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Link State Routing in Regions of Interest

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Abstract—We present LVRI, a hybrid link-state routing protocol based on exchange of link states in a region of interest. The region of interest (ROI) is defined as a connected component of the network that includes the source, destination nodes and the nodes that act as relays for the data. An ROI is established on-demand and exists as long as there are data to be sent. Each node in the region of interest constructs a source-routing tree from proactive link state updates sent within the ROI and maintains paths to all the nodes in the ROI. Simulations in mobile scenarios show LVRI has much lower end-to-end delay compared to traditional proactive and on-demand protocols such as OLSR and AODV. The delivery ratio of LVRI is comparable to that of OLSR and AODV but with a significantly lower control overhead.

I. INTRODUCTION

Proactive protocols use destination driven flooding of link states in the entire network to maintain routes. OLSR [2] is a proactive link state protocol that disseminates complete topology information to all nodes in the network. STAR [5] is another proactive link state protocol that communicates link states in the preferred paths to all destinations. STAR requires all nodes to keep routing information for all destinations in a network, which does not scale well for large networks or in ad-hoc networks where the nodes have low battery life. On-demand routing protocols have been developed to reduce system-wide control broadcasts needed in proactive protocols. Examples are AODV [1] and DSR [4]. On-demand routing protocols use source-driven flooding of control messages to discover routes, which either give the source the complete path to destination as in DSR or provide next hops to destinations as in AODV. OLIVE [6] is an on-demand link-state protocol that uses path information from neighbors to generate partial network topology. None of these protocols scale well to networks with a large number of on-off flows.

This paper introduces the Link Vectors in Regions of Interest (LVRI) protocol for unicast routing. LVRI is the first routing protocol that uses link-state routing in regions of interest (ROI). An ROI is a connected component of the network that includes a source, a destination and the nodes that can serve as relays for the data traffic. LVRI is a hybrid protocol that uses on-demand signaling to establish ROIs and proactive signaling inside the ROIs for route maintenance. The ROIs are maintained as long as there are data to be sent to the destinations. A source node can join the ROI if it has data to

send to the destination and leave when it has no more data. In LVRI, link states are exchanged with neighbors only for those links that are inside the ROI. The nodes inside the ROI communicate their source trees (i.e. link states of links on preferred paths to destinations) with neighbors incrementally. Each node builds the topology graph of the ROI from its adjacent links and links from the source trees of its neighbors. Then it runs a local path-selection algorithm to generate its own source tree. All nodes in the ROI maintain paths to all the other nodes in the ROI. This reduces the route establishment delay. The control overhead of LVRI is significantly low due to confining the control messages in the ROI.

Section II presents LVRI. Section III describes the simulation results of LVRI and its comparison with OLSR and AODV. The results show that LVRI incurs considerable less network load and much shorter end-to-end delays than traditional on-demand and proactive routing, while maintaining similar packet delivery ratios.

II. LVRI DESCRIPTION

A. Overview

The network is modeled as a graph $G = (V, E)$ where V is the set of nodes in the network and E is the set of links between the nodes. Each link has a cost associated with it. The cost is set to infinity for a broken link.

LVRI discovers routes on-demand and maintains routes proactively. LVRI keeps the route maintenance overhead low by restricting the control messages to the region of interest that includes the source, destination and relay nodes.

When a node S has data to send to a destination D , it broadcasts a Mesh Request (MR) in the network. The MR orders the nodes with respect to S . When the MR reaches D , *existence bound (EB)* is set based on ordering of D with respect to S . Node D sends a Mesh Announcement (MA), which is limited broadcast using the EB and orders the nodes with respect to D . When the MA reaches S , it sets the *interest bound (IB)* based on the ordering of S with respect to D . The ROI is defined from the bounds. Once the ROI is set up, the subsequent periodic MA packet that originates at the node D , is relayed by each node of the ROI. The MA sent by a node A contains the link states of the source tree A uses to reach the destinations inside the ROI. MA packet also is used to determine and monitor link connectivity to a neighbor.

Once the ROI is set up, each node in the ROI maintains the topology of the ROI. The node runs a local path selection algorithm on the topology graph to generate its source tree which has paths to all other nodes in the ROI. Accordingly, nodes do not have to discover routes to other nodes in the ROI. For sources outside the ROI, the MR for path establishment can be answered by the first ROI node, which reduces the route establishment time.

In LVRI each link has a sequence number set by the sequence number of the most recent MA that contains the link. A node accepts a link state for a link if it has a higher sequence number than what is currently stored.

B. Information Stored at each node

A node A can be part of multiple ROI enclaves. Each ROI enclave corresponds to a source and destination pair, $\langle S, D \rangle$. For each of these $\langle S, D \rangle$ it maintains the ordering with respect to D , L_D^A , which is called the D-label. The node also maintains the ordering with respect to S , L_S^A , which is called the S-label, and the D-label reported by the label successor x , $L_{D,x}^A$. For enclaves sharing a destination, D , only one copy of the L_D^A and $L_{D,x}^A$ are stored.

The set of D-label successors, s_D^A , is different from the neighbor list, N_A . s_D^A stores only neighbors that satisfy the feasible D-label ordering and is a subset of N_A . The node sequence number, sn_D^A , is set from the last MA received at node A for D .

A node A inside an ROI maintains the *topology graph*, TG_A of the ROI, *source tree* ST_A and the *neighbor table* N_A . ST_A is a subset of TG_A . For each member B of N_A , A maintains the corresponding neighbor topology graph TG_B^A and neighbor source tree ST_B^A . ST_B^A is a subset of TG_B^A right after receiving a fresh neighbor update from B and before ST_B^A is rebuilt. After ST_B^A is rebuilt, TG_B^A and ST_B^A have the same links.

The information stored at each node for creating and maintaining ROI and storing the link states is summarized in Table I.

C. Information Exchanged between nodes

The two messages exchanged in LVRI are:

- Mesh Request (MR) which consists of $\{dst, src, req_id, L_D^{MR}, L_S^{MR}, L_D^S, L_S^D, ttl\}$. L_D^S is the interest bound for $\langle S, D \rangle$ and L_S^D is the existence bound for $\langle S, D \rangle$.
- Mesh Announcement (MA) which consists of $\{dst, src, sn_D^{MA}, L_D^{MA}, L_S^{MA}, L_D^S, L_S^D, \langle LSU \rangle\}$.

MR is sent on-demand for route establishment. MA is initially sent in response to an MR and then is sent periodically as updates. LVRI appends the link updates to the periodic MA messages. There is a frequent short MA update that includes a partial update of changed links in the source tree. The long MA update includes all the changes in the source tree and is sent at a longer interval. LVRI uses MA for the neighbor protocol to conserve bandwidth.

TABLE I
LVRI NOTATION

s_D^i	Set of label successors for destination D at node i
sn_D^i	Destination sequence number at node i
L_D^i	The label stored for destination D at node i
L_S^i	The label stored for source S at node i
$L_{D,x}^i$	The label reported by label successor x for destination D known at node i
L_D^{msg}	D-label carried in msg (MR/MA)
L_S^{msg}	S-label carried in msg (MR/MA)
δ	Adjusted to allow for a hysteresis zone inside the enclave
N_i	Set of neighbors at node i
TG_i	Topology Graph at node i
TG_x^i	Topology Graph reported by neighbor x at node i
ST_i	Source Tree at node i
ST_x^i	Source Tree reported by neighbor x at node i
c_k^i	The cost of link (i, k)
sn_k^i	The sequence number of link (i, k)

The link-state update (LSU) for link (i, k) in MA is of the form $\{i, k, c_k^i, sn_k^i\}$ where c_k^i is the cost and sn_k^i is the sequence number of the link. The links that a node A uses to reach destinations inside the ROI constitute its source tree, ST_A . Each node inside the ROI sends its source tree to its neighbors. The node creates the topology graph of the ROI, TG_A , from the source trees of the neighbors and its adjacent links. LVRI runs a local route-selection algorithm (e.g., Dijkstra's Shortest Path First [3]) on TG_A to calculate the preferred routes at the node.

A node A discovers a new neighbor B when it receives the first MA from the B and adds it in N_A . Then A sends its entire source tree in the next update MA to B . If A does not hear an MA from B for several update MA intervals, it assumes B is down, removes it from the N_A , removes the link to B from TG_A and re-builds ST_A . The node A also assumes B is down if A receives a link layer notification of failure to deliver data packets or acknowledgements for data packets are not received after several network layer retransmissions.

D. LVRI Operation

1) *Processing Control Packets*: When a node receives an MR for destination D , it checks if it is acyclic and satisfies the ROI bounds, if available. If not, the node drops the MR. If the MR is accepted and the node has a route for D , it sends an MA with its source tree information to its neighbors.

If a node A receives an MA from neighbor B , it first adds B to N_A . If the neighbor is a new neighbor, A sends its entire source tree to node B in the next update MA. Node A adds each link (u, v) from the MA from B into the topology graphs TG_A and TG_B^A and generates ST_A and ST_B^A . The new link information is added only if the new sequence number is higher than the existing sequence number of the link. Every added link in ST_A is reported by A in the next update MA. For deleted links, the link is reported only if the neighbor or destination is unreachable.

Node A accepts a new D-label from an MA only if either one of the following two conditions are satisfied:

$$sn_D^{MA} > sn_D^A$$

$$sn_D^{MA} = sn_D^A \wedge L_D^{MA} < L_D^A$$

The ordering that maintains these conditions is called the feasible ordering.

2) *Sending Control Messages*: Node A sends an MA on a short or long timeout only if it is part of the ROI. The condition that determines if a node is part of an ROI is as follows:

$$L_D^A + L_S^A \leq \varepsilon$$

$$\varepsilon = \max\{L_D^A, L_S^A\} + \delta$$

The nodes that are one-hop from the ROI receive the MA but do not re-send it. These nodes form the *hysteresis zone* that maintain the ROI ordering. When a node moves, it gets assigned new labels by MA updates if it has a neighbor that is either in the ROI or in the hysteresis zone. The nodes in the ROI and hysteresis zone also reply to a new MR with the MA, which reduces the route establishment delay for new flows.

When node A sends an MA, L_D^{MA} and L_S^{MA} are set for each ROI of which node A is part. These are set equal to L_D^A and L_S^A for each ROI. Then it sets the sn_D^{MA} from sn_D^A and appends the LSUs.

Node A sends a short MA on a timeout only when at least one link is added, modified or deleted from ST_A . The short MA also includes links for a newly discovered destination. Deleted links are added in the MA only when the destination becomes unreachable as a result of link deletion. Otherwise, delete updates are implicit with the addition of new links. For a lost destination, all failed links to the destination are included. For a failed neighbor the deleted link to the neighbor is sent as an infinite cost link. The short MA is disseminated in the ROIs that have updated links. If a lot of ROI enclaves have updated links, a few are chosen for each short MA. A short MA also has a limit on the number of LSUs included. Any LSU that could not be included in the short MA due to size limit, is sent in the next short MA. The short MA is not sent if there are no changes in labels or link states.

In a long MA update sent from a node A , all the new and changed links in ST_A for all the ROIs are appended. The long MA originates in the destination on the expiry of a timer with a new sequence number. Then it is relayed by every node in the ROI and the relaying node updates the LSUs with its own source tree links. The link states at each node receiving the long MA are refreshed by the higher sequence number of the LSUs.

3) *Example*: Figure 1(a) shows an ad hoc network of 12 nodes and the S-label and D-labels of the nodes assigned by initial MR and MA exchanges for an ROI between S and D . In this example the S and D-labels are allocated based on the number of hops from S and D respectively. The initial MR and MA exchange also sets the EB and IB which are both 300 in this case. The bound of the ROI is set to $300 + \delta$, δ being 100. Therefore, a node A that satisfies $L_S^A + L_D^A \leq 400$

is defined to be part of the ROI. The ROI is the connected component of all such nodes as shown in figure 1(a). Let us assume the nodes have all converged to the same sequence number.

Figure 1(b) and figure 1(c) show the source trees at nodes A and C . Figure 1(d) shows the topology graph at node S . The topology graph is generated from the MAs that propagate inside the ROI and therefore it only includes links inside the ROI. Node S generates the source tree from this topology graph that gives shortest paths to all nodes in the ROI. Figure 1(e) shows the source tree at node S . Now let us assume that link (A, B) goes down. As a result, node A re-builds its source tree and sends it to its neighbors including S in the MA update. Figure 1(f) shows A 's new source tree without the (A, B) link. The subsequent source tree at node S is shown in figure 1(g). All nodes converge to the new topology with higher sequence number of the MA update.

III. PERFORMANCE EVALUATION

We present simulation results comparing LVRI with AODV and OLSR. AODV is an on-demand routing protocol and OLSR is a proactive routing protocol that are widely accepted as baselines for performance comparisons. LVRI being a hybrid protocol, it also helps us understand how the hybrid design compares with these other protocol design choices.

A. Metrics

The metrics used are end to end delay, delivery ratio and network load. End to end delay is the one-way delay between a source sending the packet and the destination receiving it. The delivery ratio is the ratio of number of packets received by the destinations to the number of packets sent by the sources. Network load is the control overhead per node.

B. Simulation parameters

The Qualnet simulator [7] has been used with IEEE 802.11 DCF as the MAC protocol at 2 Mbps bandwidth. Nodes are simulated in an area of 1800m x 1800m. The mean performance of several simulations with random seeds with 95% confidence interval has been reported.

Each flow is peer-to-peer constant bit rate (CBR). We used a random topology of nodes with mobility.

C. Increasing number of concurrent flows

For this scenario we use a topology with 100 nodes. The number of flows has been increased from 5 to 35. Each flow has a different set of source and destination nodes. The data sent by each source is 1000 packets of size 256 bytes. The data rate is 10 m/s. The mobility is 1-10 m/s with pause time of 10s. Figures 2(a)- 2(c) show the results for delay, delivery ratio and network load.

LVRI has lower end-to-end delay than OLSR at all network sizes. As the number of flows increases, LVRI shows lower delay than AODV. At 35 nodes the delay of LVRI is half of AODV and about 1/15th of OLSR. The delay of LVRI is low due to the region of interests. A route request can be answered

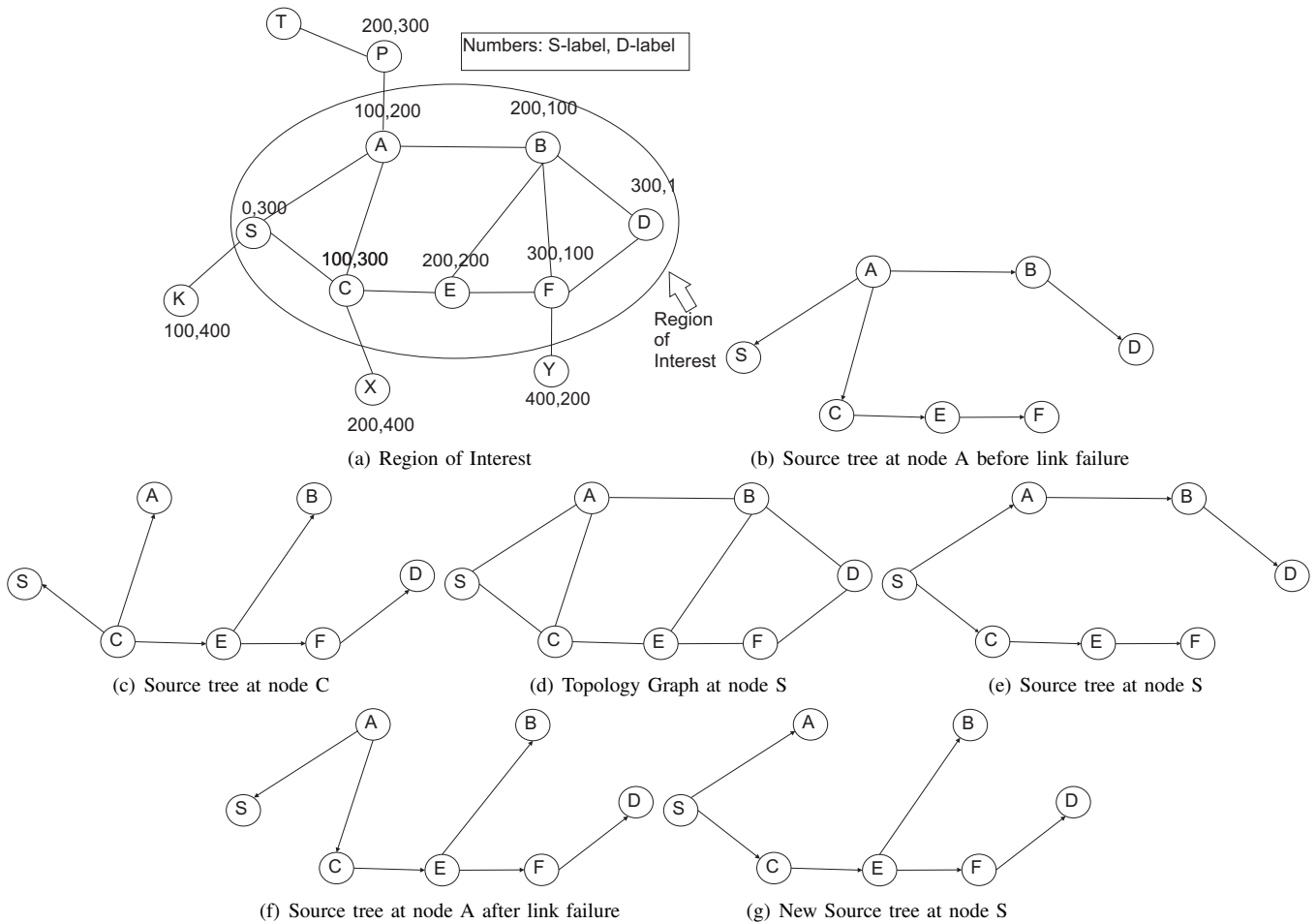


Fig. 1. Setup of the ROI and source trees

by any node in the ROI or hysteresis zone. Also every node has the topology of the entire ROI and constructs source trees with routes to every other node in ROI. This leads to fast route establishment. Use of labels for ordering ensures faster route repair using the label spacings. The delay for LVRI goes up initially with increase of number of flows because routes to new destinations have to be discovered. But as number of flows increases there is a higher probability that the destinations fall in the ROIs and the path to the destination is known. So the delay does not increase much with increase of number of flows. This is also seen on the network load graph of LVRI. The network load of LVRI is the lowest of all protocols and does not increase much with increase of flows. At 35 nodes the network load of OLSR is 2.5 times of LVRI and that of AODV is 20 times of LVRI! The delivery ratio of LVRI is comparable with OLSR at all number of flows and is the highest at 35 nodes.

AODV on the other hand has to discover routes for every new flow. As the number of flows increase, AODV interprets the loss of packets due to congestion as failed links and further congests the network with more and more route requests and replies. This can be observed in the network load graph

of AODV. OLSR being a proactive protocol, does not have much increase of network load with increase of number of flows. OLSR, however, has a consistently higher network load than LVRI since it maintains the topology information of the entire network. The resulting overhead congests the network at higher load, resulting in a higher delay and lower delivery ratio than LVRI. LVRI benefits from only having to maintain the topology information of a part of the network. The network load of OLSR is about 3 times of LVRI.

D. Increasing mobility

For this scenario, we used high data load and varied the mobility of the nodes. We used lots of flows which are on-off and uniformly distributed. Each node has a round-robin schedule of flows to every other node. From node n_1 , the flows look like: off, on to n_2 , off, on to n_3 , off, ..., off, on to n_N , with N being the number of nodes in the network. When the on period starts, the node finds a route and then it sends packets at a constant packet rate. Then the flow stays off for some time and starts a flow to a different node. In a network of N nodes, the number of concurrent flows is N and the total number of flows is N^2 .

The nodes are mobile with pause times of 0s (always mobile) to 300s. The number of nodes is constant at 50. Random way point mobility with speed of 1-20 m/s has been used. The high mobility is chosen to exercise the signaling due to frequent route breaks.

Figures 2(d)- 2(f) show the results for delay, delivery ratio and network load.

The end-to-end delay is high for all protocols due to the high mobility. The delay of LVRI is the lowest due to ROIs, topology information of ROI at each node and efficient local repairs. AODV has similar or slightly lower delay than OLSR at low mobility. But as mobility increases, AODV incurs considerable control overhead due to route re-establishment. This can be seen in the control overhead graph. At 0s pause time, AODV has the worst delay of the three protocols. LVRI has the lowest delay at all mobility values. At 0s pause time the delay of LVRI is 10% of AODV and 30% of OLSR. At 300s pause time the delay of LVRI is about 20% of AODV and OLSR.

LVRI has the lowest network load of the three protocols. The control overhead of LVRI is about 50% of AODV at 300s and about 2% of AODV at 0s pause time. It is also about 18% of OLSR. The delivery ratios of all the protocols are statistically equivalent at all mobility values. The delivery ratios of OLSR and LVRI stay more or less the same with increased mobility, but for AODV it falls with increase of mobility. This is due to increased network load with increase of mobility.

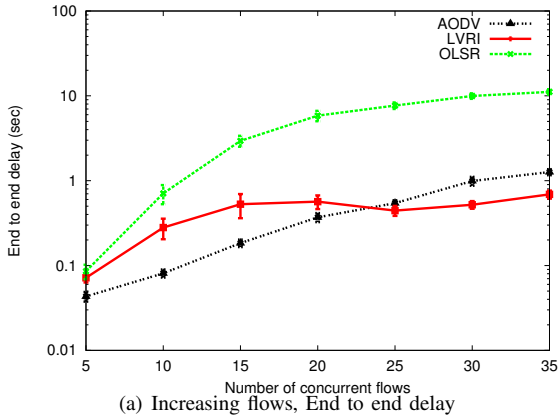
IV. CONCLUSION

We presented LVRI, the first hybrid link state routing protocol for mobile ad hoc networks. Qualnet simulations show LVRI has substantially less control overhead than OLSR and AODV. LVRI also performs better than OLSR and AODV in terms of end-to-end delays. LVRI achieves this by restricting the proactive link-state flooding to only parts of the network called the regions of interest. The regions of interest are created on-demand and maintained proactively. They are deleted when there is no interest in the destination by any of the sources. The link-state updates are appended to the proactive updates and thus all nodes in the region of interest have the topology information of the region of interest. The nodes use this information to calculate and maintain paths to all nodes in the region of interest. The low control overhead and low end-to-end delay of LVRI makes it a scalable routing scheme for mobile ad-hoc networks.

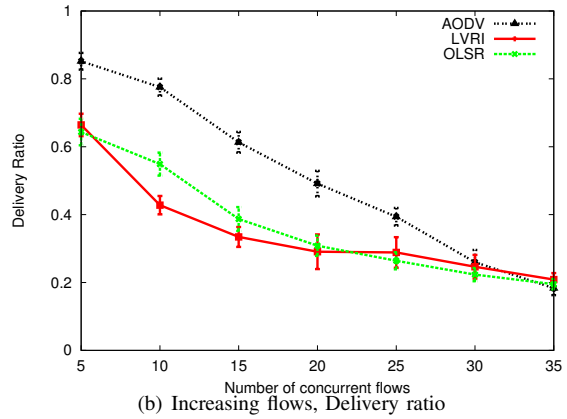
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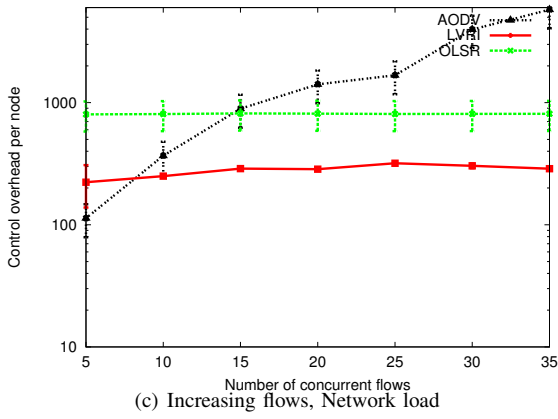
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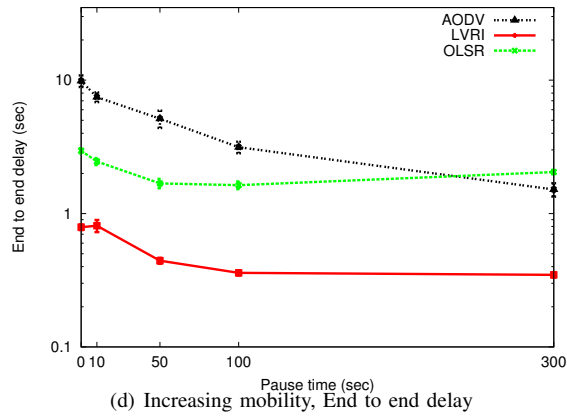
(a) Increasing flows, End to end delay



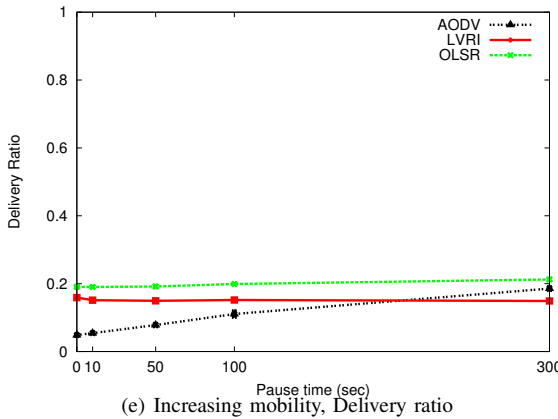
(b) Increasing flows, Delivery ratio



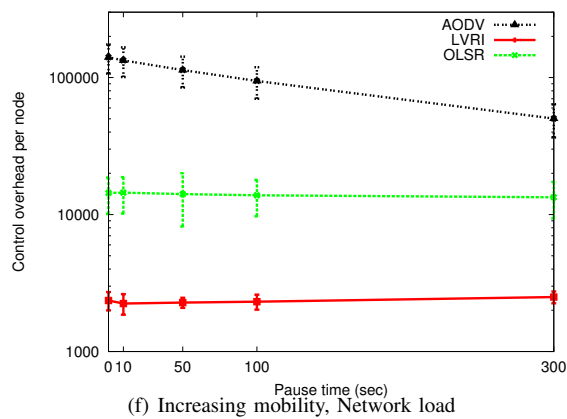
(c) Increasing flows, Network load



(d) Increasing mobility, End to end delay



(e) Increasing mobility, Delivery ratio



(f) Increasing mobility, Network load

Fig. 2. Performance of LVRI with increasing number of flows and increasing mobility