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# DTN Based Dominating Set Routing for MANET in Heterogeneous Wireless Networking

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**Abstract** In mobile communications, effective internetworking is mandatory in order to support user roaming among various types of wireless networks while maintaining connectivity. In this paper, we propose a super node system architecture to achieve the connectivity over interconnected heterogeneous wireless access networks, which employs the delay-tolerant network (DTN) concept to overcome the problem of potential intermittent connections caused by user roaming and ensures message delivery in the presence of a long disconnection period. By introducing the concept of virtual network topology, we present a new routing technique for mobile ad hoc networks (MANETs) within the system architecture, which redefines the dominating-set based routing for the challenged network environment. A time based methodology is presented to predict the probability of future contacts between node pairs for constructing the virtual network topology. Simulation results demonstrate the effectiveness of the proposed dominating-set based routing scheme under the DTN system architecture.

**Keywords** routing · delay tolerant network (DTN) · intermittent links · user mobility · mobile ad hoc network (MANET)

## 1 Introduction

The recent years have seen enormous advances in wireless communication technology and co-existence of various types of wireless networks. Each type of the networks is optimized for a specific networking environment, and it is impossible to have only one type of wireless networks that suits all the environments. As a result, it has become necessary to internetwork various types of wireless networks, leading to the necessity of heterogeneous wireless networking. As mobile ad hoc networks (MANETs) are an important component of the heterogeneous wireless networks for ubiquitous communications, in order to maintain continuous connectivity for a mobile user, it is necessary to include MANETs in the heterogeneous wireless interworking. In such an interworking scenario, how to maintain the connectivity of a mobile user poses significant technical challenges as the user roaming can introduce an intermittent connection situation associated with challenged networks. How to efficiently route messages over MANETs under the constraint of intermittent connections is an essential problem to be addressed.

User roaming over heterogeneous wireless networks is an area that has been extensively researched (e.g.,

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[4, 8, 12]). One limitation with the previous techniques is that, if a user is disconnected for a long period before reconnecting through another network, the current connection is terminated. Another problem is how to maintain the connection for intermittently connected users even over the same network. On the other hand, the delay tolerant network (DTN) architecture [2] is proposed to handle communications over challenged networks. It is based on an Internet-independent middleware, which handles the sending and receiving of the bundles (self contained messages) across the network using the underlying protocols stack. Due to the expected long delays, DTNs cannot accommodate any real-time applications, but mainly support time insensitive applications. Message delivery in DTN is done by first storing the message (i.e. bundle) and then forwarding it either to its destination or to an intermediate node that has a high probability to deliver it to the destination. For example, in the epidemic routing technique [13], each node forwards 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 with the message's destination node.

Some research efforts are devoted to routing in a sparse ad hoc network (e.g. [11, 15, 16]), which depends on known routes and movements for some nodes to deliver messages. Moreover, a request may need to be sent to a moving node to change its movement trajectory to deliver the message [6]. Some routing schemes require collecting information from the moving nodes about their destination, velocity and direction of movement, which means much computations and the awareness of destination node locations to find the best moving node to carry messages. That is, these techniques make routing decisions based on a pre-known movement schedule of the mobile nodes. Such schemes are not suitable to the MANETs of interest where mobile nodes move randomly (freely) without a known schedule. The other extreme in routing is to assume no knowledge about the network, such as epidemic routing [13] which uses flooding to deliver messages and is therefore inefficient in terms of network resource usage 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 [1, 7]. The previous work predicts future contacts based on the number of previous contacts, which suffers from some deficiency (see Section 4.2). To overcome the inadequacy, we propose here a time-based methodology for predicting the future contacts.

In this paper, we first propose a super-node system architecture based on the DTN framework, as a solution for providing a continuous connection to mobile nodes that experience intermittent connections. In the system architecture, heterogeneous wireless networks are interconnected to achieve continuous connectivity for roaming users. We then present a novel DTN based routing technique for challenged MANETs, with a main goal to ensure reliable message delivery with minimum cost. Our contributions are four-fold: (i) the super-node system architecture is proposed and its effectiveness is demonstrated based on computer simulations; (ii) the concept of *virtual network topology* is introduced, which is adaptation of the network topology in a DTN context; (iii) a new approach for calculating the probability of future contacts in DTN networks is presented; and (iv) a routing technique that is based on calculating the dominating set for the virtual network topology is developed, using a new algorithm for dominating set calculations. The effectiveness of the proposed routing scheme is demonstrated based on computer simulations, using a user mobility model that represents the real life behavior of roaming users.

## 2 The system model

We consider a global information transport platform, which consists of a number of heterogeneous wireless networks (e.g., cellular networks, mobile ad-hoc networks, WLANs, etc.) that are interconnected over an Internet backbone [5], as shown in Fig. 1. Each network is connected to the Internet through a DTN gateway [2]. Each mobile node is able to connect to the platform through a subset of the wireless access networks. A node may be connected for a period through one access network, disappear for an extended period, and then reappear from the same access network or from a different access network. Here, we focus on data communications for delay insensitive applications.

The access networks include MANETs. The coverage of each MANET is limited by a geographical area. In the area resides a DTN gateway which connects the access network to the system. Within the MANET, there are a number of mobile nodes that can freely roam over the network coverage area. These nodes may have different communication capabilities in terms of wireless transmission range, memory size, and available transmission power. The nodes are free to enter or leave the area and consequently join or leave the network. A node can be unreliable as it can switch off at any time with or without a warning. Figure 2

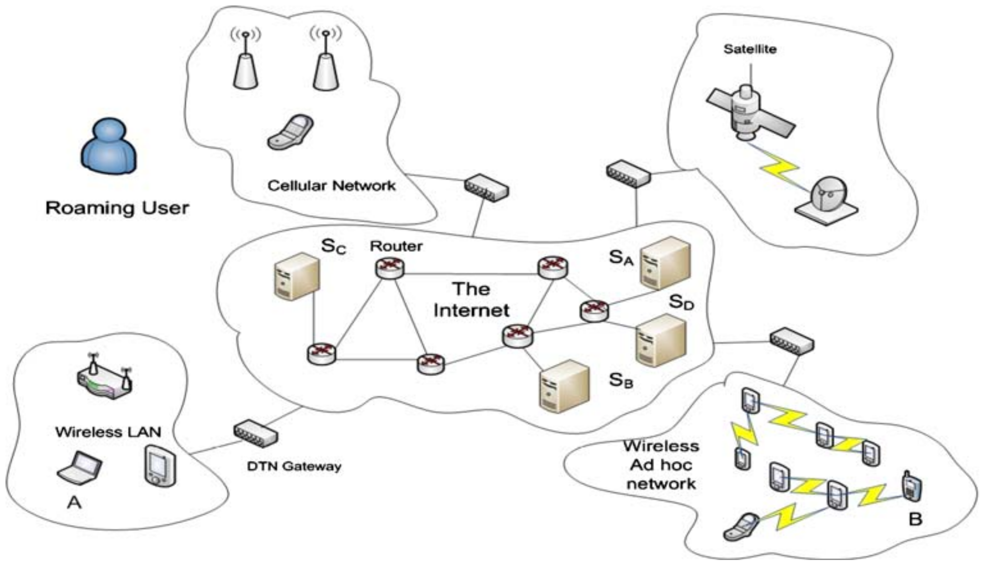


**Fig. 1** The system architecture with super nodes

illustrates a schematic diagram for the MANET model. The nodes are free to enter the area covered by the network such as node $E$ or leave the area such node $F$. Two nodes are connected when they are able to communicate with each other, i.e., when they are within each other's transmission range. For simplicity, we assume that all nodes have the same transmission range and that, if node $A$ can receive message from node $B$, node $B$ can receive from node $A$ as well. We are interested in a situation where the mobile nodes are sparsely located and the network is very likely to be partitioned, such that an end-to-end path between a pair of communicating nodes is very rare.

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 portion of the MANET geographical area. On the other hand, the gateway has higher processing power and larger storage (buffer) space than other roaming nodes. In terms of node mobility pattern, there is no restriction on node movements (except a reasonable upper bound on the velocity). An assumption is that some nodes usually roam toward the gateway, so that the gateway can communicate with the roaming nodes from time to time. This assumption can be satisfied by carefully choosing the gateway location, depending on the geographical features of the service coverage area.

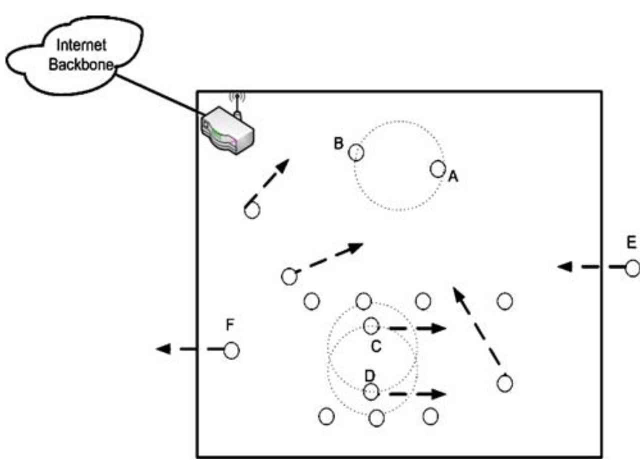


**Fig. 2** An illustration of the MANET under consideration

## 3 The super-node system architecture

In the system model, a user connection over the access networks can be intermittent with frequent disconnections. To deal with the potential long delays encountered in the presence of frequent disconnections, the only effective way for successful message delivery is to use an asynchronous message forwarding mechanism, also known as *store and forward* mechanism. The main research issue is to find a route from a traffic source node to the destination node to deliver the message even if the route does not really exist at any time. In the following, we first discuss two possible approaches, and then propose our main scheme based on a concept of super nodes [10].

*Epidemic routing based scheme* This is a distributed routing approach that makes use of the epidemic routing idea [13]. This approach assumes no knowledge of user location or availability. The problem with this approach is that, for a large network size, the number of forwarded messages required to deliver one message is huge. Also, the message flooding in the network results in a large number of lost messages.

*Centralized node scheme* The scheme assumes that a single server resides in the Internet and is able to communicate with all the gateways. Every user upon connecting to the system must inform the server of its current location. When a node wants to send a message, it first contacts the server to find out where the destination node is located, and then the source node can try to establish a direct connection with the destination node. If the path setup fails or the connection drops at any time, all the messages are sent to and stored at the server for retrieval from the destination node upon reconnecting. The main problem with this solution is scalability.

We propose to combine the preceding two approaches to overcome their limitations. Instead of having a single server, a number of servers at fixed locations, referred to as super nodes, are used. Each super node is responsible for a set of subscribers. Each user (mobile node) has a unique and fixed super node, independent of its location changes. Communications among super nodes and DTN gateways are assumed to be reliable over the Internet. In fact, a super node can also act as a DTN gateway; in this case, the super node is responsible for message delivery over the wireless access networks for which it acts as a DTN gateway. Each mobile node should contact its super node to update its location upon connecting to any access network. To send a message, the source node first locates the super node of the destination node based on the user ID. With the most updated location of the destination node provided by its super node, the source node then tries to establish an end-to-end connection with the destination. If the connection setup fails or the connection drops at any time, all the messages are sent to and stored at the destination super node for forwarding to the destination node upon its reconnection. Depending on the current access network of the destination node, its super node may transfer the user message custody to another super node near the access network for the period of user existence in the access network. This super node is called *custodian* super node for the user during the period. It should be noted that the number of super nodes in the system is not dependent on the number of the access networks (unless a super node also functions as the gateway of the access network). The number of the super node is a function of the number of the users in the system. The centralized node scheme can be regarded as a special case of the super node scheme that suits a very small number of users. Also, the super node is similar to the home agent in mobile IP, as it serves as the anchor point for routing. The difference in this approach from Mobile IP lies in the custodial nature of the super node.

Routing in the super-node network model can be regarded on two levels. The high-level routing is among super-nodes and gateways, while the low-level routing is between an end user and the gateway over an access network. With reliable communications among super nodes and gateways over the Internet, many existing routing techniques can be applied to the high-level routing. In the following, we focus on the low-level routing with intermittent connections.

## 4 Routing over MANET

Routing over access networks is a challenge because of the potential unavailability of the users or/and physical end-to-end path. It highly depends on the access network. For infrastructure based networks such as cellular networks and WLAN, regular routing techniques can be applied when the destination user is available. Routing becomes more complicated for infrastructure-less networks such as MANETs.

As the first step, in our previous work [10], we use epidemic routing for MANETs, which turns to be inefficient in terms of resource utilization. The main problem with epidemic routing is that message will keep being forwarded even after it is delivered. Limiting the message live time can partially solve this problem, but may prevent the message from being delivered if it expires before a contact occurs with the destination node or one of the message carriers.

In the following, we propose a technique to limit the number of forwarded messages by limiting the number of message carriers. In the scheme, a message is forwarded to a subset of nodes. The approach reduces the number of forwarded messages, at the cost of a potentially increased message delivery delay. To achieve better performance tradeoff, the set of carriers should consist of the nodes that are most likely to be encountered. We propose an algorithm to choose the set of nodes based on the idea of dominating set for the virtual network topology.

### 4.1 Virtual network topology

To route a message is to find a path from the traffic source to send this message to its destination. For challenged networks, it is difficult, if not impossible, to find such a path. All MANET routing algorithms depend mainly on constructing the network topology and then processing this topology to find a path (or paths). This technique requires that each node to have full or partial knowledge about the network topology. Constructing and maintaining this kind of topology in our case means unnecessary overhead as the network is expected to be sparse most of the time. Furthermore, the technique fails if there is no end-to-end path between the source and destination nodes, which can happen with a high probability. Our approach to address the routing issue is to construct a virtual network topology, where a link between two mobile nodes represents the probability of future contacts (i.e. meetings) between the two nodes within the network, instead of representing the existing physical connection between the nodes. A *contact* is defined as the opportunity of transmitting and receiving data between two nodes as they fall within each other's transmission range. As shown in Fig. 3, the network 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. Note that Fig. 3 illustrates only the links having a nonzero probability of future contacts.

### 4.2 Probability of future contacts

The main challenge in developing an efficient routing algorithm for the MANET is how to construct the *virtual network topology*, i.e., how to calculate the probability of future contacts between a pair of nodes. Techniques proposed for DTN routing use different criteria for predicting future contacts, e.g., the idea that a most recently met node is more probably to be met [7]. Some techniques assume that each user has a predefined movement pattern that rarely changes and the routing decisions are based on these patterns [3]. However, it is not clear how to determine the mobility patterns. Other techniques assume that the future events in the network are known in advance, which is unreasonable for our system where mobile users roam freely anytime and anywhere. There is no general solution to the problem; however, the solution mainly depends on network constraints. Here, we do not assume any knowledge of the future events (e.g., node velocity, node movement direction, time instants of power on and off). Instead, we make use of network statistics that are collected and stored on the DTN gateway. The statistics are collected based on all the user sessions in the access network in the system, not only the current or most recent session. Previous techniques [1, 7] predict future contacts based on the number of previous contacts. Such an approach has two problems: One is multiple *falsely detected contacts*, as shown in Fig. 2, where node $B$ is in the communication range of node $A$. As node $B$ may switch its power off and then switch it back on, node $A$ will falsely detect more than one contact with node $B$. The same situation can happen when node $B$ exhibits an intermittent connection with node $A$, e.g., due a communication barrier between them or the presence of node $B$ on the edge of node $A$'s communication range. The other problem is related to *permanent neighbors*, as shown in Fig. 2 where node $C$ and node $D$ move with the same velocity and in the same direction. One contact between the two nodes would be counted because no disconnection happens, independent of the long duration that the contact lasts. On the other hand, both nodes encounter other nodes as they move, which can result in multiple contacts for these nodes due to on and off links. A routing decision based on the number of contacts makes node $C$ a less suitable candidate to carry message for node $D$ than other nodes having a larger number of contacts, although node $C$ should be the favorite candidate to carry the messages as it is in continuous contact with node $D$. To address the problems, we propose routing based on the durations of previous contacts, instead of the number of previous contacts. Taking the total duration of all the contacts as the parameter is expected to give a better reflection of the likelihood that the nodes are in contact with each other. Without loss of generality, consider two

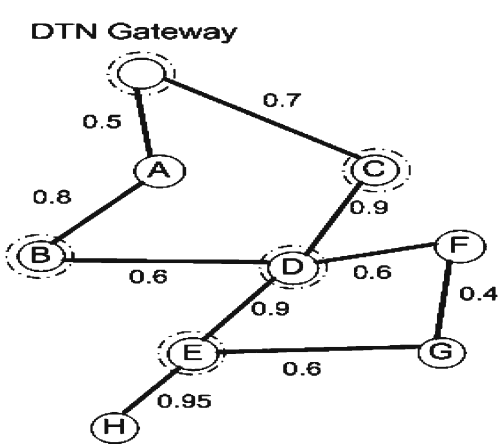


**Fig. 3** A simple example of virtual network topology

nodes, $A$ and $B$. At any time, let $T_{AB}$ denote the total time that nodes $A$ and $B$ were in contact up to the moment. Regardless of time synchronization and the time durations that nodes $A$ and $B$ respectively stayed connected to the network, $T_{AB} = T_{BA}$. The probability of a future contact between nodes $A$ and $B$ is estimated approximately by

$$P_{AB} = \frac{T_{AB}}{[T_A + T_B]/2} \tag{1}$$

where $T_A$ and $T_B$ are the total time durations, up to the moment of estimation, that nodes $A$ and $B$ respectively are on and reside in the network coverage (i.e., connected to the network). Equation 1 takes into account the time durations that the nodes are connected to the network. This is different from the previous techniques where the probability of meeting decreases with the time if no contact occurs, even if any or both of the nodes were not connected prior to the time of estimation. The assumption that a node is always connected is not practical for our problem.

Each node in the network keeps a list that contains the total duration of the meetings for each encountered node. The node sends this list to the gateway the first time it connects to the network. During the node life time in the network, it sends updates of the list to the gateway by piggyback on regular messages, or by sending special update messages if no regular messages.

### 4.3 Dominating-set based routing

Our newly proposed routing scheme is based on calculating the dominating set for the 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 [14]. In our routing scheme for the MANET, the formulation of the virtual network topology and the determination of its dominating set take place at the gateway. The results are broadcast to all the mobile nodes in the network via the epidemic routing. That is, the gateway sends the information to all the nodes it encounters. These nodes, during their movements, forward the message to all other contacted nodes. The procedure continues until the information reaches all the mobile nodes in the network. On the other hand, for routing of a data packet from the source node to the destination node, the packet is forwarded only to the nodes in the dominating set, different from the epidemic routing for the message broadcasting. When a node is to send a message, it either transmits it to a node in the dominating set or to the destination node itself (if there is a direct contact). Different from the epidemic routing which forwards the message to all the neighboring nodes, our proposed technique counts on forwarding the message only to the dominating set members. The dominating set represents the set of nodes that have high probability to meet with all the other nodes in the network; the expected number of forwarded messages is proportional to the size of the dominating set.

To determine the dominating set, the technique given in [14] is not suitable to our virtual network topology. We should take the edge weights into consideration, as we may have a fully connected graph where most of the edges have very low weights. Our procedure for formulating the dominating set contains two phases. In the first phase, we process all the nodes one by one in ascending order of their IDs; for each node not already in the set, we add the node that is most probable to meet to the dominating set. The second phase ensures that the dominating set is connected, which is necessary for proper forwarding of a message to the destination. As the gateway connects the MANET to the overall system, it should always be included in the dominating set. Algorithm 1 shows the details of our proposed algorithm, where $DS$ represents the dominating-set and $N(i)$ represents the set of neighbors for node $i$. As an example to explain the algorithm, consider the simple virtual network topology in Fig. 3. After constructing the virtual network topology based on the probability information of future contacts, the procedure to determine the dominating set starts as follows. First, we start with the $DS$ containing only the gateway node. Processing node $A$ adds node $B$ to the $DS$. As node $B$ is now an element of $DS$, it is not processed. Processing node $C$ adds node $D$ to the $DS$. Processing node $E$ and node $F$ would add node $D$ which is already in the

**Algorithm 1** Calculation of the dominating set (DS)

Start with $DS$ contains only the gateway node
**for all** node $i \in V$ and $i \notin DS$ and $N(i) \nsubseteq DS$ **do**
  get max $P_{ij}$ where $j \in N(i) and N(j) - i \neq \phi$
  **if** $j \notin DS$ **then**
    add $j$ to $DS$
  **end if**
**end for**
**for all** node $i \in DS$ **do**
  **if** $j \notin DS,\ \forall j \in N(i)$ **then**
    get max $P_{ij}$ where $j \in N(i)$ *and* $j \in N(k)$ *where* $k \in DS$
    add $j$ to $DS$
  **end if**
**end for**

$DS$. Processing node $G$ adds node $E$ to the $DS$. Note that node $H$ will not be processed as all its neighbors are already in the $DS$. After the first phase, $DS$ = {gateway, node $B$, node $D$, node $E$}. The second phase finds that the $DS$ is not connected as the gateway has no neighbor in the $DS$, and therefore adds node $C$ to the dominating set. Note that the proposed algorithm may not result in the minimum dominating set. Minimizing the dominating set is a topic for further research.

## 5 Performance evaluation

### 5.1 The node mobility model

As in real life users usually follow specific patterns in their movements, we consider the following user mobility model. The geographical area covered by the MANET is partitioned to $m$ partitions. When a node is connected to the network, it visits each of the partitions with a certain probability. The location of a mobile node in the future is independent of its location in the past, given its current location. Denote the location state of a mobile node by the partition it resides, and assume the residence times of all the mobile nodes in each partition are iid exponential random variables. Then, the user mobility model can be characterized by a one-dimensional continuous-time Markov chain, with location state space $\{1, 2, \ldots, m\}$. The user movement model over the network coverage area is described by the transition matrix $M$ of the Markov chain, given by

$$\mathbf{M} = \begin{pmatrix} P_{L_{11}} & P_{L_{12}} & \ldots & P_{L_{1m}} \\ P_{L_{21}} & P_{L_{22}} & \ldots & P_{L_{2m}} \\ \ldots & \ldots & \ldots & \ldots \\ P_{L_{m1}} & P_{L_{m2}} & \ldots & P_{L_{mm}} \end{pmatrix} \tag{2}$$

where $P_{L_{ij}}$ is the conditional probability that a mobile node will enter partition $L_j$ given that it is still connected to the network and it leaves its current partition $L_i$. For any partition $L_i$, we have $\sum_j P_{L_{ij}} = 1$. The transition probability matrix depends on the geographical characteristics of the service area and the network environment under study.

### 5.2 Simulation results

We compare the performance of the super node scheme with the epidemic routing based scheme. The performance is measured in terms of the number of exchanged messages over the network to capture how each scheme uses the available resources such as radio bandwidth, and the number of undelivered messages to indicate how successful the scheme is in delivering messages. In our experiments, the simulation proceeds in steps. At each step (simulation time), a mobile node can send a new message or handover to a new access network. The system has 4 super nodes, 5 wireless access networks (i.e., 3 sparse ad hoc networks, 1 WLAN, and 1 cellular network) each connected via a gateway to the Internet backbone, and 50 or 100 mobile nodes distributed randomly within the access networks. Each super node is assigned an (approximately) equal number of users. A user can roam over all the access networks, the residence time over each network is an exponentially distributed random variable with mean of 10 simulation steps. Each user is disconnected for a random period of time (which is an exponential random variable with mean of 10 simulation steps), then reconnected either from the same access network (with probability 0.7) or from any other access network equally likely. All the messages are equal in size, with the same message live time of 4 simulation steps. The buffer space is 20 messages at each mobile node and 2000 messages at each super node. For simplicity in simulation, we use the epidemic routing over ad hoc networks. For each experiment, a communication scenario (i.e., set of messages, user connections, user disconnections, user movements) is set up randomly and run for each scheme.

Figure 4 shows the total number of message exchanges for 50 and 100 mobile nodes respectively. It is clear that the super node scheme outperforms the epidemic routing based scheme. It is noted that the performance improvement increases with the network sizes. Figure 5 shows the number of undelivered messages. It is observed that the super node scheme is much better than the epidemic routing based scheme. The main problem with the epidemic routing based scheme is that the user messages are forwarded to many other intermediate mobile nodes which may never meet the destination node or drop the messages before delivery.

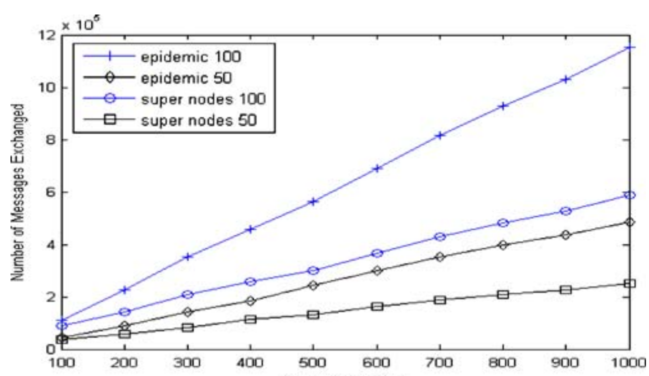


**Fig. 4** The total number of forwarded messages

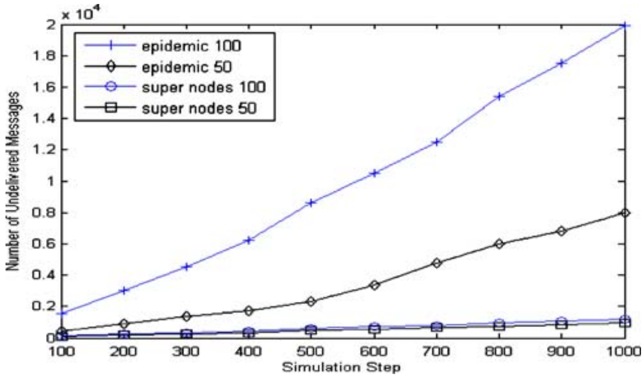


**Fig. 5** The number of undelivered (i.e., lost) messages

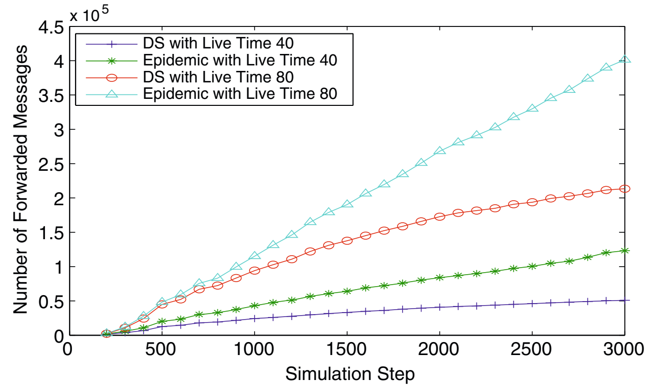


**Fig. 7** The effect of the different message live times

It is observed that the super node scheme requires big number of message exchanges because the majority of the access networks are MANETs, and message delivery over MANETs requires many messages forwarding when using the epidemic routing. Next, we study the performance of the newly proposed MANET routing technique in the system.

To compare the performance of the proposed routing technique with that of the epidemic routing over a MANET, we consider that the MANET coverage area is a rectangle of size 1500 m × 1500 m. The area is partitioned into 150 m × 150 m partitions. Each simulation proceeds in discrete time steps. Mobile nodes have mobility trajectories independent of each other. We experiment with 50 nodes. For each simulation run, a transition matrix $M$ is randomly generated 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 (if connected) moves randomly according to the transition matrix. When a node moves to a new partition, it stays there for a residence time that is an exponential random variable with an average of 20 simulation steps. At the end of the residence time, the node will move to a new partition with a probability of 0.7, or will disconnect from the network with a probability of 0.3. If the node disconnects, it will stay disconnected for a duration that is exponentially distributed with an average of 20 time steps. For simplicity, we assume that a node is able to communicate only with other nodes in the same partition. Messages are generated based on a Poisson process with mean rate of $\frac{10}{3}$ messages per time step. The source and destination mobile nodes for each message are selected at random. All the messages are equal in size, with the same message live time of 40 simulation steps. The buffer space is 15 messages at each mobile node and 2000 messages at the gateway. When the node buffer is full and a new message is received, the oldest message in the buffer is removed to receive the new message. 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 routing technique used. Each node also updates its buffer by removing the expired messages. For each experiment,

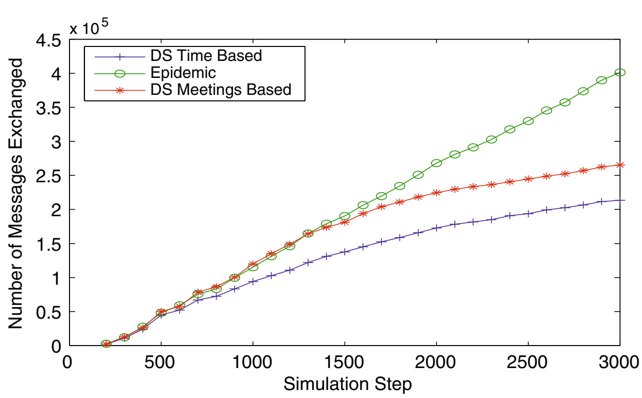


**Fig. 6** Epidemic routing versus dominating set routing with respect to the number of messages exchanged

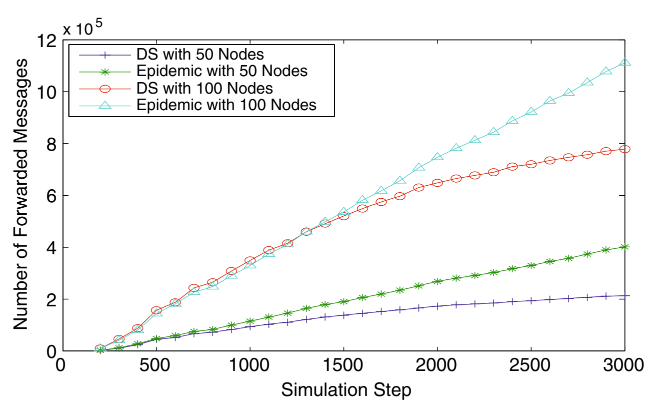


**Fig. 8** The effect of increasing the number of nodes

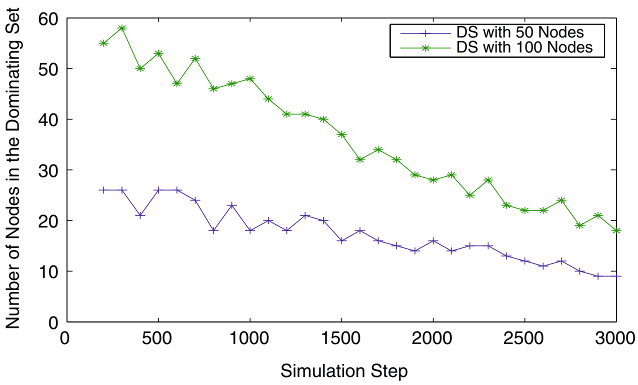


**Fig. 9** The dominating set size versus the system operation time

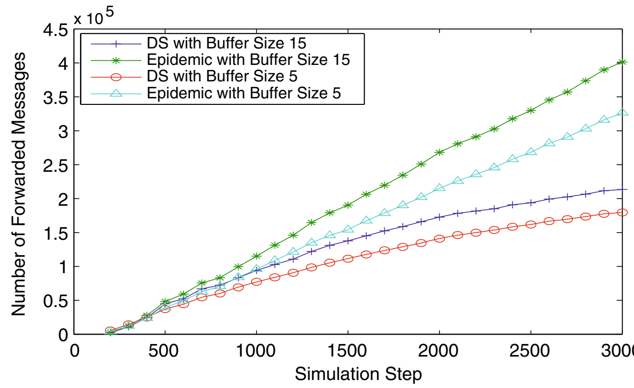


**Fig. 11** The effect of decreasing node's buffer size

a communication scenario (i.e., set of messages, user connections, user disconnections, user movements) is set up randomly and run for each routing technique. Figure 6 shows a comparison between the epidemic routing technique and the dominating-set based routing technique in terms of the total number of forwarded messages. It includes the results for the dominating-set routing technique based on two different ways of calculating the probability of future contacts. One is based on the number of previous contacts and the other is based on the total contact time as discussed in Section 4.2. It is clear that the dominating-set based technique is much better than the epidemic routing in terms of the number of forwarded messages. It is also observed from the figure that the time based calculation for the dominating set gives better performance than the calculation based on the number of previous contacts. On the other hand, we found that dominating-set based routing leads to more lost messages than the epidemic routing. However, when the message live time is increases the two routing schemes give comparable performance [9]. On the other hand, increasing the message live time increases the number of forwarded messages for both schemes as shown in Fig. 7, mainly due to the retransmission of dropped messages due to the limited buffer space. It is observed that the dominating set routing scheme outperforms, in terms of the number of forwarded messages, the epidemic routing scheme for the different message live times.

We perform the experiments for different sizes of the network and have the same observations as shown in Fig. 8. It is noted that, as the MANET operation time increases, the number of forwarded messages decreases as more observation data are available for estimating the probability of future contacts, resulting in a more accurate virtual network topology and a smaller dominating set as shown in Fig. 9.

To study the buffer size effect, we increase the message live time to 80, so that both schemes have comparable performance in terms of the percentage of undelivered messages. As shown in Fig. 10 the performance of both routing schemes degrades (in terms of the number of undelivered messages) when the buffer size is reduced, but the dominating-set based routing still outperforms the epidemic routing.

As shown in Fig. 11, due to a large number of lost messages the total number of messages forwarded with a smaller buffer size decreases in comparison with the case of a larger buffer size, but not proportional to the decrease of the buffer size. That is because reducing the buffer size not only increases the number of undelivered messages (as expected), but also the number of forwarded messages due to a larger number of retransmissions of dropped messages.

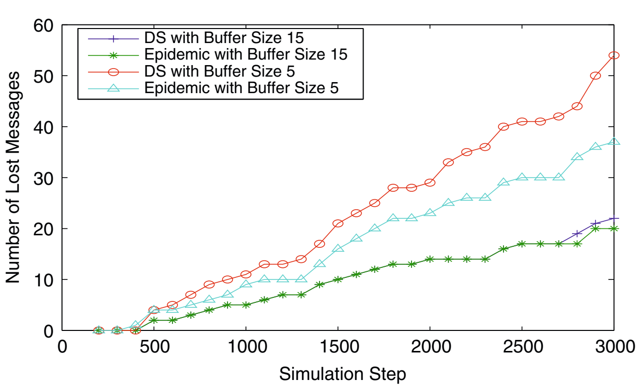


**Fig. 10** The effect of decreasing node buffer size

## 6 Conclusions

In this paper, we propose the super node architecture to ensure connectivity to roaming users with intermittent connections over heterogeneous wireless access networks. We then present the new dominating-set routing technique for MANET as an access network, based on the concept of virtual network topology to adequately model a DTN based network. Constructing this topology requires a methodology to estimate the probability of future contacts between nodes in the network, and we propose to determine the estimate for MANETs based on the duration of previous contacts. A calculation of the dominating set is discussed for the virtual network topology graph. Simulation results demonstrate the effectiveness of the super node architecture, and that the newly proposed routing scheme outperforms the epidemic routing in both resource utilization and QoS provisioning, and that the estimation of the probability of future contacts between two nodes based on previous contact durations yields better routing performance than the estimation based on the number of contacts.

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