Network Topology Information Based Source Routing Protocol for Mobile Ad Hoc Networks

T.Naresh[#1], Siva Nageswara Rao.S[*2], Sk. Mahaboob Subhani[*3]

[#] *M.Tech student, Dept. of Computer Science and Technology, Narasaraopeta Engineering College, Narasaraopeta, India.*

[*] *Assistant Professor, Dept. of Computer Science and Technology, Narasaraopeta Engineering College, Narasaraopeta, India.*

[1] naresh515.thota@gmail.com

[2] sivanag58@yahoo.co.in

[3] subhaniskn@gmail.com

***Abstract*—Opportunistic data forwarding has drawn much attention in the research community of multihop wireless networking, with most research conducted for stationary wireless networks. One of the reasons why** *opportunistic* **data forwarding has not been widely utilized in mobile ad hoc networks (MANETs) is the lack of an efficient lightweight proactive routing scheme with strong source routing capability. In this paper, we propose a network topology information based source routing protocol. This Protocol can maintain more network topology information than distance vector (DV) routing to facilitate source routing, although it has much smaller overhead than traditional DV-based protocols [e.g., destination-sequenced DV (DSDV)], link state (LS)-based routing [e.g., optimized link state routing (OLSR)], and reactive source routing [e.g., dynamic source routing (DSR)]. Our tests using computer simulation in Network Simulator 2 (ns-2) indicate that the overhead in this protocol is only a fraction of the overhead of these baseline protocols, and this protocol yields better data transportation performance than these baseline protocols.**

I. Introduction

A mobile ad hoc network (MANET) is a wireless communication network, where nodes that are not within the direct transmission range of each other require other nodes to forward data. It can operate without existing infrastructure and support mobile users, and it falls under the general scope of multihop wireless networking. This networking paradigm originated from the needs in battlefield communications, emergency operations, search and rescue, and disaster relief operations. It has more recently been used for civilian applications such as community networks.

In this paper, we propose a network topology information based source routing protocol to facilitate opportunistic data forwarding in MANETs. In this protocol, each node maintains a breadth-first search spanning tree of the network rooted at it. This information is periodically exchanged among neighboring nodes for updated network topology information. This protocol allows a node to have full-path information to all other nodes in the network, although the communication cost is only linear to the number of the nodes. This allows it to support both source routing and conventional IP forwarding. When doing this, we try to reduce the routing overhead of network topology information based source routing protocol as much as we can. Our simulation results indicate that network topology information based source routing protocol has only a fraction of overhead of OLSR, DSDV, and DSR but still offers a better data transportation capability compared with these protocols.

II. Related Work

In fact, many lightweight routing protocols had been proposed for the Internet to address its scalability issue, i.e., all naturally "table driven." The path-finding algorithm (PFA) [11] is based on DVs and improves them by incorporating the predecessor of a destination in a routing update. Hence, the entire path to each node can be reconstructed by connecting the predecessors and destinations; therefore, the source node will have a tree topology rooted at itself. In the meantime, the link vector (LV) algorithm [12] reduces the overhead of LS algorithms to a great deal by only including links to be used in data forwarding in routing updates. The extreme case of LV, where only one link is included per destination, coincides with the PFA.

PFA and LV were both originally proposed for the Internet, but their ideas were later used to devise routing protocols in the MANET. The Wireless Routing Protocol (WRP) [13] was an early attempt to port the routing capabilities of LS routing protocols to MANETs. It is built on the same framework of the PFA for each node to use a tree to achieve loop-free routing. Although it is an innovative exploration in the research on MANETs, it has a rather high communication overhead due to the amount of information stored at and exchanged by the nodes. This is exacerbated by the same route update strategy as in the PFA, where routing updates are triggered by topology changes. Although this routing update strategy is reasonable for the PFA in the Internet, where the topology is relatively stable, this turns out to be fairly resource demanding in MANETs. (Our original intention was to include the WRP in the experimental comparison later in this paper, and we have implemented WRP in ns2. Unfortunately, our preliminary tests indicate that the changing topology in the MANET incurs an overwhelming amount of Overhead, i.e., at least an order of magnitude higher than the other mainstream protocols. Thus, we do not include the simulation result of WRP as a baseline in our comparison.)

The network topology information based source routing protocol proposed in this paper uses tree-based routing as in PFA and WRP. To make our network topology information based source routing protocol more suitable for the MANETs, we adopt a combined route update strategy that takes advantage of both "event-driven" and "timer-driven" approaches. Specifically, nodes would hold their broadcast after receiving a route update for a period of time. If more updates have been received in this window, all updates are consolidated before triggering one broadcast. The period of the update cycle is an important parameter in network topology information based source routing protocol. Furthermore, we go an extra mile to reduce its routing overhead. First, we interleave full dump and differential updates to strike the balance between efficient and robust network operation. Second, we package affected links into forests to avoid duplicating nodes in the data structure. Finally, to further reduce the size of differential update messages, each node tries to minimize the alteration of the routing tree that it maintains as the network changes its structure.

A. DESIGN OF PROACTIVE SOURCE ROUTING

Essentially, network topology information based source routing protocol provides every node with a breadth-first spanning tree (BFST) of the entire network rooted at it. To do that, nodes periodically broadcast the tree structure to their best knowledge in each iteration. Based on the information collected from neighbors during the most recent iteration, a node can expand and refresh its knowledge about the network topology by constructing a deeper and more recent BFST.

Before describing the details of network topology information based source routing protocol, we will first review some graph-theoretic terms used here. Let us model the network as undirected graph $G = (V, E)$, where V is the set of nodes (or vertices) in the network, and E is the set of wireless links (or edges). Two nodes u and v are connected by edge $e = (u, v) \in E$ if they are close to each other and can directly communicate with given reliability. Given node v, we use $N(v)$ to denote its open neighborhood, i.e., $\{u \in V \mid (u, v) \in E\}$. Similarly, we use $N[v]$ to denote its closed neighborhood, i.e., $N(v) \cup \{v\}$.

a) Route Update

Due to its proactive nature, the update operation of network topology information based source routing protocol is iterative and distributed among all nodes in the network. At the beginning, node v is only aware of the existence of itself; therefore, there is only a single node in its BFST, which is root node v. By exchanging the BFSTs with the neighbors, it is able to construct a BFST within $N[v]$, i.e., the star graph centered at v, which is denoted Sv.

In each subsequent iteration, nodes exchange their spanning trees with their neighbors. From the perspective of node v, toward the end of each operation interval, it has received a set of routing messages from its neighbors packaging the BFSTs. Note that, in fact, more nodes may be situated within the transmission range of v, but their periodic updates were not received by v due to, for example, bad channel conditions. After all, the definition of a neighbor in MANETs is a fickle one. (We have more details on how we handle lost neighbors subsequently.) Node v *incorporates* the most recent information from each neighbor to update its own BFST. It then broadcasts this tree to its neighbors at the end of the period. Formally, v has received the BFSTs from some of its neighbors. Including those from whom v has received updates in recent previous iterations, node v has a BFST, which is denoted Tu, cached for each neighbor $u \in N(v)$. Node v constructs a union graph, i.e.,

$$Gv = Sv \cup\_ u{\in}N(v)\ (Tu - v).$$

Here, we use $T - x$ to denote the operation of removing the subtree of T rooted at node x. As special cases, $T - x = T$ if x is not in T, and $T - x = \emptyset$ if x is the root of T. Then, node v calculates a BFST of Gv, which is denoted Tv, and places Tv in a routing packet to broadcast to its neighbors.

In fact, in our implementation, the given update of the BFST happens multiple times within a single update interval so that a node can incorporate new route information to its knowledge base more quickly. To the extreme, Tv is modified every time a new tree is received from a neighbor. Apparently, there is a tradeoff between the routing agent's adaptively to network changes and computational cost. Here, we choose routing adaptively as a higher priority assuming that the nodes are becoming increasingly powerful in packet processing. Nevertheless, this does not increase the communication overhead at all because one routing message is always sent per update interval. Assume that the network diameter, i.e., the maximum pairwise distance, is D hops. After D iterations of operation, each node in the network has constructed a BFST of the entire network rooted at it since nodes are timer driven and, thus, synchronized. This information can be used for any source routing protocol. The amount of information that each node broadcasts in an iteration is bounded by $O(|V|)$, and the algorithm converges in D iterations.

b) Neighborhood Trimming

The periodically broadcast routing messages in Network topology information based source routing protocol also double as “hello” messages for a node to identify which other nodes are its neighbors. When a neighbor is deemed lost, its contribution to the network connectivity should be removed; this process is called neighbor trimming. Consider node v. The neighbor trimming procedure is triggered at v about neighbor u either by the following cases:

1) No routing update or data packet has been received from this neighbor for a given period of time.

2) A data transmission to node u has failed, as reported by the link layer.

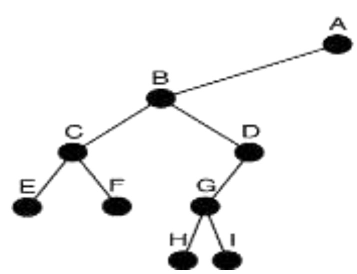

Fig. 1. Binary tree.

Node v responds by:
1) First, updating $N(v)$ with $N(v) - \{u\}$;
2) Then, constructing the union graph with the information
Of u removed, i.e.,

$$Gv = Sv \cup \_ \ w \in N(v)\ (Tw - v)$$

3) Finally, computing BFST Tv. Notice that Tv, which is thus calculated, is not broadcast Immediately to avoid excessive messaging. With this updated BFST at v, it is able to avoid sending data packets via lost neighbors. Thus, multiple neighbor trimming procedures may be triggered within one period.

III. Performance Evaluation

We study the performance of network topology information based source routing protocol using computer simulation with Network Simulator 2 version 2.34 (ns-2). We compare network topology information based source routing protocol against OLSR [7], DSDV [9], and DSR [8], which are three fundamentally different routing protocols in MANETs, with varying network densities and node mobility rates. We measure the data transportation capacity of these protocols supporting the Transmission Control Protocol (TCP) and the User Datagram Protocol (UDP) with different data flow deployment characteristics. Our tests show that the overhead of network topology information based source routing protocol is indeed only a fraction of that of the baseline protocols. Nevertheless, as it provides global routing information at such a small cost, PSR offers similar or even better data delivery performance. Here, we first describe how the experiment scenarios are configured and what measurements are collected. Then, we present and interpret the data collected from networks with heavy TCP flows and from those with light UDP streams.

A.TCP with Node Density

We first study the performance of PSR, OLSR, DSDV, and DSR in supporting 20 TCP flows in networks with different node densities. Specifically, with the default 250-m transmission range in ns-2, we deploy our 50-node network in a square space of varying side lengths that yield node densities of approximately 5, 6, 7, . . . , 12 neighbors per node. These nodes move following the random waypoint model with $v$max = 30 m/s. We plot in Fig. 2 the per-node per-second routing overhead, i.e., the amount of routing information transmitted by the routing agents measured in B/node/s, of the four protocols when they transport a large number of TCP flows. This figure shows

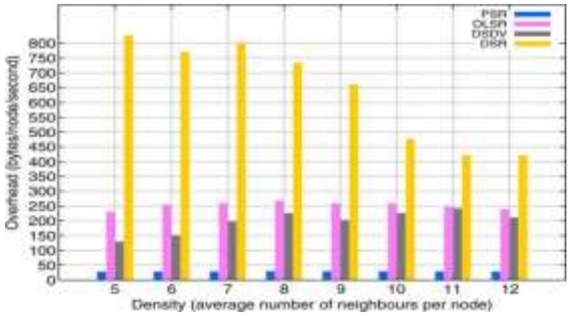

Fig. 2. Routing overhead with density.

that the overhead of PSR (20 to 30) is just a fraction of that of OLSR and DSDV (140 to 260) and more than an order of magnitude smaller than DSR (420 to 830). The routing overhead of PSR, OLSR, and DSDV goes up gradually as the node density increases. This is a typical behavior of proactive routing protocols in MANETs. These protocols usually use a fixed-time interval to schedule route exchanges. While the number of routing messages transmitted in the network is always constant for a given network, the size of such message is determined by the Node density.

Fig. 3 plots the TCP throughput of the four protocols for the same node density levels as before. The total throughput of the 20 TCP flows of PSR, OLSR, and DSDV is noticeably higher than that of DSR. In addition, while the TCP throughput of DSR decreases with node density, that for the other three are somewhat unaffected, hovering at around 500 kb/s. Apparently, the large routing overhead of DSR, particularly in dense networks, consumes a fair amount of channel bandwidth, leaving less room for data transportation. In most cases, PSR has the highest throughput because it needs to give up the least network resources for routing.

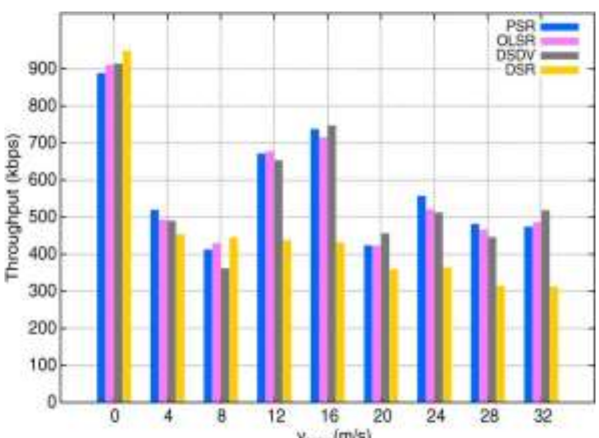

Fig. 5. TCP throughput with velocity

The network thus has an effective node density of around seven neighbors per node, i.e., a medium density among those configured earlier. As with before,

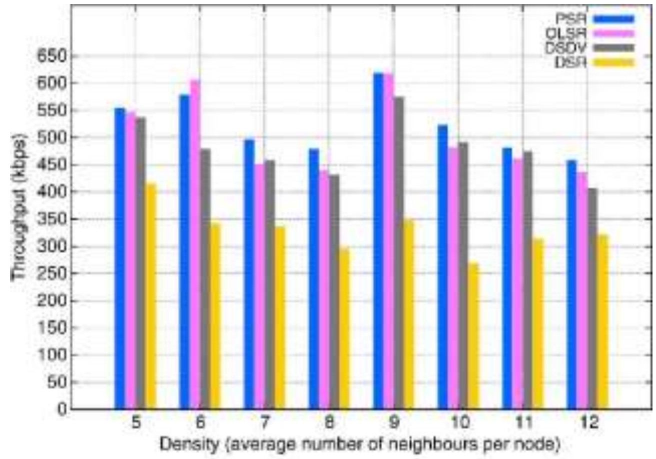

Fig. 3. TCP throughput with density.

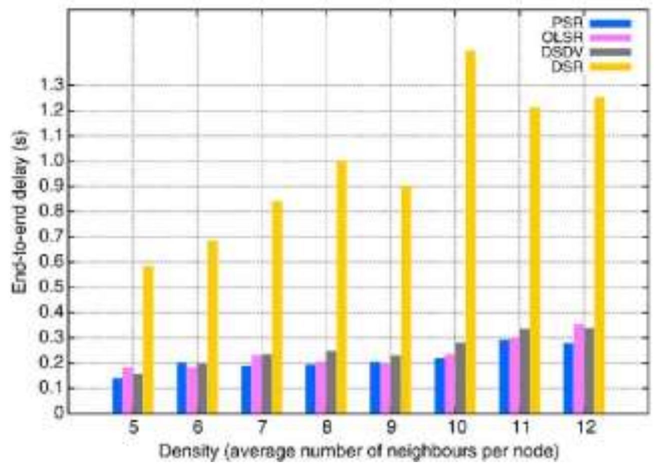

Fig. 4. End-to-end delay in TCP with density.

B.TCP with velocity

We also study the performance of network topology information based source routing protocol and compare it to OLSR, DSDV, and DSR with different rates of node velocity. In particular, we conduct another series of tests in networks of 50 nodes deployed in a 1100 × 1100 (m2) square area with *v*max set to 0, 4, 8, 12, . . . , 32 (m/s).

20 TCP one-way flows are deployed between 40 nodes, and we measure the routing overhead, TCP throughput, and end-to-end delay (see Figs. 5–7).

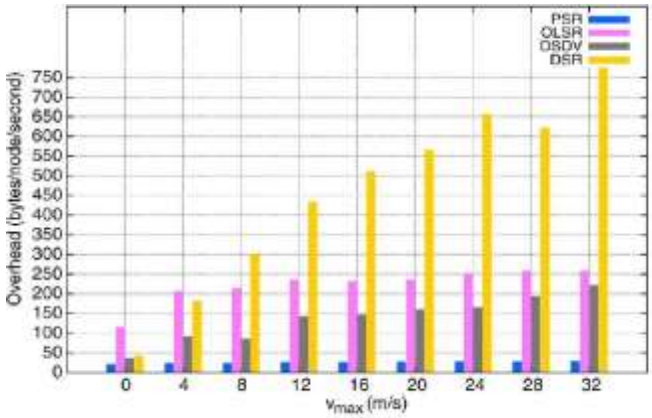

Fig. 6. Routing overhead with velocity.

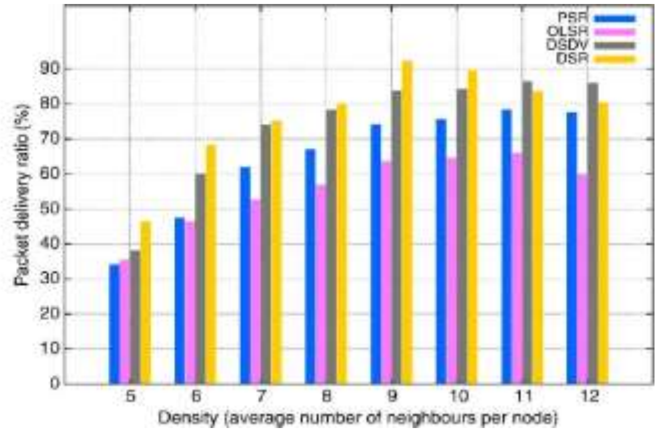

Fig. 7. End-to-end delay in TCP with velocity

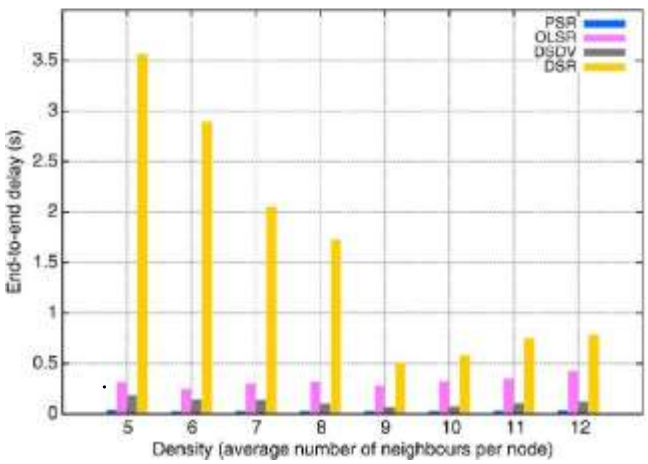

Fig. 8. PDR in UDP with density.

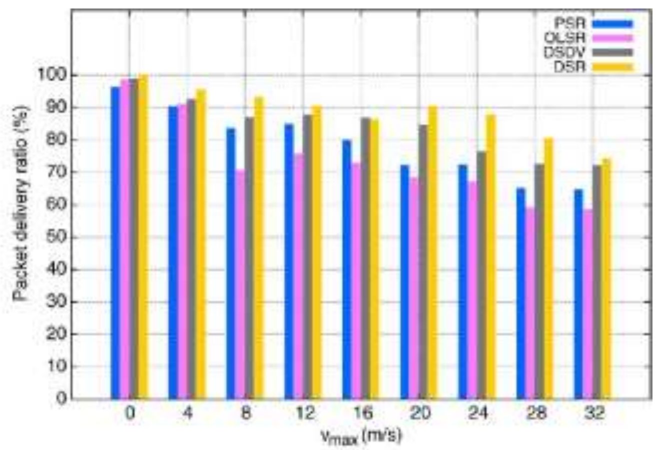

Fig. 10. End-to-end delay in UDP

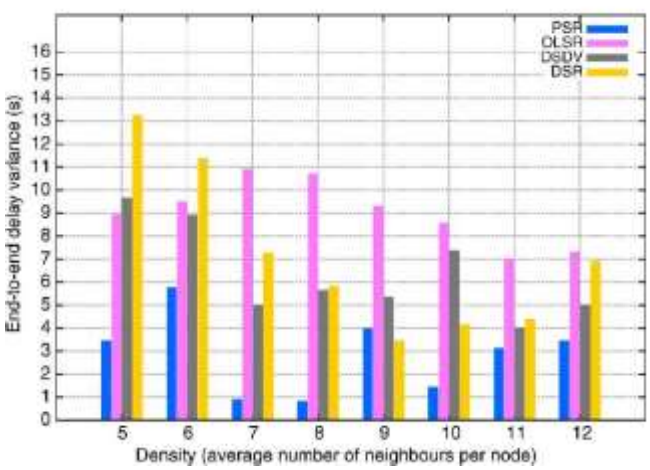

Fig. 9. End-to-end delay in UDP with density.

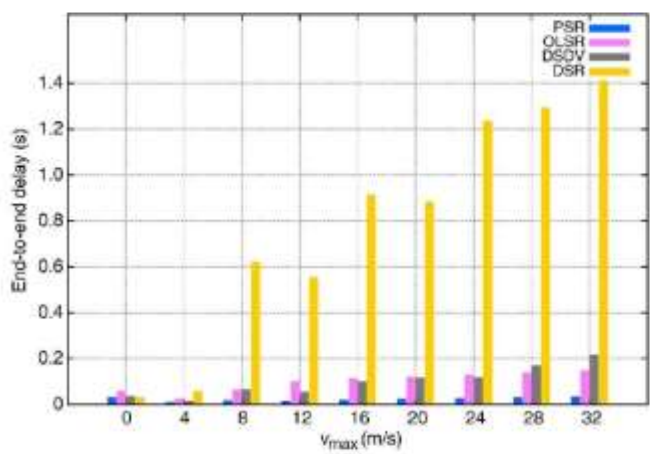

Fig. 11. End-to-end delay in UDP

C.UDP with density

We also tested the four protocols for their performance in transporting a small number of UDP streams. This is a typical assumption for ideal scenarios of reactive routing protocols. Here, we deploy three two-way UDP streams to simulate compressed voice communications. To find out about how node density affects these protocols, we use the same network and mobility configurations as in Section IV-B. We measure and plot the PDR (see Fig. 8), delay (see Fig. 9), and delay jitter (see Fig. 10) against varying node densities. In Fig. 8, the PDRs of all four protocols are in the same ball park across different node densities, with DSR slightly in the lead and OLSR trailing behind. This verifies that the traffic configuration is favorable for DSR. The relatively high loss rate of OLSR among the proactive routing protocols is caused by the higher routing overhead compared with PSR and DSDV.

When we turn to end-to-end delay (see Fig. 9), there is a noticeable difference between DSR and the proactive protocols. In particular, DSR as a reactive protocol has a rather large delay in sparse networks. This is because the long vulnerable routes discovered during the search procedure break frequently, forcing nodes to hold packets back for an extended period before new routes are identified. Conversely, the network sparsity does not affect proactive protocols as much because their periodic routing information exchange makes them more prepared for network structure alteration. While the delay of DSR is off the chart, that of PSR is always less than 0.05 s, which is also much less than that for DSDV and OLSR (0.1–0.43 s). On a related note, the delay jitter (see Fig. 10) of PSR is significantly lower than the other three. Note that voice-over-IP (VoIP) applications usually discard packets that arrive too late. Therefore, the jitter among the packets actually used by the VoIP receiving agent is much smaller. Nevertheless, our metric still reflects how consistent these protocols are in delivering best-effort packets.

IV. CONCLUSION

This paper has been motivated by the need to support opportunistic data forwarding in *MANETs*. To generalize the milestone work of ExOR for it to function in such networks, we needed a PSR protocol. Such a protocol should provide more topology information than DVs but must have significantly smaller overhead than LS routing protocols; even the MPR technique in OLSR would not suffice. Thus, we put forward a tree-based routing protocol, i.e., network topology information based source routing protocol, which is inspired by the PFA and the WRP. Its routing overhead per time unit per node is on the order of the number of the nodes in the network as with DSDV, but each node has the full-path information to reach all other nodes.

First, it uses only one type of message, i.e., the periodic route update, both to exchange routing information and as hello beacon messages. Second, rather than packaging a set of discrete tree edges in the routing messages, we package a converted binary tree to reduce the size of the payload by about a half. As a result, the routing overhead of PSR is only a fraction or less compared with DSDV, OLSR, and DSR, as evidenced by our experiments. Yet, it still has similar or better performance in transporting TCP and UDP data flows in mobile networks of different velocity rates and densities.

Although out of the scope of this paper, it would be an interesting exploration to allow intermediate nodes running DSR to modify the path carried by a source-routed packet for it to use its more updated knowledge to route data to the destination. This is in fact exactly what network topology information based source routing protocol does when we used it to carry source routed data in CORMAN. Granted, this opens up an array of security issues, which they are part of a vast research area.

Finally our tests using computer simulation in Network Simulator 2 (ns-2) indicate that the overhead in this protocol is only a fraction of the overhead of these baseline protocols, and this protocol yields better data transportation performance than these baseline protocols.

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