANET that is connected to the supernode system through a DTN gateway. Within the MANET, nodes roam freely in a limited geographical area. Any two nodes are connected when they are able to communicate directly with each other, that is, when they are within each other's transmission range. For simplicity, we assume that all nodes have the same transmission range and that if a node A can receive message from a node B then node B can receive from node A as well. A contact occurs when any two nodes are connected. We mainly consider mobile nodes to be sparsely located so that the network is likely to be partitioned and an end-to-end path between a message source and the destination rarely exists. As a result, message delivery is accomplished through the store and forward mechanism in the DTN framework.

The DTN gateway has a fixed location within the geographical area, with communication functions and capabilities similar to those of an ordinary mobile node, that is, the gateway is assumed to have a limited transmission range and can communicate only with the nodes within its transmission range. The gateway transmission range covers only a small geographical area. However, the gateway has higher processing power and larger buffer space than mobile nodes. The gateway location within the network geographical area should be carefully selected in order to allow the gateway to directly communicate with some roaming nodes from time to time.

As in real life, users usually have some patterns in their movements; we consider a Markov-chain-based user mobility model as in our previous work [20]. Similar models are also adapted by other researchers such as in [24]. In this mobility model, the geographical service area of the MANET is partitioned to m partitions. A node-to-node direct communication takes place among nodes within the same partition. Node future location is independent of its past location, given its current location. The residence time of a node in a partition in each visit is an exponential random variable with parameter λ. For simplicity, we assume this parameter is the same for all the nodes and network partitions. Denote the location state of a mobile node by its current partition. Then, the user mobility model can be characterized by a one-dimensional continuous-time Markov chain, with a location state space given by $\{L_1, L_2, \dots, L_m\}$, as shown in Figure 2. The user movement model over the network coverage area is described

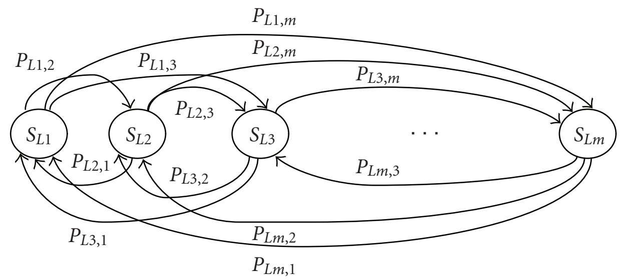

Figure 2: Modeling of user movement by a finite-state Markov chain.

by the transition matrix $\mathbb{M}$ of the Markov chain, given by

$$\mathbb{M} = \begin{pmatrix} P_{L_{1,1}} & P_{L_{1,2}} & \dots & P_{L_{1,m}} \\ P_{L_{2,1}} & P_{L_{2,2}} & \dots & P_{L_{2,m}} \\ \dots & \dots & \dots & \dots \\ P_{L_{m,1}} & P_{L_{m,2}} & \dots & P_{L_{m,m}} \end{pmatrix}, \qquad (2)$$

where $P_{L_{i,j}}$ is the conditional probability that a mobile node will enter partition L_j given that it is connected to the network and is leaving its current partition L_i. For any partition L_i, we have $\sum_j P_{L_{i,j}} = 1$. The transition probability matrix depends on the geographical characteristics of the service area and the network environment under study. As each user may have different preferences for visiting the network locations, we consider a general case where $\mathbb{M}$ is unique for each user.

4. Estimation of the Contact Probability

Our goal is to analyze the node mobility model to get an accurate estimate for the probability of a contact. We focus on the intermeeting time between two nodes. Define intermeeting time between a pair of nodes as the duration from the instant that the two nodes move out of each other's transmission range to the instant that the two nodes move within each other's transmission range the next time. Define node interarrival time for a partition as the duration from the instant that the node departs from the partition to the instant that the node arrives at the partition the next time.

In the following, we first study the distribution of the node interarrival time for a partition and then the distribution of the intermeeting time.

Theorem 1. *The inter-arrival time of a node, A, to a partition, i, is an exponential random variable with mean $1/\lambda\pi_{A_i}$, where π_{A_i} is the limiting probability in which node A resides in partition i.*

Proof. The continuous-time Markov chain for node A is irreducible. Hence, the limiting probabilities exist, satisfying the following equations:

$$\pi_{A_i} = \sum_{j=1}^{m} P_{L_{j,i}} \pi_{A_j}, \quad i = 1, 2, \ldots, m,$$
$$\sum_i \pi_{A_i} = 1. \tag{3}$$

The probability π_{A_i} is the fraction of time in which node A resides in partition i. Define $N(t)$ as the number of all visited partitions by time t for node A. Then, $N(t)$ is a Poisson process with mean λt. Define $N_i(t)$ as the number of visits of node A to partition i by time t. Then $N_i(t)$ is a Poisson process with parameter $\lambda \pi_{A_i} t$. As a result, the inter-arrival time of node A to partition i is exponential with parameter $\lambda \pi_{A_i}$, that is, with mean $1/\lambda \pi_{A_i}$. □

Theorem 2 (theory). *The intermeeting time between a node, A, and another node, B, is an exponential random variable with mean* $1/\sum_{i=1}^{m} 2\lambda \pi_{A_i} \pi_{B_i}$.

Proof. Nodes A and B meeting at partition i can occur in two scenarios: (i) node A moves to partition i while node B already resides in partition i; (ii) node B moves to partition i while node A already resides in partition i. Considering scenario (i), the number of meetings between the two nodes at partition i is the fraction of node A arrivals to partition i while node B is residing there. From Theorem 1 and noting that node B resides in partition i with probability π_{B_i}, the number of meetings between node A and node B at partition i when node A makes the movement is a Poisson process with mean $\lambda \pi_{A_i} \pi_{B_i} t$. Hence, the intermeeting time between node A and node B at partition i when node A makes the movement is an exponential random variable with parameter $\lambda \pi_{A_i} \pi_{B_i}$. Similarly, for scenario (ii), the intermeeting time between node A and node B at partition i when node B makes the movement is an exponential random variable with parameter $\lambda \pi_{B_i} \pi_{A_i}$. As a result, the intermeeting time between node A and node B at partition i is a random variable that is the minimum of the two independent exponential random variables, which follows an exponential distribution with parameter $(\lambda \pi_{A_i} \pi_{B_i} + \lambda \pi_{B_i} \pi_{A_i})$. Considering all network partitions, the intermeeting time between node A and node B is a random variable that has a distribution of the minimum of the two nodes intermeeting times at all the network partitions, which is an exponential random variable with parameter $\sum_{i=1}^{m} 2\lambda \pi_{A_i} \pi_{B_i}$. □

Consider two nodes, A and B. Let P_{AB}^{T} denote the probability that a contact occurs between A and B, given that both of them are connected to the network over a time duration T. The probability of a contact based on the intermeeting time between the nodes is

$$P_{AB}^{T} = 1 - e^{-\sum_{i=1}^{m} 2\lambda \pi_{A_i} \pi_{B_i} T}. \tag{4}$$

```
Start with DS contains only the gateway node
for all node i ∈ V and i ∉ DS and NG(i)∉DS do
    get min E[τ_ij] where j ∈ NG(i) and NG(j) − i ≠ ϕ
    if j ∉ DS then
        add j to DS
    end if
end for
for all node i ∈ DS do
    if j ∉ DS, ∀ j ∈ NG(i) then
        get min E[τ_ij] where j ∈ NG(i) and j ∈ NG(k)
            where k ∈ DS
        add j to DS
    end if
end for
```

Algorithm 2: Calculating the dominating set (DS) based on node intermeeting times.

To apply the mobility model analysis to the dominating-set routing scheme, we use the expected intermeeting time as a measure of link existence, which provides an estimation of how frequently two nodes will meet in the future. We construct a virtual network topology as an undirected graph $\widehat{G} = (V, \widehat{E})$, where V represents the set of mobile nodes currently connected to the network and $\widehat{E}$ is the set containing the expected intermeeting times between any two nodes. A dominating set for the constructed graph is calculated using Algorithm 2. Algorithm 2 is a modified version of Algorithm 1, where τ_{ij} is the intermeeting time between node i and node j.

5. Dominating-Set Selection Constraints Relaxation

Increasing the dominating-set size (i.e., number of nodes in the set) improves the probability of message delivery by reducing the number of lost (i.e., undelivered) messages, at the cost of increasing the number of message forwarded. The extreme case is that the dominating set includes all the nodes in the network, which corresponds to the epidemic routing. Selecting dominating-set members based on the greedy Algorithm 2 does not take into consideration the dominating-set size, as each node selects the node with minimum expected intermeeting time. In the following, we study the problem of reducing the dominating-set size and propose an alternative dominating-set selection algorithm. The new algorithm improves the routing performance in terms of resource utilization, while achieving acceptable performance in terms of the number of lost messages via an acceptable average message delivery time.

Message delivery in the system under consideration takes place when a message carrier comes into contact with the message destination. For the dominating-set-based routing, the message carrier can be either a dominating-set member or the message source itself (i.e., in a case of direct contact).

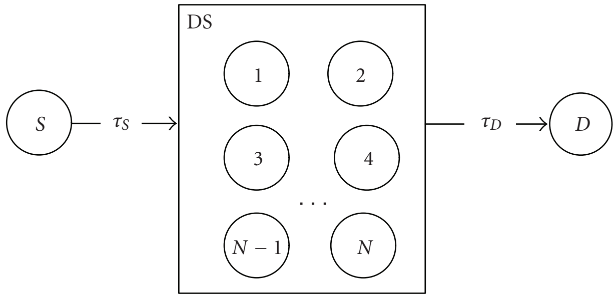

Figure 3: End-to-end message delivery under dominating-set-based routing.

Assuming a sufficiently large node buffer space, message loss mainly occurs as a result of the message expiry before a contact between a carrier and the message destination takes place. In a regular network, the end-to-end message delay can be controlled by selecting the message route to enforce certain quality of service. On the other hand, in a delay-tolerant network environment, it is so difficult to precisely estimate the end-to-end delay of delivering a message. Most research efforts in this problem try to give an estimation for the delay over a specific route. In [25], it is stated that finding all the routes from a given source to a given destination with exact calculation of the expected delay distribution is an NP-hard problem, where the delay calculation is based on the primary path that has the smallest expected delay. To apply this to the dominating set selection problem, it requires to calculate the shortest path between nodes for every source and destination. Based on the calculated shortest paths for all the nodes, the optimal dominating-set can be selected. Considering network size and dynamics (i.e., expected change in network memberships due to user roaming, disconnection, and power failure), the calculations will be very complicated and impractical.

As shown in Figure 3, where the dominating set has N, nodes, the message end-to-end delay, denoted by T_D, for a no-direct contact case under the dominating-set routing consists of three delay components: the delay τ_S for the message source to deliver the message to the dominating set, the delay τ_{DS} for the message over the dominating set, and the delay τ_D to deliver the message from the dominating-set to the destination node. The expected end-to-end delay can be expressed as

$$E[T_D] = E[\tau_S] + E[\tau_{\mathrm{DS}}] + E[\tau_D]. \tag{5}$$

The delay over the dominating set, τ_{DS}, can range from 0 in the case of two-hop path delivery to $\sum_{i=1}^{N-1} \tau_{i,i+1}$. Note that $\tau_{i,j}$ is a random variable that represents the time for node i to meet node j. As we assume no control on node mobility, the only way to reduce these delay components is by selecting more nodes in the dominating set. However, that will increase the number of forwarded messages, which causes inefficient use of the system resources. Minimizing the size of the dominating set improves the system performance in terms of the number of forwarded messages; however, it increases the number of lost messages as it increases the expected delivery time. As a tradeoff solution, we propose to change the dominating set selection criterion from selecting the nodes most likely to meet with each node in the network to selecting a minimum set of nodes so that every node in the network is expected to meet with a member of the set within a time interval less than certain threshold value θ_t on average.

Based on Theorem 2 in Section 4, the intermeeting time between a node, A, and a dominating set member, X, is an exponential random variable with parameter λ_{AX}, given by

$$\lambda_{AX} = \sum_{i=1}^{m} 2\lambda \pi_{A_i} \pi_{X_i} \tag{6}$$

for the network coverage with m partitions.

As a result, the intermeeting time between node A and the dominating set (excluding A if A is a DS member) is the minimum of the intermeeting times between A and the DS members, which is an exponential random variable with parameter λ_A, where

$$\lambda_A = \sum_{\substack{X \in DS \\ X \neq A}} \lambda_{AX}. \tag{7}$$

Using (5), reducing the expected end-to-end delay can be achieved by reducing the individual delay components, such as by reducing the expected intermeeting time between an individual node and the dominating-set. The newly proposed algorithm, given in Algorithm 3, selects dominating-set members by including a small set of nodes so that every node in the network has an expected intermeeting time with the set less than θ_t. The algorithm starts with a set, DS, containing only the gateway node. A node, A, will be added to DS only if there exists a node B where $E[\tau_B] \geq \theta_t$ and $E[\tau_{AB}] = \min(E[\tau_{XB}])$, for all $X \in NG(B)$, where τ_{AB} is the intermeeting time between A and B, τ_B is the intermeeting time between B and DS, and $NG(B)$ is the set of neighbours for node B. As a result, increasing θ_t is expected to reduce the DS size.

Unlike Algorithms 1 and 2, processing a node, A, will result in adding its most probable node to be met, B, to the DS, only if the expected time for node A to meet with a dominating set member does not satisfy the required criterion θ_t. The worst case scenario for the new algorithm is the same dominating set as that from Algorithm 2, for a very small θ_t. On the other hand, for sufficiently large θ_t, the dominating set may contain only the gateway, which is similar to the case of direct transmissions. As a result, the newly proposed algorithm, Algorithm 3, is expected to improve the system performance in terms of the number of forwarded messages as it can result in a reduced DS, as will be discussed next.

6. A Network Example

In this section, we consider an example based on a typical simulation experiment to show how the different algorithms will process a typical scenario. The network consists of 7 nodes and the gateway S. This network is a fully connected

```
Start with DS contains only the gateway node
for all node i ∈ V and i ∉ DS and NG(i) ∉ DS do
    λ_i = Σ_{X∈DS, X≠i} λ_iX
    τ_i = 1/λ_i
    if τ_i < θ_t then
        Skip next steps and get next i
    end if
    get min E[τ_ij] where j ∈ NG(i) and NG(j) − i ≠ φ
    if j ∉ DS then
        add j to DS
    end if
end for
for all node i ∈ DS do
    if j ∉ DS, ∀ j ∈ NG(i) then
    get min E[τ_ij] where j ∈ NG(i) and j ∈ NG(k)
        where k ∈ DS
    add j to DS
    end if
end for
```

Algorithm 3: Calculating the dominating set (DS) based on constraints relaxation.

Table 1: Probability of contacts based on previous contact duration (percentage).

	Node ID							
	S	A	B	C	D	E	F	G
S	—	86	55	10	75	81	10	41
A	86	—	49	49	57	58	49	43
B	55	49	—	71	56	62	33	38
C	10	49	71	—	49	78	71	84
D	75	57	56	49	—	35	80	25
E	81	58	62	78	35	—	27	91
F	10	49	33	71	80	27	—	37
G	41	43	38	84	25	91	37	—

graph. For presentation clarity, the topology is represented in a table format, given in Table 1. This table presents the probability of contact for each pair of nodes in the network based on the processed statistics of the contact duration among the nodes. For example, node A has a probability of 49% to contact node B, when both are connected to the network, and a probability of 86% to contact the gateway S. It is important to note that contacts between any pair of nodes are disjoint events.

Applying Algorithm 1 over the virtual network topology presented in Table 1, the algorithm starts with a set, DS, that contains only the gateway S. Processing each node in an ascending order of node ID, the most probable node to be met node A is S which is already in DS. For node B, as the most probable node to be met is node C, node C is added to DS. Node C is not processed as it is already in DS. For node D, node F is the most probable node to be met and it is added to DS. For node E, the most probable node to meet is node G, so node G is added to DS. Nodes E and G are skipped from processing as they are members of the selected set. At the end of the first phase, the dominating set is DS $= \{S, C, F, G\}$. The second phase that guarantees the connectivity of the set is not necessary in this scenario as the graph is fully connected.

Table 2: Intermeeting time (simulation step).

	Node ID							
	S	A	B	C	D	E	F	G
S	—	41	31	180	35	28	91	77
A	41	—	52	49	53	40	60	54
B	31	52	—	46	50	50	60	46
C	180	49	46	—	42	46	46	41
D	35	53	50	42	—	40	33	48
E	28	40	50	46	40	—	50	47
F	91	60	60	46	33	50	—	52
G	77	54	46	41	48	47	52	—

To apply Algorithm 2, it is required to calculate the expected intermeeting time between each pair of nodes based on their mobility pattern, which is given in Table 2. Based on Table 2, Algorithm 2 starts with a set, DS, that contains only the gateway S. Processing each node in an ascending order of node ID, the resulting DS $= \{S, E, G, F\}$, which is a connected set.

It should be noticed that Algorithms 1 and 2 result in different sets for the same problem as they process virtual network topology constructed based on different criteria, given in Tables 1 and 2, respectively.

Reducing the size of the dominating set is the main design goal for Algorithm 3. This algorithm ensures that each node in the network has an expected intermeeting time with the selected dominating set members less than a specific threshold value. If this cannot be achieved, the algorithm adds (to the selected set) the node with the least expected intermeeting time (similar to Algorithm 2).

For the network scenario, assume that message lifetime $= 90$ and θ_t = message lifetime/2. Algorithm 3 starts with a set, DS, that contains only the gateway S. For node A, $\tau_A = 41$, so node A will not select any more nodes to be in DS as $\tau_A < \theta_t$. For node B, $\tau_B = 31$; similar to node A case, processing node B will not add any nodes to DS. For node C, $\tau_C = 180$, so node C selects the node with the least expected intermeeting time which is node G to be added to DS. For node D, where DS $= \{S, G\}$, $\tau_D = 1/(1/35) + (1/48) = 23.23$, so node D will not select any more nodes to be in DS. For node E, $\tau_E = 1/(1/28) + (1/47) = 17.54$, so node E will not select any more nodes to be in DS. For node F, $\tau_F = 1/(1/91) + (1/52) = 33.09$, so node F will not select any more nodes to be in DS. Node G is not processed as it is already member in DS. The selected dominating set will be DS $= \{S, G\}$.

It is clear that the new algorithm should result in a reduced size dominating set given a reasonable value of θ_t. In the extreme case for very small value θ_t, the algorithm will result in the same dominating set as Algorithm 2. Section 7 shows how different values of θ_t affect the routing performance.

It can be seen that all the algorithms for determining a dominating set for a virtual network topology are based on the idea of selecting a set of carrier nodes that cover the whole graph. It is expected that with a smaller dominating set size, the routing performance will be improved as the number of forwarded messages will decrease. With a fully connected network topology, selecting a random set of nodes can be regarded as an alternative technique. With the random set selection, there is no actual need for collecting network statistics and performing dominating set selection computation, which is expected to reduce the overhead induced by the link statistics computations. This alternative technique is evaluated through our experiments in Section 7.

7. Performance Evaluation

This section presents analytical results in comparison with simulation results for the inter-arrival time and the intermeeting time. Moreover, we evaluate the performance of the dominating-set-based routing scheme based on the user mobility model analysis and the newly proposed algorithm that relaxes the selection constraints. The performance is compared with that of epidemic routing and of the dominating-set-based routing scheme using Algorithm 1. The performance is measured in terms of (i) the numbers of delivered and lost messages to indicate how reliable each technique is in delivering messages and (ii) the number of forwarded messages over the network to demonstrate how efficiently each technique uses the available resources (i.e., radio bandwidth and node buffer space).

In the simulation, the number of partitions of the MANET coverage area varies in range of 10–50. Each simulation proceeds in discrete time steps. Mobile nodes move with mobility trajectories independent of each other. For each simulation run, the movement matrix $\mathbb{M}$ of each node is generated at random and stays fixed till the end of the simulation. Initially, the node locations are uniformly distributed over the service area. As the simulation time increases, each node moves randomly according to its transition matrix. The node residence time at each partition is an exponential random variable with an average of 10 simulation steps. At the end of the residence time, the node moves to a new partition based on its mobility matrix. Messages are generated in the network based on a Poisson process with mean rate of 910 messages per simulation time step, with a constant message size. The source and the destination for each message are selected at random. The message lifetime is constant with a value of 50 simulation steps. Each mobile node has a buffer space of 15 messages. The gateway has a buffer space of 2000 messages. A buffer overflow occurs when a node buffer is full and a new message is received. When a buffer overflow occurs, the oldest message in the buffer is discarded. Message exchanges occur among nodes residing in the same partition. We assume that the traveling time between partitions is small and can be neglected as compared to the partition residence time. At each time step, the node detects its neighbor nodes and exchanges the buffered messages with them (the messages they do not already have) based on the used routing technique. For each experiment, a communication scenario (i.e., set of messages, user connections, user disconnections, and user movements) is set up randomly and run for each routing technique. For simplicity of simulation, we assume that each node can access the medium reliably.

Table 3: Statistics of the node inter-arrival time.

Partition	Simulation		Analysis
ID	Mean	Confidence interval	Mean
1	62.59	54.10–71.08	66.25
3	80.54	65.69–95.39	80.63
4	51.83	44.01–59.65	56.36
5	59.57	51.11–68.03	57.04
8	90.64	73.60–107.68	90.59
9	127.44	99.00–155.88	120.04
10	126.58	104.35–148.80	122.12

Table 4: Statistics of the node intermeeting time.

Node	Simulation		Analysis
pair	Mean	Confidence interval	Mean
1, 2	59.00	49.82–68.18	54.83
1, 3	52.97	45.38–60.55	50.24
1, 4	51.87	44.60–59.14	49.53
2, 3	48.83	41.80–55.87	44.77
2, 4	78.63	62.67–94.59	79.92
3, 4	61.82	50.89–72.75	62.70

Our first experiment is to validate the distribution of the inter-arrival time by simulation. In this experiment, we record node inter-arrival times for different partitions in the network. The mean and its 95% confidence interval based on the simulation data are calculated and compared with the theoretical values based on Theorem 1. It is observed that the theoretical mean gives a very good approximation to the simulated data mean, which lies within the calculated 95% confidence interval of the simulation data. Table 3 shows a sample of the simulation results for a node moving over a network consisting of 10 partitions.

Our next experiment is to validate the distribution of the node intermeeting times by simulation. In this experiment, we track node-to-node intermeeting times for each pair of nodes in the network. Table 4 shows the simulation results for tracking 4 nodes over a network of 10 partitions and compares them with the results calculated based on Theorem 2. It is observed that the simulation and analytical results match well.

In the following, we study the performance of the dominating-set-based routing scheme using the node intermeeting time as an indication of node-to-node future contact frequency. The results are obtained by simulating a network with 20 partitions and 70 nodes.

Figure 4 shows a performance comparison in terms of the number of delivered messages between the epidemic routing scheme and the dominating-set-based routing scheme using both criteria of (i) the intermeeting time and (ii) the duration

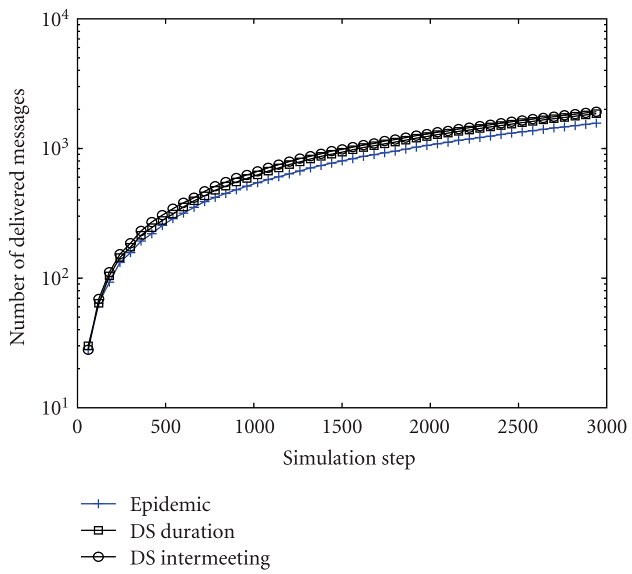

Figure 4: Number of delivered messages under different routing schemes.

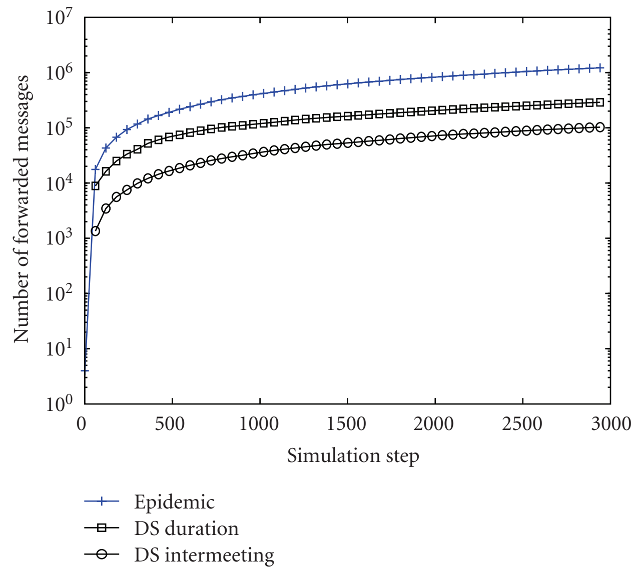

Figure 6: Number of forwarded messages under different routing schemes.

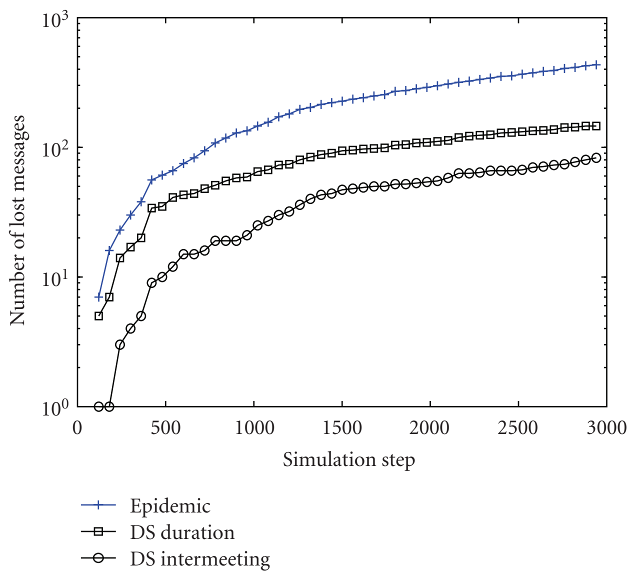

Figure 5: Number of lost messages under different routing schemes.

based estimate of the probability of future contacts according to (1). The dominating-set routing technique based on node intermeeting times is found to slightly outperform the other two schemes. This is demonstrated more clearly in Figure 5, which shows a comparison among the three schemes in terms of the number of undelivered (lost) messages. With the node limited buffer space and an increasing number of exchanged messages, some messages are lost due to buffer overflow. Using the node intermeeting times as a selection criterion ensures that message carriers are more likely to be in contact with the message destination in a shorter duration. Figure 6 shows a performance comparison in terms of the number of forwarded messages as a measure for the network resource utilization. It is clear that the dominating-set routing scheme based on the node intermeeting times gives the best performance among the three schemes. This is mainly due to the accurate selection of the dominating set members that results in a reduced number of forwarded messages required to achieve message delivery.

On the other hand, experimenting with an increased node buffer size shows that the three schemes give comparable results in terms of the number of delivered messages and the number of lost messages (due to a decrease in buffer overflow). However, the dominating-set routing scheme based on the node intermeeting times consistently gives the best performance in terms of the number of forwarded messages. Considering the inevitability of having a limited node buffer space, it is clear that a more intelligent buffer management scheme can improve the performance of the routing schemes, which is an interesting topic for further research.

We extend our experiments by implementing the newly proposed algorithm (i.e., Algorithm 3) for selecting dominating set members based on the criterion of limiting the expected node intermeeting with the dominating-set to a threshold value θ_t. Figures 7 and 8 show the results with different values of θ_t, where θ_1 = Message lifetime/2 and θ_2 = message lifetime/5.

Figure 7 shows how the new algorithm improves the performance dramatically in terms of the number of forwarded messages as compared to the case of using Algorithm 2 and the case of epidemic routing. Increasing the threshold value gives better results in terms of forwarded messages but decreases the performance in terms of the number of lost messages as shown in Figure 8. It is noticed that Algorithm 3 outperforms Algorithm 2 in terms of the number of forwarded messages with acceptable performance in terms of

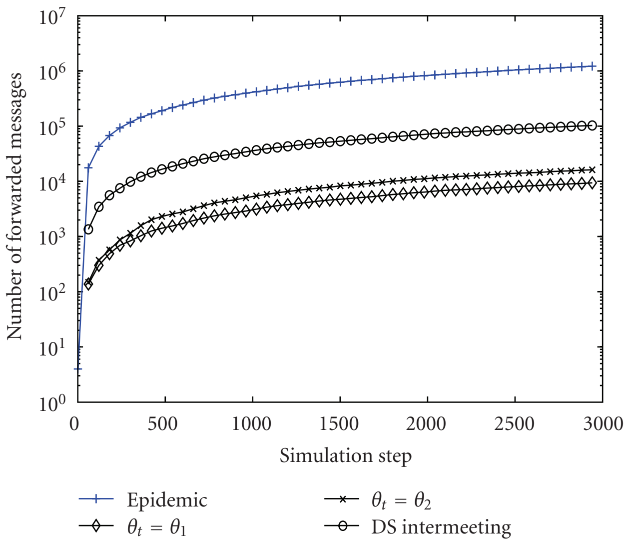

Figure 7: Number of forwarded messages under different routing schemes and different threshold values.

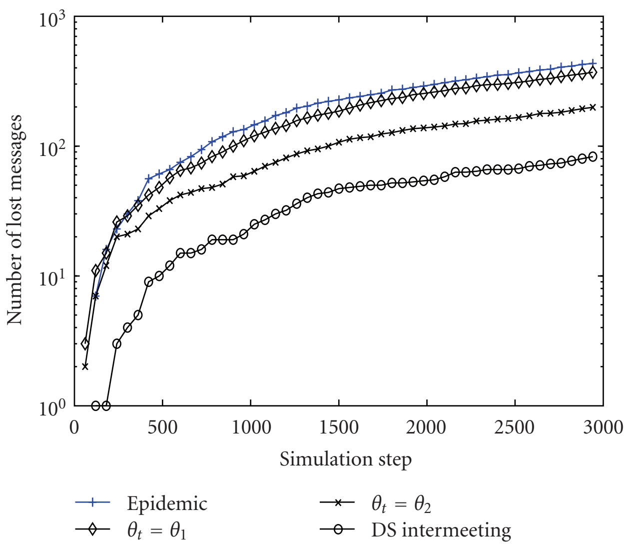

Figure 8: Number of lost messages under different routing schemes and different threshold values.

the number of lost messages. This is mainly because, under the new criterion, the dominating set size is reduced.

As Figure 8 shows, the number of the lost message under Algorithm 3 is larger than that under Algorithm 2. This is because increasing message holding time at a carrier node (i.e., DS member) increases the probability that of message being discarded before being delivered due to a buffer overflow. With a larger node buffer space, it is noted that both Algorithms 2 and 3 give comparable results. This is because message loss in this case is mainly due to the message expiry, but less likely due to buffer overflow. It is also noted that, regardless of the buffer space, Algorithm 3 outperforms Algorithm 2 in terms of the number of forwarded messages. The threshold value θ_t plays an important role in the

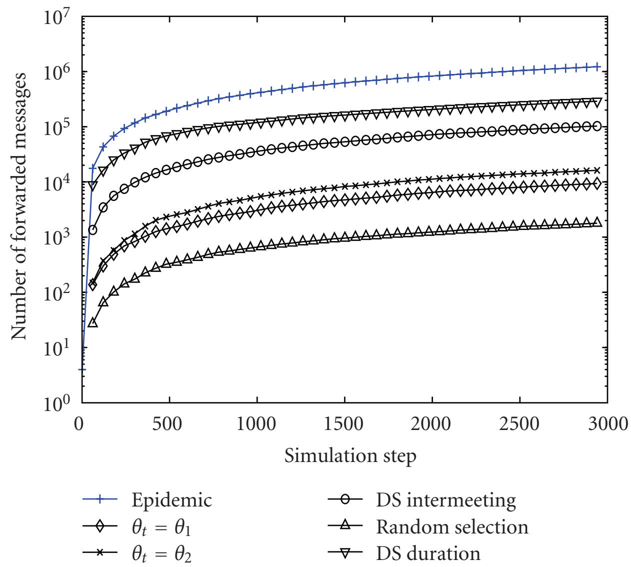

Figure 9: The random selection technique performance compared to the other techniques in terms of the number of forwarded messages.

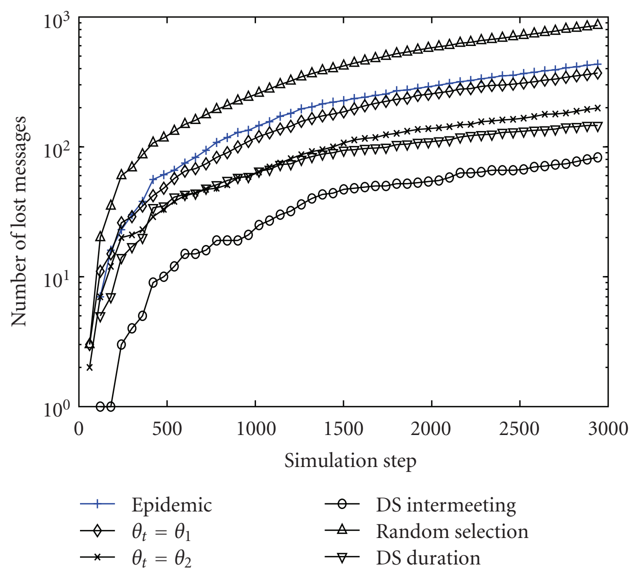

Figure 10: The random selection technique performance compared to the other techniques in terms of the number of lost messages.

performance based on Algorithm 3. How to determine a proper θ_t value, for a given network scenario, requires further investigation.

Our last experiments investigate the performance of the random set selection technique (discussed in Section 6), in comparison with the other techniques, as illustrated in Figures 9 and 10. The DS size is set to the smallest DS size from the discussed algorithms, but the DS members are selected randomly. Figure 10 shows that the random selection technique degrades the performance significantly even when compared with the worst performance of the other techniques. In other words, reducing DS size alone does not improve the performance unless an accurate selection methodology for the DS members is employed to guarantee proper contacts between the set members and the other nodes. The number of lost messages increases due to the lack of contacts between the set members and the other nodes, which causes messages to expire before being delivered. This decrease in contacts also leads to the smallest number of forwarded messages (as shown in Figure 10) as compared to the other techniques. Reducing the number of forwarded messages in this case cannot be regarded as a performance improvement because of the significant degradation in the performance in terms of the number of lost messages.

8. Conclusions

In this paper, we consider the dominating-set-based routing for a DTN-based MANET within the supernode system. We analyze the node mobility to better estimate node-to-node future contact statistics for improving message delivery. The node intermeeting time distribution is derived based on a Markovian node mobility model, which is validated by a simulation study. The node mean intermeeting time is used in the dominating-set routing scheme. Computer simulation results demonstrate that the dominating-set routing scheme based on the node mean intermeeting time outperforms epidemic routing and dominating set routing based on previous contact duration, in terms of both message delivery rate and resource utilization. Moreover, we propose a new algorithm for selecting the dominating-set based on the distribution of node intermeeting time, which results in a smaller dominating-set size. The newly proposed algorithm chooses a set of nodes so that every node in the network should have an expected intermeeting time with the set members under a certain threshold value. The computer simulation results show the effectiveness of the proposed new algorithm.

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