On-Demand Multipath Routing for Mobile Ad Hoc Networks

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Abstract: A Mobile Ad hoc NETwork (MANET) is a collection of wireless mobile computers forming a temporary network without any existing wire line infrastructure. Due to the dynamic nature of the network topology and the resource constraints, routing in MANETs is a challenging task. Multipath routing can increase end-to-end throughput and provide load balancing in wired networks. However, its advantage is not obvious in MANETs because the traffic along the multiple paths will interfere with each other. In this paper, we propose the path selection criteria and an on-demand multipath calculation method. We also perform a simulation study on the proposed on-demand multipath routing in MANETs. Results show that the multipath routing can evenly distribute the network load. This feature is important to protect a node from heavy tasks and power depletion.

1 Introduction

A Mobile Ad hoc NETwork (MANET) is a collection of wireless mobile computers forming a temporary network, which is based on radio to radio multi-hopping and has neither fixed base stations nor a wired backbone infrastructure. Routing in MANETs is a non-trivial task because hosts' movements cause frequent topology changes and require robust and flexible mechanisms to discover and maintain the routes. In addition, due to the power and bandwidth limitations, a routing protocol in MANETs should fairly distribute the routing tasks among the mobile hosts. However, most current proposed routing protocols [1, 2, 4] have not considered the load balancing problem. An unbalanced assignment of data traffic will lead to power depletion on heavily loaded hosts. With more hosts powered down, the connectivity of the network will be reduced, which will lead to the failure of calls due to network partitions.

Multipath routing aims to establish multiple paths between source-destination pairs. A lot of benefits have been explored for multipath routing in wired networks [5, 6, 7]. In MANETs, we can also find the use of the multipath method in some proposed routing protocols. For example, the Temporally Ordered Routing Algorithm (TORA) [4] provides multiple paths by maintaining a destination-oriented directed acyclic graph from the source node. The Dynamic Source Routing (DSR) [1] has an option to use an alternate path if the primary path fails. However, these protocols do not study the multipath selection criteria, the "quality" of the multiple paths, and how to efficiently use the multiple paths. The benefits of multipath routing have not been deeply explored in those protocols.

In [2], A. Nasipuri and S. R. Das prove that the use of multiple paths could keep correct end-to-end transmission for a longer time than a single path. In other words, the frequency of searching for new routes is much lower if a node keeps multiple paths to the destination. This is the first deep study on performance benefits of multipath routing in MANETs. However, they did not study the performance improvement of multipath routing on the network load balancing. M. R. Perlman et al. demonstrates that the multipath routing can balance network loads in their recent paper [9]. However, their work is based on multiple channel networks, which are contention free but may not be available in most cases.

In this paper, we perform a simulation study on multipath routing in MANETs. The motivation of this paper is to explore an on-demand multipath routing protocol and present the benefits as well as the disadvantages of the on-demand multipath routing in a shared channel wireless mobile network. The rest of the paper is organized as follows. In Section 2, we demonstrate that the interference of the data traffic along different paths will influence the performance of multipath routing in MANETs. Section 3 introduces a multipath calculation algorithm based on an on-demand routing method. Section 4 describes the simulation model. We present our performance results in Section 5, and conclude the paper in Section 6.

2 Multiple Path Selection Criteria

If we assume all mobile hosts' radio transmission range is the same, a MANET could be modeled as an undirected

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graph $G = (V, E)$, where V is a set of $|V|$ nodes and E is a set of $|E|$ undirected links connecting nodes in V. Each node has a unique identifier and represents a mobile host with a wireless communication range of R. There is an undirected link (i, j) connecting two nodes i and j when the two nodes are within each other's transmission range.

Definition 1: The correlation factor (η) of two node-disjoint paths is defined as the number of the links connecting the two paths. If there is no link (η=0) between two node-disjoint paths, we say the two node-disjoint paths are unrelated. Otherwise, the two node-disjoint paths are η-related. The total correlation factor of a set of multiple paths is defined as the sum of the correlation factor of each pair of paths.

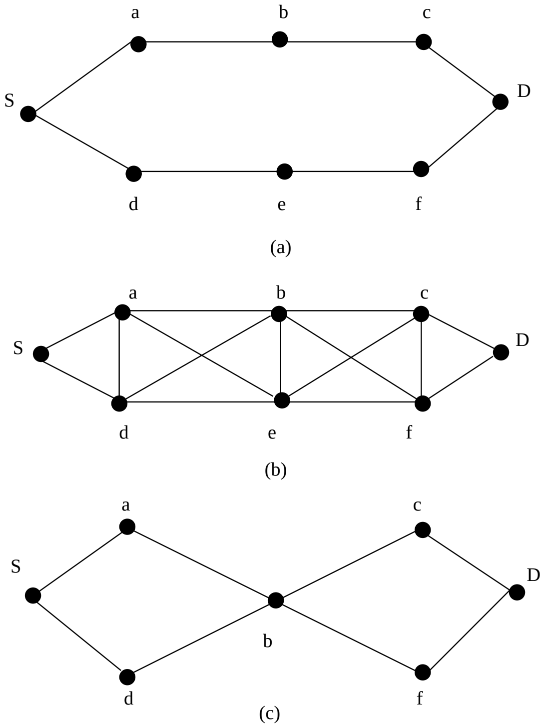

Fig. 1. (a) Two node-disjoint paths are unrelated
(b) Two node-disjoint paths are 7-related.
(c) Two paths are link-disjointed.

As shown in Figure 1(a) and 1(b), the source node S sends Constant Bit Rate (CBR) traffic to the destination node D, using two node-disjoint paths between S and D, which are S→a→b→c→D and S→d→e→f→D. In Figure 1(a), the two node-disjoint paths are unrelated. But in Figure 1(b), the two node-disjoint paths are 7-related. In order to study the influence of the correlation factor, we initially select static topologies. In our simulation, we change the initial positions of the nodes to obtain different correlation factors of the two node-disjoint paths. We use a shared channel model, in which all hosts use the same radio spectrum and compete for the radio channel. For example, in Figure 1(b), if S is sending messages to a, then node d could not send messages to node e since both transmissions will collide at node a. Other parameters such as bandwidth, radio transmission range etc. are the same as in Section 4.

Figure 2 shows the result of the average end-to-end delays along these two node-disjoint paths for different correlation factors. The larger the correlation factor, the larger the average end-to-end delay for both paths. This is because two paths with larger correlation factor have more chances to interfere with each other's transmission due to the broadcast feature of radio propagation. In addition, with the increase of the correlation factor, the difference between the average end-to-end delay along the two paths is also increased even if the two paths have the same length and the same traffic load. The reason is that the traffic from node S to the different paths is not simultaneous. As a result, the data traffic sent a little bit ahead will have more chances to capture the transmission channel and the lagged data traffic will have to defer its transmission. The larger the correlation factor, the larger the influence on the difference of end-to-end delay.

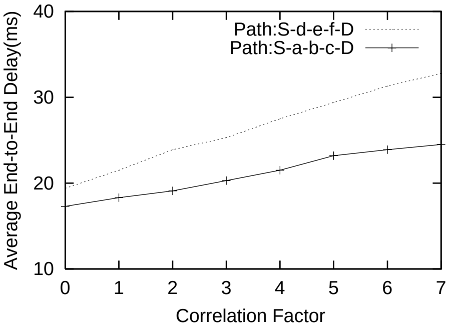

Fig. 2. Average end-to-end delay vs. correlation factor

In addition, we send the same traffic load from S to D in the static topology shown in Figure 1(c), using two link-disjoint but not node-disjoint paths, which are S→a→b→c→D and S→d→b→f→D. The average end-to-end delay is 21.3 ms along the path S→a→b→c→D and 30.5 ms along the path S→d→b→f→D. Compared with the results in Figure 2, we can see that the traffic along these two paths could dramatically interfere with each other, since the traffic along the different paths compete for the transmission channel in the common node b. Thus, if the paths are only link-disjoint, good performance can not be guaranteed.

Path length is also an important factor in multipath routing. A longer path will increase the end-to-end delay and waste more bandwidth. When we use the multiple paths simultaneously between a source-destination pair, the difference of the end-to-end delay among the multiple paths requires more buffer space in the destination to deal with the disordered data packets. Although this may not be a serious problem considering that the radio transmission rate is relatively slow compared with high-speed wireline networks, we should not ignore the influence of the different path length.

Based on the above observation, our path selection criteria in MANETs includes properties of (1) node-disjoint, (2) small length difference between the primary (shortest) path and the alternate paths, and (3) small correlation factor between any two of the multiple paths. Since the path correlation factor is always changing when the nodes are moving, maintaining the property of small correlation factor will be costly. However, we can use this criterion at the initial path selection.

3 Multipath Routing in MANETs

Finding node-disjoint multiple paths is not an easy task when the whole topology is unknown. The Dynamic Source Routing (DSR) [1] protocol finds multiple paths, but does not take the property of node-disjoint or link-disjoint into account. We introduce our multipath calculation method and how we use the multiple paths in this section.

3.1 Multipath Calculation

In our multipath calculation approach, we combine the path selection criteria in Section 2 with the path calculation method in DSR. When the route query messages are initiated by a source node to search for paths to a destination, besides the information required for DSR such as the destination address and the sequence number, they include a parameter *d*, which indicates the permitted maximal difference of the length between the primary (shortest) path and the alternate paths. This parameter corresponds to the path selection criterion (2) in Section 2.

In [1] and [2], any node that receives the same query messages, say, same source address and same sequence number, will not broadcast it again. This method can reduce the routing cost but greatly reduces the possibility of finding multiple node-disjoint paths, because it quenches the diversity of the multiple paths. That is, the obtained multiple paths usually have some common nodes. In our simulation, using this method, the chance of finding node-disjoint multiple paths is almost zero. We modify the route query flooding as follows.

When a node receives a route query message, if it is the first time to receive this query message or the path included in this query message is node-disjoint with the paths included in previously cached same route query messages, then the node will cache and broadcast it again. In other cases, the node will discard this query message. This method will increase the flooding cost but also increases the diversity of the query messages. When the destination receives a query message, a reply message is sent back to the source if the query message carries a source route that is node-disjoint from the existing routes and the difference of the length between this route and the primary route is less than *d*. The primary route is usually taken by the first query message arriving at the destination. The reply message carries the whole path information between the source and the destination.

Every node has a neighborhood table to record its neighbors. The contents of the neighborhood table are refreshed by any received control and data messages. If a neighbor has not been refreshed for a timeout value, it is obsolete and erased from the table.

When the reply message traverses from the destination to the source node, it piggybacks the neighborhood information along the path. The source node will calculate the path correlation factor using the neighborhood information piggybacked in the reply message. The parameter, maximal correlation factor, is used by the source to select the proper paths. The source will select the multiple paths whose total correlation factor is less than the maximal correlation factor.

3.2 The Ability of Finding Multiple Node-Disjoint Paths

Because some route request and route reply messages may be lost due to unreliable radio transmission, our multipath calculation method can not guarantee to find node-disjoint paths even if they may exist. However, we demonstrate that our method can find most of node-disjoint paths through simulation. We compared the ability of finding multiple node-disjoint paths using a *diversity injection* method [3], DSR, and our method separately. The *diversity injection* method is proposed to increase the diversity (the node-disjoint property) of multiple paths. The broadcast of route requests in this method is the same as the one in DSR except that the middle nodes will cache all route request messages. When a route reply message is received, the remaining forward path back to the source is replaced with the shortest cached route that has been used the fewest number of times, and does not form a loop [3].

In the same simulation model described in Section 4, we randomly choose 200 source-destination pairs and calculate the maximal number of node-disjointed paths between each source-destination pair, using an off-line algorithm with knowledge of the whole topology. In the meantime, we separately use the *diversity injection* method, DSR, and our method to search for node-disjoint paths. Fig. 3 shows the result of the ratio of the number of obtained node-disjoint paths using different searching methods to the maximal number of node-disjoint paths using the off-line algorithm.

The result shows that our method can find most node-disjoint paths and more than the *diversity injection* method; while DSR has almost no chance to find node-disjoint paths.

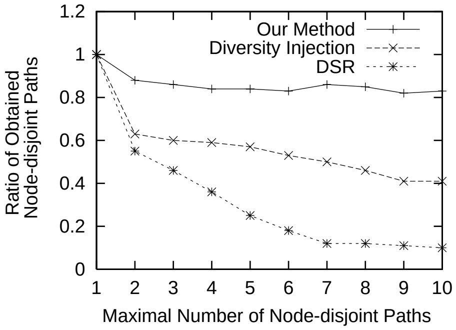

Fig. 3. Ratio of the number of obtained node-disjoint paths to the number of maximal node-disjoint paths

3.3 Multipath Routing

There are several ways to use the multiple paths. In [1] and [2], the multiple paths are not used simultaneously. The data packets are transmitted along one path. Other paths are kept as backup paths in case the used one is broken. When all possible paths are broken, a new multipath discovery procedure is initiated again.

Our approach of using multiple paths is different. In order to balance the network loads, we use the multipath simultaneously as in dispersity routing [7], which disperses the data traffic along different paths. The dispersity routing can be divided into redundant and non-redundant routing. In redundant dispersity routing, only part of the multiple paths are used to transfer data, and the other remaining paths are used to transfer redundant information such as error-correcting codes. In contrast, in non-redundant dispersity routing, all multiple paths are used to transmit data simultaneously. We use non-redundant dispersity routing. If a path is broken, an error message is sent back to the source node and the traffic on that path will be transferred to other paths that are still alive. When all paths are broken, a new multiple path discovery is initiated again.

4 Simulation Model

We use a simulation model based on GloMoSim [8]. We study the performance of multipath and unipath routing. In our simulation, the channel capacity of mobile hosts is set to the same value: 2 Mbps. A free space propagation model with a threshold cutoff is used as the channel model. In the free space model, the power of a signal attenuates as $1/r^2$, where r is the distance between mobile hosts. In the radio model, capture effects are taken into account. We use the distributed coordination function (DCF) of IEEE 802.11 for wireless LANs as the MAC layer protocol. It has the functionality to notify the network layer about link breakage.

In our simulation, 50 mobile nodes move in a 1500 meter x 500 meter rectangular region for 900 seconds simulation time. Compared with a square region, the rectangular region can enlarge the average route length so that we can easily observe the performance difference between unipath and multipath routing. Initial locations of the nodes are obtained using a uniform distribution. We assume each node moves independently with the same average speed. All nodes have the same transmission range of 250 meters. The mobility model is the random waypoint model. In this mobility model, a node randomly selects a destination from the physical terrain. It moves in the direction of the destination in a speed uniformly chosen between the minimal speed and maximal speed. After it reaches its destination, the node stays there for a *pause time* and then moves again. In our simulation, the minimal speed is 5 m/s and maximal speed is 10 m/s. We change the *pause time* from 0 seconds to 900 seconds to investigate the performance influence of different mobility. A *pause time* of 0 seconds presents continuous motion, and a *pause time* of 900 seconds corresponds to no motion.

The simulated traffic is Constant Bit Rate (CBR). 15 source nodes and 15 destination nodes were chosen randomly with uniform probabilities. The interval time to send packets is 250ms. The size of all data packets is set to 512 bytes. A packet is dropped when no acknowledgement is received after several retransmissions or there is no buffer to hold the packet. All traffic is generated and the statistical data are collected after a warm-up time of 30 seconds in order to give the nodes sufficient time to finish the initialization process. For each scenario, eight runs with different random seeds were conducted and the results were averaged.

5 Simulation Results

5.1 Performance metrics

We will compare the performance of unipath routing and multipath routing under different mobile speeds. We evaluate the performance according to the following metrics:

- *Control overhead*: The control overhead is defined as the total number of routing control packets normalized by the total number of received data packets.
- *Bandwidth cost for data*: The bandwidth cost for data is defined as the total number of data packets transmitted at all mobile hosts normalized by the total number of received data packets.

- *Average end-to-end delay*: The end-to-end-delay is averaged over all surviving data packets from the sources to the destinations.
- *Load balancing*: We use a graph G=(*V, E*) to denote the network, where *V* is the node set and *E* is the link set. We define a state function $f: V \rightarrow I$ where *I* is the set of positive integers. *f*(v) represents the number of data packets forwarded at node v. Let CoV (*f*) = standard variance of *f* / mean of *f*. We use CoV (*f*) as a metric to evaluate the load balancing. The smaller the CoV (*f*), the better the load balancing.

We study two different ways to use the multiple paths. In one method, called multipath routing 1, we choose a path randomly from the multiple paths with the same probability. The other method, called multipath routing 2, is to choose a path with a probability inversely proportional to the length of the path. Since the packet loss rate in multipath and unipath routing is similar in our simulation, we do not present the results of packet loss rate in this paper.

5.2 The Performance Comparison of Multipath Routing with Unipath Routing

In this experiment, the maximal total correlation factor is set to 15. The maximal number of multiple paths is 4. Figure 4 shows the result of total number of routing discovery phases versus the mobility. The frequency of routing discovery for multipath routing 1 and 2 is less than for the unipath routing approach. This result is coincident with the theoretical analysis in [2]. The frequency of routing discovery for multipath routing 1 and 2 is almost the same since the number of routing discovery phrases mainly depends on the link breakage of the selected multiple paths instead of the method of using multiple paths.

However, Figure 5 shows that the control overhead for unipath routing is less than multipath routing. This is because searching for diverse multiple paths in our method could be more costly than searching for a single path using on-demand routing approaches. How to searching for diverse multiple paths with less control overhead deserves further study.

Figure 6 shows the result of total bandwidth cost for data transmission. The bandwidth cost of data transmission for unipath routing is the smallest; while the bandwidth cost of data transmission for multipath routing 1 (randomly choosing a path) is the largest. This is because the unipath routing usually uses the optimal path from a source to a destination. The alternative paths in multipath routing are usually sub-optimal, which will cost more bandwidth. For the multipath routing, randomly choosing a path will cost more bandwidth than choosing a path based on its length.

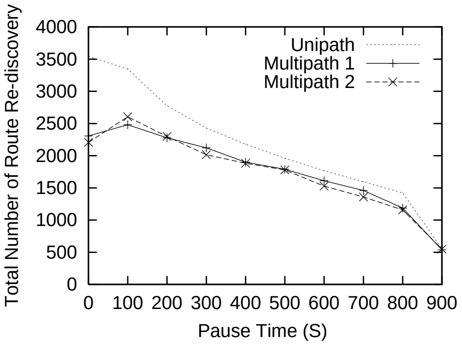

Fig. 4. The number of routing discovery with varying speed

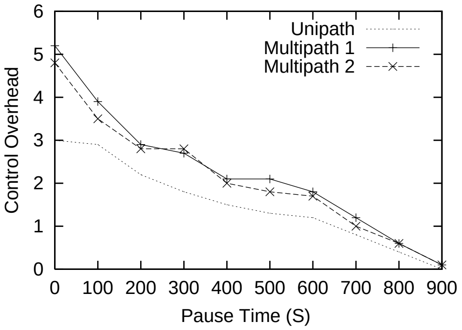

Fig. 5. The normalized control overhead with varying speed

Figure 7 shows the results of average end-to-end delay. The end-to-end delay includes the queue delay in every host and the propagation delay from the source to the destination. Multipath routing will reduce the queue delay because the traffic is distributed along different paths. On the other hand, it will increase the propagation delay since some data packets may be forwarded along the sub-optimal paths. From Figure 7, the unipath routing has slightly higher average end-to-end delay compared to multipath routing. This demonstrates that the multipath routing could distribute the traffic and improve the end-to-end delay, but the improvement is limited below *pause time* of 300 seconds. With the decrease of *pause time*, the average end-to-end delay for both multipath routing and unipath routing increases, because the network topology changes more frequently at smaller *pause time*. More route discoveries will be promoted and thus the queuing delay of the data packets in the source nodes increases, which leads to the increase of the average end-to-end delay.

Figure 8 gives the results of load balancing. The CoV of network load for the unipath routing is higher than that for the multipath routing. This is because the multipath routing can distribute the network traffic along different paths. The unipath routing always uses the shortest paths between the sources and the destinations, which will unfairly assign more duties to the nodes along the shortest paths. With the decrease of *pause time*, the CoV of network load for the unipath routing and the multipath routing also decreases. This shows that the increase in mobility could result in better load balancing of the traffic among the nodes. "Hot spots" are likely removed due to mobility.

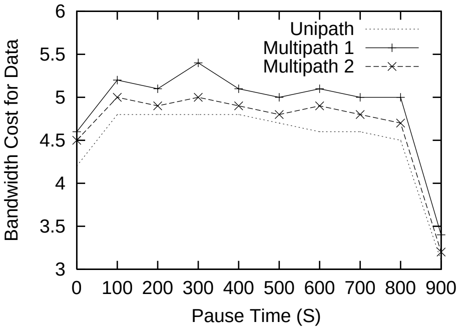

Fig. 6. The bandwidth cost for data with varying speed

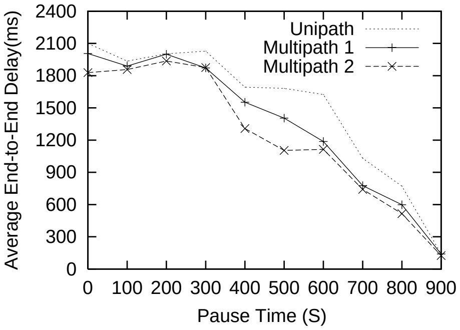

Fig. 7. The average end-to-end delay with varying speed

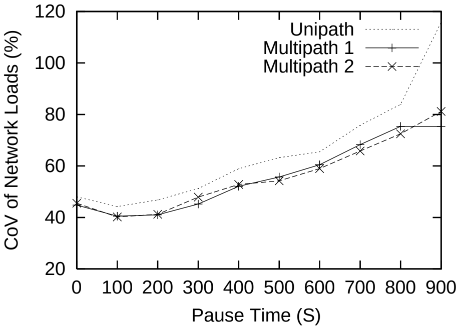

Fig. 8. The CoV of the network load with varying speed

5.3 The Performance Comparison of Multipath Routing with Different Correlation Factors

In this section, we studied how the initial selection of the multiple paths with different correlation factors could influence the routing performance. We only select two paths in this experiment. The simulation results show that when mobile speed is fast, the initial selection of the multiple paths with different correlation factors has little influence on average end-to-end delay. This is because the initial correlation factors will change quickly with the nodes' mobility. However, when the mobile speed is slow (*pause time* is large than 600 seconds in the simulation), multipath routing with initially smaller correlation factors has smaller average end-to-end delay as shown in Figure 9.

The initial selection of the multiple paths with different correlation factors does not influence the routing performance in terms of control overhead, bandwidth cost for data transmission, and load balancing. For example, the CoV of network loads with different correlation factors has no obvious differences as shown in Figure 10.

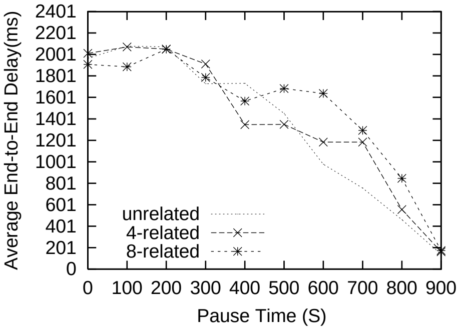

Fig. 9. The average end-to-end delay with different correlation factors

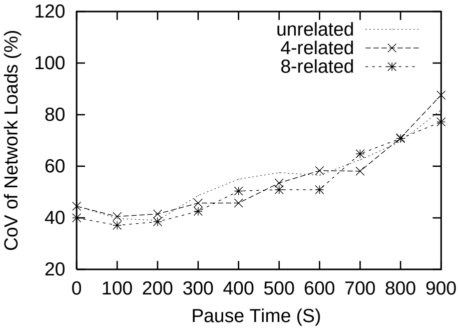

Fig. 10. The CoV of network loads with different correlation factors

6 Conclusions

Multipath routing can provide load balancing and reduce the frequency of on-demand route discovery. These benefits make multipath routing appear to be an ideal routing approach for MANETs. However, these benefits are not easily explored because (1) multiple paths will interfere with each other's transmission and (2) the cost of searching for proper multiple paths is usually larger than a single path. In a single channel MANET, our performance study on an on-demand multipath routing protocol shows that

- Although the frequency of on-demand route discovery for multipath routing is less than that for single path routing, the total control overhead is larger for on-demand multipath routing because searching for diverse multiple paths is usually more costly than searching for a single path. Without the knowledge of the whole network topology, how to efficiently finding multiple diverse paths deserves further study.
- The on-demand multipath routing can gain some improvement of end-to-end delay in a shared channel MANET.
- The network load can be distributed more evenly in multipath routing. Mobility can also contribute to the network load balancing. Load balancing is important to fairly distribute the routing task among the mobile nodes. It can also protect a node from failure considering that a node with heavy duty is likely to deplete its power quickly. In the future, we will study how multipath routing influences the power depletion.
- The initial selection of the multiple paths with different correlation factors can influence the average end-to-end delay when mobile speed is low.

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