Cross-layer Multi-hop Wireless Routing for Inter-Vehicle Communication

Jatinder Pal Singh*, Nicholas Bambos†, Bhaskar Srinivasan‡, Detlef Clawin§
*Deutsche Telekom Laboratories
Ernst-Reuter-Platz 7, 10587 Berlin, Germany
Email: jatinder.singh@telekom.de
†Department of Electrical Engineering
350 Serra Mall, Stanford University, Stanford, CA 94305
Email: bambos@stanford.edu
‡Robert Bosch Corporation
Research and Technology Center, Palo Alto, CA 94304
Email: bhaskar.srinivasan@rtc.bosch.com
§Robert-Bosch-Strasse 200
Advanced Driver Information Technology, 31139 Hildesheim, Germany
Email: dclawin@de.adit-jv.com

***Abstract*— Ad-hoc networking provides a cost-effective support structure for inter-vehicle communication. A decentralized peer-to-peer information dissemination architecture is well suited for automotive applications that need to exchange data having local relevance. Routing, however, is challenge in a vehicular scenario because of the associated dynamism in network topology and variations in driving conditions. In this work we present a cross-layer ad-hoc routing approach based on link connectivity assessment in the network topology. We suggest a framework for proactive enhancements to the Optimized Link State Routing (OLSR) [1] protocol and implement the proposed measures within the protocol format. We further deploy an IEEE 802.11b based vehicular network and demonstrate the effectiveness of link-quality assessment based enhancements in improving the performance of inter-vehicle ad-hoc routing. Through actual test-runs, we show that the enhanced protocol is more responsive to variations in network connectivity and can take preemptive actions in choosing stable and durable routes. The routing methodology suggested in this work leverages cross-layer interactions among the networking, data-link, and physical layers, for enhanced adaptability to varying network topology and link states. The main contributions of this work are as follows: introduction of link-quality assessment methodology for enhanced adaptability of ad-hoc routing in a dynamically changing topology, delineation of the framework of a proactive topology-adaptive ad-hoc routing protocol in a vehicular scenario, and demonstration of effectiveness of the proposed routing enhancements in an IEEE 802.11b based vehicular test-bed.**

I. INTRODUCTION

Owing to the versatility of application and ease of deployment, ad-hoc networking has been a focus of active research for several years. The areas of scrutiny encompass routing protocols, security, power control, deployment proposals, etc. Conventionally the notion of ad-hoc networking has been associated with communication on combat fields and sites of disaster. However, with the emergence and economy of wireless technologies like IEEE 802.11, applications of ad-hoc networks have come to include office and home networking, self-organizing multi-hop wireless meshes, sensor networks, and inter-vehicle communication.

Ad-hoc networking provides an attractive and cost-effective support for inter-vehicle communication [2], [3] based applications that need to exchange data having local relevance. Such vehicular applications target driving safety and convenience, and include dynamic traffic routing, navigation, entertainment, co-operative driving and platooning. Inter-vehicle communication support by 3G networks has been discussed in literature [4]. However, in a centralized network topology, the information has to propagate from a vehicle to a central base station and back from the base station to another vehicle. The centralized architecture is hence not very efficient for applications that distribute data only between groups of vehicles that are spatially close to each other.

There has been an increasing interest to investigate inter-vehicle communications based on ad-hoc networking [5], [6], [3]. The ongoing FleetNet [5] project aims at developing an ad-hoc network for data exchange between running vehicles and fixed gateways along the roadside. However, the project is at the proposal and demonstration stage and requires development of exclusive infrastructure (adaptation of UTRA TDD to ad-hoc mode). The unlicensed communication in the ISM bands provides a cost-effective solution for supporting applications based on vehicular communication. However, inter-vehicle ad-hoc networking is beset with challenges associated with varying vehicular traffic patterns, driving speeds, and driving scenarios. Although ad-hoc routing enhancements for better route selection and robustness to topology changes with mobility have been discussed [7], the deployment and demonstration of multi-hop routing in inter-vehicle scenario has not received its fair share of attention. Some exiting work in this regard includes position-aware routing within FleetNet infrastructure [5]. Our earlier efforts in assessment of the performance and multi-hop routing in 802.11b based WLANs in vehicular scenarios include [6] and [8].

In a network of vehicles, the dissemination of critical information pertaining to driving safety and accidents mandates small routing delays. Hence, the proactive ad-hoc routing protocols offer an edge over the on-demand protocols. In addition, a link-state routing protocol which maintains a map of the complete topology at every node presents several advantages. Firstly, metrics other than shortest path can be better leveraged than distance vector routing protocols. Secondly, a link-state routing protocol has the advantages of enabling low delay route establishment for a multitude of communication scenarios of interest including multicast, unicast and broadcast. We in our work, thus consider a proactive OLSR implementation and discuss its adaptation to a dynamically changing vehicular scenario. The adaptation is based on the cross-layer interaction of the networking layer with the underlying physical and link layers.

This paper is organized as follows. We discuss existing work on ad-hoc routing protocols and measures for their adaptation to mobility in Section II. The operational dynamics of OLSR protocol are discussed in Section III. We then describe in Section V, link-connectivity assessment based routing enhancements and performance appraisal of OLSR in an IEEE 802.11b based vehicular test-bed. The work is concluded in Section VII and scope for further research is presented in Section VIII.

II. Related Work

Several ad-hoc routing protocols that have been proposed over the years include proactive table-driven protocols like OLSR [1], DSDV [9], and on-demand protocols like DSR [10], AODV [11]. The drawback and inadequacy in realization of network capacity by shortest path routing mechanism in these protocols has been discussed in [12]. In [13], an alternate metric for realization of high throughput in a multi-hop mesh network of stationary nodes is discussed. Likewise [14] presents a high-performance path metric for a network of stationary multi-radio nodes. However, in mobile scenarios, the throughput with this metric has been stated to be worse than shortest path.

The RABR [15] protocol, proposed and evaluated for a mobile ad-hoc scenario, utilizes link connectivity information for route selection, and is demonstrated to perform better than minimum hop-count protocols. Similar proactive route selection based on the projected lifetime of routes has been proposed and evaluated in [7]. Preemptive route maintenance measures for on-demand routing protocols have been presented in [16], [17] where the authors propose generation of preemptive warnings based on the drop of received signal power below a threshold. The FleetNet project employs position-aware routing and is targeting the development of dedicated wireless multi-hop ad-hoc networking infrastructure for inter-vehicle communication.

We, in our work, explore the utilization of standard off-the-shelf IEEE 802.11 compliant infrastructure and investigate efficient multi-hop routing in a vehicular scenario. Our approach does not require the development of any dedicated hardware, and the routing measures we propose can be used with any ad-hoc MAC protocol.

III. The Optimized Link State Routing Protocol (OLSR)

OLSR [1] is a table driven and proactive protocol which involves regular exchange of topology information among the nodes in a network. It employs designated nodes called Multi Point Relays (MPRs) to facilitate controlled flooding of topology information. MPRs are also the sole constituent nodes in the route between any source-destination pair in the network. As a link-state table-driven routing protocol, OSLR proves to be meritorious under ad-hoc network conditions wherein any node may want to initiate a communication session with the other in topology and termination of connections may also occur every now and then. In a vehicular scenario, for instance, communication may be need to be initiated between any two vehicles for an interactive connection or for transfer of data of interest. Also critical updates like accident notification may need to be dispensed from any vehicle in the network.

We next present the functional details of OLSR vital to its implementation. This will provide a background for the topology-adaptive enhancements to OLSR in the next section.

A. HELLO message Broadcast and Processing

Every OLSR node periodically broadcasts heartbeat HELLO messages, with information about its neighbors and the corresponding link states. A link state can be symmetric, asymmetric or MPR. A symmetric link is one that has been verified to be bi-directional. An symmetric link signifies that this node is hearing from the relevant neighbor but it is not confirmed that the neighbor is also hearing from this node. An MPR link state with a neighbor indicates that the neighbor has been selected by this node as an MPR. MPR links are also symmetric. The HELLO messages are broadcast to all one-hop neighbors, but are not relayed to nodes which are further away.

The neighbor table at a node comprises of entries pertaining to one-hop neighbors. Such an entry comprises of the neighbor address (N_{addr}), neighbor link status (N_{status}) and the list of two hop neighbors to which this neighbor provides symmetric access ($N2hoplist$). On receiving a HELLO message, a node creates or updates the neighbor entry corresponding to the node which sent the message. The N_{addr} field of this entry corresponds to the address of the sender. If the receiving node finds its own address among the neighbor addresses in the HELLO message, it sets or updates in the neighbor table, the status of the link to the sender node as symmetric link. The $N2hoplist$ for the sender node is updated based on the neighbor entries in HELLO message. Each such entry with link type symmetric or MPR is examined and is added to $N2hoplist$ if it does not already exist.

Based on the information obtained from the HELLO message, each node constructs its MPR Selector table. In this table, a node registers the addresses of those one-hop neighbor nodes that have selected the node as a multipoint relay. Upon receiving a HELLO message, if a node finds its own address in the address list with a link type of MPR, it creates or updates the entry corresponding to the sender node in MPR selector table.

B. Multipoint Relays

Each node in the network selects a set of nodes amongst its symmetrically-linked neighbors, that help in controlled flooding of broadcast messages. This set of nodes is called the Multipoint Relay set of the node. The neighbors of the node which are not in its MPR set, receive and process broadcast messages from the node, but do not retransmit them. MPR set is selected such that it covers all the nodes that are two hops away. The smaller its size, the more controlled is the flooding.

We next describe the algorithm for MPR selection. The MPR set of node x is represented by $MPR(x)$ and the neighborhood $N(x)$ denotes set of nodes that have a symmetric link to x. The algorithm begins with an empty $MPR(x)$. For all nodes y in $N(x)$, the degree $D(x,y)$ of y is evaluated. $D(x,y)$ is defined as the number of symmetric one-hop neighbors of node y, discounting the node x and also all the symmetric one hop neighbors of node x. For each node in $N(x)$, the number of nodes in two hop neighbor set of x (denoted by $N2(x)$) which are not yet covered by $MPR(x)$ but are reachable through this one hop neighbor, is calculated. The node in $N(x)$ which reaches the maximum number of uncovered nodes in $N2(x)$ is chosen as MPR. In case of a tie, the node whose $D(x,y)$ is greater, is selected as MPR. The MPR selection procedure is repeated as long as there exist nodes in $N2(x)$ that are not covered by $MPR(x)$.

C. Topology Control (TC) Message Broadcast and Processing

The TC messages are broadcast by a node in the network to declare its Multipoint Relay Selector Set (MPRSS). The MPRSS of a node x comprises of the nodes in $N(x)$, which have selected x as an MPR. A node obtains MPRSS information from periodic HELLO messages received from its neighbors. Each node in the network maintains a topology table, in which it records the information about network topology as obtained from the TC messages. An entry in the topology table contains information pertaining to the destination address (T_{dest}) and address of the last hop to the destination (T_{last}) . Each such entry signifies that node T_{dest} has selected node T_{last} as an MPR and that node T_{last} has announced this information through a TC message. On reception of a TC message at a node, the message is dropped if there exists a topology table entry whose T_{last} is the originator of TC message and whose sequence number is greater than the sequence number of the received message (higher sequence number denotes a more recent message). Otherwise, all entries in the topology table whose T_{last} corresponds to the originator address of the TC message and whose sequence number is lesser in value than that of the received message, are purged. Furthermore, for each MPR selector address received in this TC message, a new topology entry is recorded with T_{dest} as the MPR selector address and T_{last} as originator address of TC message.

D. Routing table calculation

Routing table is evaluated based on the connectivity information in the neighbor table and topology table. Shortest path algorithm is employed for route calculation [1]. Each resulting route entry consists of the destination entry R_{dest}, the next node from the sender R_{next}, and number of hops to the destination R_{dist}.

IV. TOPOLOGY-ADAPTIVE ROUTING FOR OLSR

The lack of an adequate mobility awareness framework in OLSR can potentially lead to several routing inefficiencies. We demonstrate these effects first in MRP selection process. Consider a node designated as node-0 in a network topology. Let this node have five one-hop neighbors numbered, without loss of generality, as 1 through 5. Let these one hop neighbors respectively provide connectivity to nodes {6,7,8}, {7,8}, {9,10}, {10,11}, and {12,6}, where nodes 6 through 12 are the two-hop neighbors of node-0. The neighbor table of node-0 will have entries for each of its one-hop neighbor, and each such entry will include a list of 2 hop neighbors that the neighbor provides reachability to. As the MPR selection highlighted in Sec. V-A is executed on the neighbor entries 1 through 5, nodes 1, 3, 4 and 5 will be selected as MPRs. We note that node-1 will be preferred over node-2 as MPR because it offers connectivity to 3 two-hop neighbors while node-1 offers connectivity to only 2 two-hop neighbors. However, it could be the case that node-1 is on the verge of breach of connectivity with node-0. Hence its selection as MPR is not an advisable choice. We reiterate that MPRs form intermediate nodes for routes to destinations and also do flooding of topology information. Hence loss of connectivity to an MPR can severely undermine network connectivity. In the described topology and mobility scenario, nodes-2, 3, 4 and 5 would constitute a better MPR set.

The routing table calculation mechanisms in OLSR can adversely affect the network connectivity. For instance, consider that in the above described scenario, node-4 is on the verge of breach of connectivity with node-0. During routing table evaluation at node-0, it is possible that the shortest path algorithm selects node-4 as the next hop to destination node-10. However, it would clearly be better to select node-3 as the next hop for providing connectivity to destination node-10.

It should be noted that in the above discussion we talk about connectivity between nodes as averaged over multipath and shadowing effects. The fast time scale of variation of connectivity due to these effects may render attempts towards adaptive routing infeasible. Moreover, measures like link-adaptation, equalization, power control, can be employed to mitigate affects of mutipath and shadowing.

OLSR can also suffer from inefficient routing and routing table instability. For instance, a neighbor may be on the verge of breach of connectivity due to reasons like increasing separation, fading channel, etc. If the reachability to such a neighbor is broadcast throughout the network, MPRs and routes will be evaluated based on this information. This can lead to data loss due to packet drops along the disconnected link. Again, the connectivity of a node to a neighbor may be oscillating. Consequently, the HELLO messages from this neighbor may only sporadically reach the node at which neighbor table is being maintained. Each neighbor entry has a timer associated with it. On expiry of this timer, the entry is purged, and the MPR selection and route evaluation is performed. On rediscovery of the neighbor, an entry is added to the neighbor table, and the topology and routing table calculation is repeated. The updated neighbor and topology information is then broadcast via HELLO and TC messages. The nodes receiving new information via these messages re-evaluate their topology and routing tables, and relay any changes in topology. Hence if a neighbor oscillates in connectivity, the broadcast of its reachability causes routing table oscillations in the network. This can lead to loss of data packets being routed through transient routes.

We thus see that OLSR performance can be adversely impacted by undesirable effects in MPR selection, route evaluation and stable routing table maintenance. To counter these drawbacks, we need a measure of link connectivity among the nodes in the topology and a mechanism to dispense this information in the network. A metric representing the projected time of link breakage has been suggested in [17]. However it is dependent on the radio propagation model employed in the work. For stationary nodes in a multi-hop mesh networks authors have employed metrics [13], [14] different from shortest path. To introduce link connectivity assessment based routing enhancements in a vehicular network, we introduce a metric called affinity [1]. The affinity between two nodes n and m, a_{nm}, is defined as the time after which node m is anticipated to move out of range of node n. We next describe the methodology for its evaluation. If every node in the network can maintain the history of averaged Signal to Noise Ratio values (SNR) to its neighbors, then average rate of change of SNR between node n and its neighbor m can evaluated as follows,

$$r_{nm,ave} = \frac{1}{N-1} \sum_{k=1}^{N-1} \frac{snr_{current} - snr_{(current-k)mod(N)}}{t_{current} - t_{(current-k)mod(N)}} \tag{1}$$

where $r_{nm,ave}$ is the rate of change of SNR, N is the size of a circular linked array snr that stores the averaged SNR values to neighbor m, and t_i is the time stamp array associated with corresponding entry i in array snr. The affinity a_{nm} can then be calculated as,

$$a_{nm} = \begin{cases} high & \text{if } r_{nm,ave} > 0 \\ \frac{snr_{current} - snr_{thresh}}{|r_{nm,ave}|} & \text{otherwise} \end{cases} \tag{2}$$

where snr_{thresh} is the threshold signal below which link l_{nm} is assumed to be disconnected. The affinity is labeled as *high* when the average rate of change of SNR is positive, which implies that nodes n and m are approaching each other. On the other hand, when average rate of change of SNR is negative, affinity is calculated as the projected time after which node n is anticipated to move out of range of node m.

V. LINK CONNECTIVITY ASSESSMENT BASED ENHANCEMENTS FOR OLSR

Based on the affinity estimation procedure highlighted in the previous section, we now proceed to discuss enhancements to OLSR protocol.

A. MPR Selection Algorithm

In OLSR operation under a dynamically changing topology, a node selected as an MPR may move out of the MPR selector, thereby rendering a number of routes stale. In the transient period when route rectification is being done, packets will be lost for the data being routed. Therefore, it is desirable to come up with a metric for MPR selection at node x, that not only considers the two hop connectivity of candidate nodes in $N(x)$, but also gives preference to their affinity with x.

An affinity based algorithm that targets to alleviate the drawbacks of MPR selection process in OLSR is proposed herewith. As in Sec. V-A, the selection algorithm starts with an empty set $MPR(x)$, and then iterates over the following procedure. If there exist some nodes in $N2(x)$ that are not provided connectivity by $MPR(x)$, then for each neighbor n in $N(x)$, the number of nodes in $N2(x)$ which are not yet covered by $MPR(x)$ and are reachable through this one hop neighbor, is evaluated. This number is designated as $n.neighbor2nocov$. The procedure highlighted via Algorithm 1 is then executed. The MPR selection process is repeated until $MPR(x)$ set is able to fully provide connectivity to all nodes in $N2(x)$.

In Algorithm 1, all the nodes n in $N(x)$ are scanned for eligibility as MPR. If a node n is encountered which has $high$ affinity to x and has $neighbor2nocov$ value greater than a threshold, then it is rightaway selected as an MPR. This gives preferential treatment for MPR selection to nodes which are moving closer to x and have more than a critical coverage. The value of the threshold $COVthresh$ can be decided empirically depending on the network density. If however, such a high-affinity node does not exist, then the node n in $N(x)$ which has the maximum of the product of affinity and $neighbor2nocov$ value is selected as the MPR. The affinity is evaluated as the rate of change of SNR for nodes moving away from x and is assigned a value of $Haffinity$ for the nodes approaching x. $Haffinity$ evaluation is described in Algorithm 2. If there exist some nodes in $N(x)$ which are receding away from x, $Haffinity$ is set to slightly higher than the maximum of their affinities. By virtue of this assignment, Algorithm 1 gives preference for MPR selection to the nodes approaching x. On the other hand, if none of nodes in $N(x)$ are receding away from x, $Haffinity$ is set to the value $high$. This characterization of affinity is subjective and $high$ can be set to any value not realizable, in a general scenario, by the

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[1] The concept of affinity was proposed by the first author jointly with Sulabh Agarwal, Ashish Ahuja, and Rajiv Shorey in [15]

```
output: MPR returned by mpr_candidate
max ⟵ 0;
for $n \in N(x)$ do
    if n.affinity is high then
        if n.neighbor2nocov $\geq$ COVthresh then
            mpr_candidate ⟵ n;
            break;
        else
            if n.neighbor2nocov $\times$ Haffinity $>$ max then
                max ⟵ n.neighbor2nocov $\times$ Haffinity;
                mpr_candidate ⟵ n;
            end
        end
    else
        if n.neighbor2nocov $\times$ n.affinity $>$ max then
            max ⟵ n.neighbor2nocov $\times$ n.affinity;
            mpr_candidate ⟵ n;
        end
    end
end
```

Algorithm 1: MPR Selection Algorithm with affinity ehancements

```
Nh(x) ⟵ {n $\in$ N(x), n.affinity is high};
Nl(x) ⟵ N(x) - Nh(x);
$\epsilon$ ⟵ $0^+$;
if Nl(x) is empty then
    Haffinity ⟵ high;
else
    Haffinity ⟵ $\max_{n \in Nl(x)}\{n.affinity\}$ + $\epsilon$;
end
```

***Algorithm 2**: $Haffinity$ evaluation*

rate of change of SNR for nodes moving away from x. The MPR selection algorithm is not impacted by the chosen value since the only case in which this value of $Haffinity$ is used is when all nodes in $N(x)$ are approaching x. With all nodes in $N(x)$ approaching x (and therefore $Haffinity$ set to $high$) the choice of node offering the maximum product of $Haffinity$ and $neighbor2nocov$ does not depend on the specific value assigned to $high$.

B. Route Selection Algorithm

In routing table evaluation [1] via shortest path algorithm, OLSR disregards alternate available routes having the same path length. However such routes to a destination may be a better in terms of anticipated time after which they are likely to break. Consider a route with weakest link affinity a_{min}. This route is expected be useful until the time the weakest link in the route breaks: this time is the same as a_{min}. A route with same number of hops but a greater value of a_{min} is thus better than another with lesser value of minimum link affinity [15].

We now discuss some affinity based route selection enhancements to OLSR. At the time of evaluation [1] of routing table from the neighbor table and topology table, it is possible that topology table provides an alternate route ($R2$) to some destination which is already entered in the routing table and recorded as reachable via route $R1$ through equal number of hops as $R2$. In such an event OLSR disregards the new route $R2$. However the alternate route may provide longer lasting connectivity to the destination in question. Let $R.affinity$ and $R.SNR_a$ denote the minimum of affinities amongst the hops in route R and the most recent SNR observation for minimum affinity hop. We then select $R2$ over the currently recorded route $R1$ in the routing table, if

- R2.affinity is *high* and R1.affinity is not *high*, or
- R2.affinty and R1.affinity are both *high*, but $R2.SNR_a > R1.SNR_a$, or
- R2.affinity and R1.affinity are both not *high* and $R2.SNR_a > R1.SNR_a$

It can be seen that the enhanced route algorithm selects the route that provisions a higher minimum affinity and/or SNR along its hops to the destination.

C. Neighbor classification for improved performance and stability

For stability in topology and routing tables of the nodes in the network, we propose a classification of neighbors based on average SNR measurements. We define two upper and lower SNR threshold levels, SNR_U and SNR_L. The connectivity to a neighbor can be assumed to be on the verge of breach if the SNR to this neighbor is below SNR_L value. On the other hand with SNR above the threshold SNR_U, the neighbors can be taken to be fairly strongly connected. The threshold levels can be empirically evaluated depending on the topology and routing scenario.

When a node is initially detected via a HELLO message it is entered in the neighbor table. We categorize it as $usable$ if the SNR to this neighbor is found to be above SNR_U and $unusable$ otherwise. Once a neighbor is categorized as $usable$ it is not rendered $unusable$ until the SNR to this neighbor falls below SNR_L. Whenever a message is received from a node categorized as $unusable$, the node status is set to $usable$ if the SNR to this node is found to be greater than the average of upper and lower SNR thresholds.

All protocol operations related to a neighbor in OLSR without affinity based classification, apply to a $usable$ neighbor. On the other hand, while an $unusable$ node is not deleted from the neighbor table, it is not broadcast to other nodes in the HELLO message and is not selected as an MPR. When any message is received from a neighbor that is classified as $unusable$, the message is not processed. Also such a neighbor is not considered during routing table calculation.

The above neighbor classification policy has various merits. By not using a weakly connected node in routing table calculation, the risk of sending data packets to a neighbor to which SNR is below some lower threshold, and having them dropped, is avoided. Such a neighbor is not made known to the topology as being connected to the node, so that routes are not formed that pass through the link between the node and this weakly connected neighbor. Again, control and overhead information from this weakly connected neighbor is not processed. This prevents calculation of routes passing through a weak link and this information being dispensed to other nodes in the network.

VI. OLSR OPERATION WITH AFFINITY BASED ENHANCEMENTS: THE SBRS-OLSR PROTOCOL

We introduce operational modifications in OLSR to incorporate affinity-based enhancements discussed in the previous section. A node running the enhanced protocol measures the average SNR to all its neighbors and dispenses this information via HELLO messages. On receiving a HELLO message, the SNR to the neighbor entries is parsed and stored in the neighbor table. Similarly, each MPRSS entry in a TC message is made to incorporate the affinity and most recent SNR value. When a TC message is processed, the affinity and SNR information is stored in the topology table. Furthermore, the routing table entries now contain $affinity$ and SNR_a parameters which respectively denote the minimum affinity along a route and the corresponding SNR value. These quantities are ascertained when the routing table is evaluated from the neighbor and topology tables. The average SNR values for the snr array in (2) are evaluated by averaging a sequence of SNR observations.

We call the protocol with these operational modifications as the SBRS-OLSR (Signal-strength-assessment Based Route Selection for OLSR) protocol. In the remainder of this section, we will discuss the performance appraisal of SBRS-OLSR.

A. *Evaluation Methodology and Test-bed Setup*

For the work in this paper, we choose OLSR protocol implementation [18] by INRIA as our basic framework. By introducing SNR measurement and affinity evaluation functionality, we implement the enhancements in the OLSR message formats (HELLO and TC messages), MPR selection procedures, routing-table evaluation and stable neighbor classification.

We evaluate the performance of SBRS-OLSR by deploying a test-bed comprising of a network of vehicles bearing laptops running Linux and equipped with ORiNOCO IEEE 802.11b WLAN cards. The tests are conducted in a parking lot (Fig. 1) which is surrounded by and located in between buildings and tree plantations. The range of connectivity of the wireless cards is enhanced by omni-directional antennae mounted on top of the vehicles. Amongst the nodes in the network, two are set up as UDP sender and receiver. The wireless cards are configured to operate in the ad-hoc mode. Netperf [19], a Hewlett-Packard software utility, is modified and used as a network performance assessment tool. Wireless MAC software utilities [20] for Linux are used to log the signal quality information at all nodes in the network with respect to the their neighbors. The UDP throughput, which is the bit reception rate at the receiver, is calculated on the basis of number packets received every second and is logged at the receiver end. Fig. 2 displays the employed equipment.

Fig. 1. Network Set-up for Multihop Routing Experiments. The receiver moves clockwise along the indicated trajectory

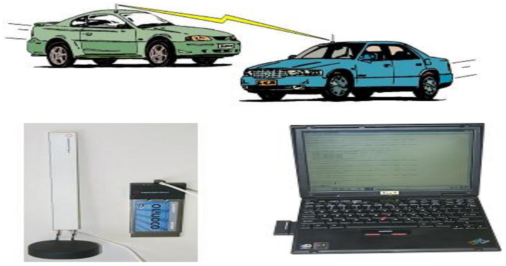

Fig. 2. Equipment for inter-vehicle communication: Vehicles with Laptops bearing 802.11b cards and Omnidirectional Antennae.

We deploy just as many nodes in the network that enable us to have sufficient control over experimentation and still permit the demonstration of routing effectiveness. A large fleet of mobile vehicles is not only hard to deploy but also raises issues of inadequacy in control over the environment. Our testbed comprises of four nodes: a stationary UDP sender, a mobile receiver and two stationary relays to aid routing of packets. Fig. 1 shows the arrangement of nodes in the network. The placement of the nodes and the trajectory is chosen such that the mobile node moves in and out of the range of UDP sender node. When the receiver is not within the reach of the sender, the other two stationary nodes (relay-1 and relay-2) aid multi-hop routing between them. We note that the scenario, though simple, is not simplistic. It permits a reasonably well evaluation of a routing protocol as the route between the sender and the receiver switches between one, two, and three hops.

The OLSR and SBRS-OLSR daemons are installed on each laptop in the network. Netperf is run on the sender and receiver nodes to send and receive UDP packets. During a test run, the receiver vehicle traverses the designated closed path in the topology. The observation log at each node includes records of the routing table and SNR of links with neighboring nodes. Furthermore, the number of received packets, the number of lost packets and the UDP throughput is logged at the receiver.

B. *SBRS-OLSR Performance Appraisal*

We next discuss the performance of SBRS-OLSR in the multi-hop experimentation test-bed. The packet size for the UDP stream is chosen to be 512 bytes. The thresholds SNR_U and SNR_L, as described in Section V-C, are taken as 14 dB and 5 dB respectively. The parameter $COVthresh$ in Sec. V-A is selected to be 2.

1) Adaptation to Mobility: We first present results demonstrating enhanced mobility adaptation in SBRS-OLSR. The network set up shown in Fig. 1 is deployed and test runs are performed each with OLSR and SBRS-OLSR protocols for a receiver vehicle speed of 5 miles per hour. The receiver being the mobile node in the network, the SNRs to each of the stationary nodes vary noticeably with time. The routing protocol performance can hence be judged effectively by observing the change of route from receiver to sender node with respect to SNR variation to other nodes. We evaluate the routing table variation from the routing table logs at the receiver node. The SNR values from the receiver to the other nodes are noted by parsing the SNR logs at the receiver.

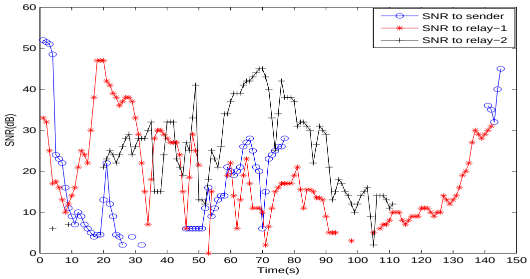

Fig. 3. SNR measured from the receiver

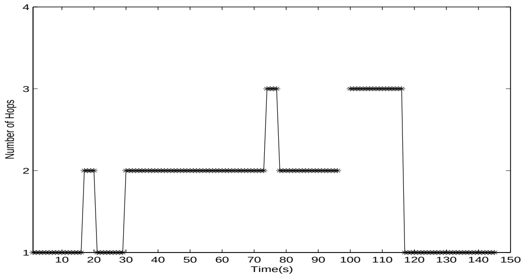

Fig. 4. Number of hops between receiver and sender for SBRS-OLSR

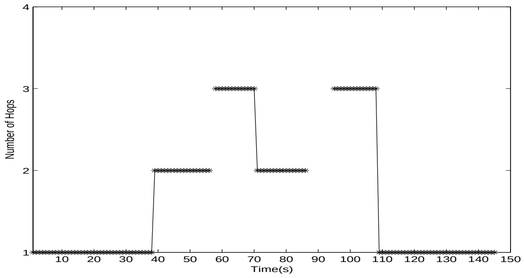

Fig. 5. Number of hops between receiver and sender for OLSR

TABLE I

RECEIVER TO SENDER ROUTE VARIATION WITH TIME, FOR SBRS-OLSR TEST RUN AT 5 MPH.

Time(s)	Next Hop	Number of Hops
1-15	Sender	1
16-19	Relay-1	2
20-28	Sender	1
29-58	Relay-1	2
59	Relay-2	2
60-65	Relay-1	2
66-70	Relay-2	2
71-72	Relay-1	2
73-76	Relay-2	2
76-78	Relay-1	2
79-89	Relay-2	2
90-96	Relay-1	2
97-116	Relay-2	3
117-144	Sender	1

TABLE II

RECEIVER TO SENDER ROUTE VARIATION WITH TIME, FOR OLSR TEST RUN AT 5 MPH.

Time(s)	Next Hop	Number of Hops
1-38	Sender	1
39-56	Relay-1	2
57-70	Ralay-2	2
71-93	Relay-1	2
94-107	Relay-2	3
108-145	Sender	1

The SNRs from the receiver to three stationary nodes and the number of hops in the route from the receiver to the sender are plotted versus time for a sample test run with SBRS-OLSR protocol in Figs. 3 and 4 respectively. Table I shows the next hop information for the route from receiver to the sender. The missing SNR values in Fig. 3 indicate loss of connectivity or unreliable data from the wireless utilities. For routing with OLSR, the variation in number of hops with time is plotted in Fig. 5 and Table II shows the corresponding next hop information.

Based on the obtained results, we compare the responsiveness of SBRS-OLSR and OLSR to SNR variations. The receiver mobility can be tracked from Fig. 1. The SBRS-OLSR test run begins with the mobile receiver starting from a location near the sender. There is a direct link from the sender to the receiver and transmission occurs along one hop (Fig. 4). At time t=16s, the running average of SNR from receiver to sender falls below SNR_L and the route changes to two hops passing through relay-1 as the intermediate node. At t=20s, as the average SNR to sender becomes significant and the sender becomes a usable node in receiver's neighbor table. Since lower hop count path is preferred in route-selection, the route changes to direct one hop. In the subsequent period, appropriate high-affinity relay is chosen as the next hop for the route to the sender node. This reflects the effect of enhancements discussed in Sections V-A and V-B. For instance consider the time after t=29s. At t=29s the connectivity to sender is almost lost (Fig. 3) and relay-1 is chosen as next hop for the route to the source node. Subsequently, the next hop from the receiver switches to relay-2 at certain times (Table I). Lets discuss one such switch at t = 66s. As can be seen from Fig. 3, the average SNR to relay-2 is increasing, so that the affinity of the receiver to relay-2 is high. On the other hand the SNR to relay-1 demonstrates a decreasing trend. Hence relay-2 is chosen as the next hop to the source node. Similar choice patterns can be observed at other instants of next hop switch.

At t=96s, the connectivity to relay-1 is lost and the sender is also not reachable. A three-hop route is then selected by SBRS-OLSR, with relay-2 being the next hop. As the sender node comes back in direct connectivity with the receiver, the route switches to single hop after t=117s. Because of the absence of reliable readings from the wireless utilities, the SNR values to the sender during this phase can be seen to be missing in Fig. 3.

The SBRS-OLSR protocol can be observed to be take preemptory actions based on mobility prediction. For instance at t=15s and 28s when the running average of SNR to the sender node falls below the SNR_L, the route switches to 2 hops. Similarly at t=66 when the average SNR to relay-1 is decreasing, SBRS-OLSR switches the route to pass through relay-2 with larger affinity.

For the OLSR test run at 5 miles per hour receiver speed, the route from the receiver to sender switches to 2 hops no earlier that t=38s, and no preemptive action is taken to render the sender node unusable (as in SBRS-OLSR) the SNR to which is falling. Eventually the sender moves out of range of the receiver node, and new route is calculated (at t=38s) when the neighbor table entry corresponding to the sender times out. During the course of route evaluation by OSLR, the switching of the route from one relay to the other relay as the next hop, occurs only upon loss of connectivity or expiration of timers of topology, neighbor or routing tables. Also, no preference is given to a better route when multiple routes with same hop length can be evaluated from topology information. For instance during the interval 71-93s, relay-1 remains as the next hop for the route from receiver to sender. No criterion (like affinity) is employed by OLSR to ascertain that the route through relay-2 may be a better one. Only when connectivity to relay-1 is lost, does the route switch to the one with relay-2 as the next hop. On the other hand, switches to better routes are more pronounced with SBRS-OLSR (Table I).

2) Throughput Performance: We next evaluate the throughput performance benefits of SBRS-OLRS. To demonstrate that the routing performance enhancement is not dependent on the location of the nodes in the network, we choose to present results for changed deployment positions of the UDP sender node and the relays. The receiver now spans a wider area of the parking lot, has a longer trajectory, and travels at a greater speed of 15 miles per hour. However, the relative orientation of the nodes, the testbed surroundings, and the receiver position at beginning of the test run is kept similar to the scenario shown in Fig. 1. Therefore, and as also confirmed by our gathered data, the throughput variation and the related statistical analysis presented in this subsection apply similarly to the test-runs discussed in the previous subsection.

Fig. 6 plots the typical throughput of OLSR and SBRS-OLSR as recorded during a test run. Four different throughput patterns can be observed in roughly divided time phases. A test round begins at t=1s, with the receiver node driving towards the sender location (clockwise in Fig. 1). In the first phase, a direct one-hop connection exists between the sender and the receiver nodes. This phase lasts roughly till t=27s when the receiver node reaches the location in vicinity of relay 1 node. From t=28s to t=61s (Phase II), the receiver node moves away from relay 1 node, towards relay 2 node. From t=62-71s (Phase III), the receiver node moves away from the relay-2 node deployment position. From t=72-75s, the receiver node drives into no-connectivity zone near the blind corner of a building (Fig. 1). After t=75s (Phase IV), direct connection is established between the sender and receiver.

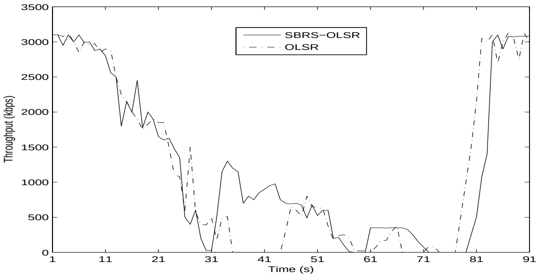

Fig. 6. Throughput variation for OLSR and SBRS-OLSR rounds

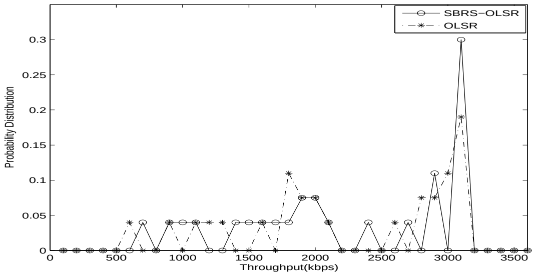

Fig. 7. Throughput distribution for phase I.

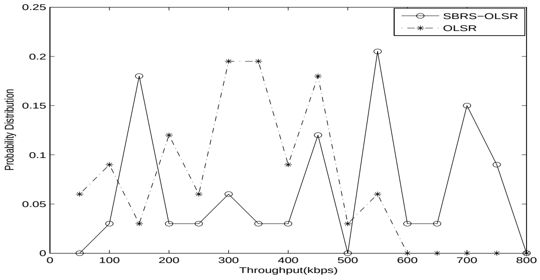

Fig. 8. Throughput distribution for phase II.

We choose the above described time phases to compare the throughput distribution of SBRS-OLSR and OLSR protocols. Figs. 7, 8, 9 and 10 show the probability distribution of the throughput in phases I, II, III and IV respectively over several test runs. In Fig. 11, we record the standard deviation of the average throughput for these test runs. During phase I

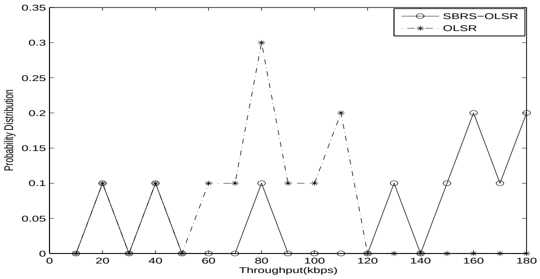

Fig. 9. Throughput distribution for phase III.

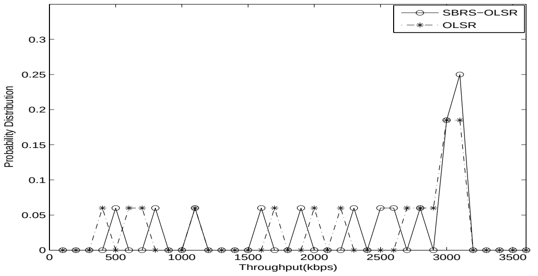

Fig. 10. Throughput distribution for phase IV.

there is a direct link from the sender node to the receiver node and communication occurs along one hop. Hence the throughput performance of SBRS-OLSR and OLSR can be seen to be similar in Fig. 7. As the receiver node moves further away from the sender node, throughput keeps dropping (Fig. 6) until when the relay-1 node is chosen as next hop for routing packets to the receiver node. During phase II, SNR from the receiver node to relay-2 node increases as the receiver approaches relay-2 (implying that the affinity of the receiver to relay-2 is *high*). On the other hand, SNR to relay-1 node decreases. The affinity based enhancements in SBRS-OLSR allow the route between the sender and receiver to adapt to changing network conditions and accordingly switch between relay-1 and relay-2 nodes as the intermediate hop. For the OLSR case, the throughput remains zero at a stretch during phase II. The protocol fails to take a preemptive action when the receiver is moving away from relay-1 node. The new route calculation at the sender node occurs only when the neighbor table entry for the receiver node at the relay-1 times out and this information is dispensed through the network. Furthermore, oscillations in routing tables cause the throughput to take a severe hit. On the other hand SBRS-OLSR proactively makes switches to a better relay as the next hop all along the phase duration. Therefore, in phase II, SBRS-OLSR shows much better probability of higher throughput (Fig. 8) than OLSR. Routing with SBSR-OLSR protocol achieves 50% throughput enhancement over OLSR from 316kbps to 463kbps. In phase III beginning at t=61s, the receiver connectivity to relay-1 node is lost and the sender node is also not reachable. A three-hop route from the sender to the receiver is hence selected by the routing protocols. Again SBRS-OLSR demonstrates performance improvement (Fig. 9) due to faster responsiveness to SNR variations. A 65% increase in throughput from 78 kbps to 127kbps is realized in phase III. Three hop routing continues until time t=71s when the receiver node drives into a blocked area without any connection to the rest of the network. After that, direct connection results between sender and receiver at t=75s (phase IV), and the throughput increases as the receiver node approaches the sender node. Due to single hop connectivity, SBRS-OLSR and OLSR shows similar performance (Fig. 10) in handling network traffic in phase IV. SBRS-OLSR is able to achieve a better uniformity in connectivity than OLSR. In Fig. 11, SBRS-OLSR can be seen to achieve with higher probability, lower standard deviation of average throughput.

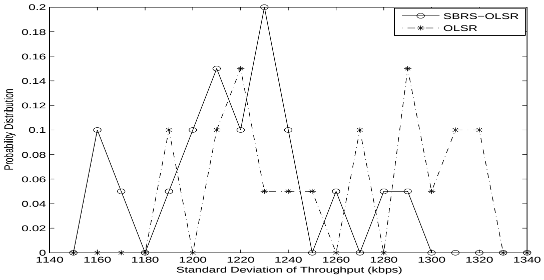

Fig. 11. Distribution of Standard Deviation of Throughput.

VII. CONCLUSION

We present a cross-layer ad-hoc routing approach based on link connectivity assessment in network topology and suggest a framework for proactive enhancements to the OLSR protocol. We further deploy an IEEE 802.11b based vehicular network and demonstrate the effectiveness of link-quality assessment based enhancements in improving the performance of inter-vehicle ad-hoc routing. Through actual test-runs, we show that the enhanced protocol is more responsive to variations in network connectivity and can take preemptive actions in choosing stable and durable routes. The enhanced protocol utilizes the benefits of cross-layer interaction amongst physical, data-link and network layers. We recommend SBRS-OLSR scheme for further consideration as a standard routing protocol for vehicular ad-hoc networks.

VIII. SCOPE FOR FURTHER RESEARCH

We are investigating the feasibility of deployment of a larger fleet of vehicles for assessing multi-hop routing performance. We also intend to conduct inter-vehicular communication experiments in dense networks, with higher mobility and diverse mobility patterns. It is also of interest to us to investigate and compare routing performance with different mobility-prediction metrics.

The merit of link-connectivity assessment measures for ad-hoc routing has been demonstrated for a simplified scenario with UDP traffic flow between two nodes. It would be worthwhile to explore the routing performance by having multiple

TCP and UDP flows in a dense fleet of vehicles. It would also be interesting to assess the performance of a real-time application running in the vehicular ad-hoc network while the vehicles drives through freeway, sub-urban and downtown traffic.

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REFERENCES

[1] T. Clausen and P. Jacquest, “Optimized link state routing protocol (OLSR),” RFC 3626, Oct. 2003.

[2] X. Lu, “Coordination layer control and decision making for automated ground vehicles,” in *Proc. American Control Conference*, 2002, pp. 3034–3039.

[3] J. P. Singh, N. Bambos, B. Srinivasan, and D. Clawin, “Wireless LAN performance under varied stress conditions in vehicular traffic scenarios,” in *Proc. IEEE Vehicular Technology Conference (VTC 2002)*, vol. 2, 2002, pp. 743–747.

[4] O. Andrisano and R. Verdone, “Intelligent transportation systems: The role of third-generation mobile radio networks,” *IEEE Communications Magazine*, vol. 38, no. 9, 2000.

[5] H. Hartenstein, B. Bochow, A. Ebner, M. Lott, M. Radimirsch, and D.Vollmer, “Position-aware ad hoc wireless networks for inter-vehicle communications: the fleetnet project,” in *Proc. 2nd ACM International Symposium on Mobile Ad-hoc Networking*, 2001, pp. 259–262.

[6] J. P. Singh, N. Bambos, B. Srinivasan, D. Clawin, and Y. Yan, “Proposal and demonstration of link connectivity assessment based enhancements to routing in mobile ad-hoc networks,” in *Proc. IEEE Vehicular Technology Conference (VTC 2003)*, vol. 5, 2003, pp. 2834–2838.

[7] Z. Cheng and W. B. Heinzelman, “Exploring long lifetime routing (LLR) in ad-hoc networks,” in *Proc. 7th ACM International Symposium on Modeling Analysis and Simulation of Wireless and Mobile Systems (MSWiM 2004)*, vol. 2, 2004, pp. 203–210.

[8] J. P. Singh, N. Bambos, B. Srinivasan, D. Clawin, and Y. Yan, “Empirical observations on wireless LAN performance in vehicular traffic scenarios and link connectivity based enhancements for multihop routing,” in *Proc. IEEE Wireless Communications and Networking Conference (WCNC 2005)*, vol. 3, 2005, pp. 1676–1682.

[9] C. E. Perkins and P. Bhagwat, “Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers,” *SIGCOMM Computer Communications Review*, vol. 24, no. 4, 1994.

[10] D. Johnson and D. Maltz, “Dynamic source routing in ad-hoc wireless networks,” IETF Draft, 1998.

[11] C. Perkins and E. Royer, “Ad-hoc on-demand distance vector (AODV) routing,” IETF Draft, 1998.

[12] D. S. J. D. Couto, D. Aguayo, B. A. Chambers, and R. Morris, “Performance of multi-hop wireless networks: shortest path is not enough,” *SIGCOMM Computer Communications Review*, vol. 33, no. 1, pp. 83–88, 2003.

[13] ——, “A high-throughput path metric for multi-hop wireless routing,” in *Proc. 9th Annual International Conference on Mobile Computing and Networking (MobiCom 2003)*, 2003, pp. 134–146.

[14] R. Draves, J. Padhye, and B. Zill, “Routing in multi-radio, multi-hop wireless mesh networks,” in *Proc. 10th Annual International Conference on Mobile Computing and Networking (MobiCom 2004)*, 2004, pp. 114–128.

[15] S. Agarwal, A. Ahuja, J. P. Singh, and R. Shorey, “Route-lifetime assessment based routing (RABR) protocol for mobile ad-hoc networks,” in *Proc. IEEE International Conference on Communications (ICC 2000)*, vol. 3, 2000, pp. 1697–1701.

[16] T. Goff, N. B. Abu-Ghazaleh, D. S. Pathak, and R. Kahvecioglu, “Preemptive routing in ad-hoc networks,” in *Proc. 7th Annual International Conference on Mobile Computing and Networking (MobiCom 2001)*, 2001, pp. 43–52.

[17] L. Qin and T. Kunz, “Pro-active route maintenance in DSR,” *SIGMOBILE Mobile Computing and Communications Review*, vol. 6, no. 3, pp. 79–89, 2002.

[18] OLSR: Optimized link state routing protocol. [Online]. Available: http://hipercom.inria.fr/olsr/

[19] Netperf. [Online]. Available: http://www.netperf.org/netperf/NetperfPage.html

[20] J. Tourrilhes. (1997) Wireless extensions for linux. [Online]. Available: http://www.hpl.hp.com/personal/Jean_Tourrilhes/Linux/Linux.Wireless.Ext%ensions.html