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An Interest-Driven Approach for Unicast Routing in MANETs with Labeled Paths and Proactive Path Maintenance

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***Abstract*—We present the Ordered Proactive Enclave-based Routing for Ad-hoc networks (OPERA) protocol for unicast routing in mobile ad hoc networks (MANETs). OPERA uses source and destination labels to define elliptical interest-driven enclaves to reduce control overhead. A topological sort of destination labels is used for loop freedom. The use of label spacing allows effective local repairs. Simulation results comparing OPERA with traditional routing schemes such as AODV and OLSR show that it has a better delivery ratio and smaller delay in realistic load situations. The network load with OPERA is much smaller than with the traditional on-demand and proactive routing schemes.**

I. Introduction

There have been several efforts to reduce the communication overhead of propagating the link-state or distance updates in multi-hop mobile ad-hoc networks (MANET). This includes cluster based approaches and location based approaches to restrict the control packet flooding by location information [15], [17]. Other schemes like the Fisheye state routing protocol [14] sends updates to remote destinations at a reduced rate. Protocols like EDIT [6] use hybrid routing using a region of interest to reduce the control overhead. The on-demand protocols obtain loop freedom through different schemes. DSR [10] uses source routing. AODV [2] uses distance labels (hop count). DYMO [11] uses distance labels and sequence numbers. Protocols like LDR [16] and DOS [7] use the successor feasibility conditions introduced by DUAL [1] to choose a next hop. LDR uses integer distance labels and a sequence number. DOS uses a topological sort using abstract node labels and maintains label spacing between nodes so it can perform localized route repairs through relabeling part of the path if possible.

The main contribution of this paper is to introduce the Ordered Proactive Enclave-based Routing for Ad-hoc networks (OPERA) protocol for unicast routing. Our work has been motivated by the performance gains of region of interest (ROI) based hybrid routing. OPERA is the first ROI based protocol that uses topological sorting of node labels instead of hop counts or distances to order nodes with respect to destinations. The advantage of using labels is that route repairs can be resolved quickly by inserting new nodes in the gap in the label spacings. Labels can also be set according to a QoS metric, enabling node ordering based on the QoS metric. This allows path selection according to cumulative values of the QoS metric. OPERA uses labels for route computation and for the definition of ROI.

The ROI for each source-destination pair is an elliptical enclave created on-demand and determined by the source labels in conjunction with the destination labels. It includes the source and unicast destination for which it has interest (traffic) as the foci and the nodes that can serve as relays of traffic. Proactive signaling is used inside an ROI to maintain the routes to the destination, until there is no interest in the destination any more. All the sources having interest in the destination join the region of interest. OPERA uses a graph labeling scheme with source and destination labels to order the nodes in the region of interest. Packets are routed towards nodes that are in order with respect to the destination label. This maintains loop-free paths and enables localized route repairs.

Section III presents the OPERA protocol. Section IV shows the simulation results of OPERA and comparison with OLSR and AODV. The results show that OPERA has better delay and delivery ratio at a fraction of the control overhead compared to traditional routing schemes like AODV and OLSR.

II. Related Work

The routing protocols for multi-hop mobile ad-hoc networks(MANET) can be classified as proactive or reactive. The proactive protocols that have attained the RFC status are OLSR [3] and TBRPF [9] both of which are link-state protocols. The on-demand routing protocols have been developed to reduce the systems wide control broadcasts of the proactive protocols. Examples are AODV, DSR, DYMO which are distance vector and TORA [12] which follows a link-reversal algorithm. All of these protocols are have RFC or Internet Draft status. Most on-demand protocols discover routes by route request (RREQ) floods in the network and unicast the route replies (RREP).

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Hybrid schemes that are combinations of proactive and on-demand routing are used to create a backbone to limit the route discovery overhead. ZRP [5] limits the proactive update to a node's local neighborhood defined as a zone. In NEST [13] table-driven routing is maintained for special destinations called netmarks which are points of attachment to the internet and therefore are more likely to have traffic from other nodes. The rest of the nodes maintain on-demand routing. The OPRAH [8] and EDIT [6] protocols reduce the signaling overhead by threshold based approaches. EDIT uses an elliptical region of interest with distance from source and destination as the two foci. OPRAH uses local broadcasts for all transmissions to establish and update a list of potential relays between the source and destination. It uses thresholds to restrict the flooding of messages and to ensure loop freedom. Directed Diffusion [4] for sensor networks proposes an interest-driven approach where directional flooding is used to set up a number of paths and data messages are sent along this paths redundantly. Later reinforcements based on path performance are used on some paths to reduce the number of possible paths.

The OPERA protocol combines the benefits of interest driven ROI based routing with loop free routing based on a topological sort of abstract node labels. Each node has a source and destination label and the elliptical region of interest is defined based on the source and destination labels of each node. None of the earlier ROI based protocols use labels for ROI defintion and loop freedom. The node label spacings help in insertion of new nodes that generate alternate routes used to cope with route failures.

III. OPERA Description

A. Protocol Description

OPERA defines *enclaves* or *regions of interest* as connected components of the network that include the source, destination and the relay nodes. There is one region of interest per destination. The nodes in the region of interest proactively maintain the path to the destination after it is setup as long as there is at least one active source interested in the destination.

OPERA uses the lexicographic ordering of labels of nodes in the path from each source to destination. If the source is *S* and the destination *D*, the label *L* of node *A* for the $< S, D >$ pair, has two components $\{L_D^A, L_S^A\}$. The nodes closer to the destination have smaller D-label, L_D^A, representing paths that are lexicographically smaller. The D-label is used to maintain the loop free paths. The S-label, L_S^A, increases along the path from the source to destination. L_D^A and L_S^A are both used for defining the region of interest. Node *A* can be part of multiple enclaves and therefore have multiple labels.

When a source *S* shows interest in a destination *D*, the route is setup on-demand by sending Mesh Request (MR). An elliptical region of interest is defined with the source, destination and relay nodes. *S* and *D* are the two foci of the ellipse. The routes to *D* are maintained proactively inside the region of interest by periodic Mesh Announcement (MA) updates sent by the destination and relayed by other nodes. The *existence bound* is set up from the S-label of *D* and *interest bound* is set up based on the D-label of *S* during the initial route establishment. Any other source *S´* that also wants to send data to *D* joins the region of interest by sending an MR which is answered by the first node within the region of interest that gets it. When the destination detects that any of the sources has stopped sending data, it stops the periodic update for that source. If a node doesn't fall in the enclave for the $< S, D >$, or hasn't received data or MA packet for *D* in the specified interval, it doesn't send or relay the update MA for the $< S, D >$ entry.

The MR is sent with a piggybacked data packet. The very first MR for a destination is broadcast network wide. The subsequent MRs are broadcast within the existence bound. If the first MR shows a persistent interest in the destination the enclave is created and the destination starts sending MA advertisements. MAs are limited broadcast within the region of interest. Data packets are transmitted in broadcast mode for low network load and in unicast mode (RTS-CTS-Data Pkt-Ack) to next hop nodes for high network load. The network load is determined by the contention at the MAC layer.

Each destination node sends proactive route updates with a new sequence number on expiry of a timer. For each $< S, D >$ pair it constructs a route update with the *existence bound, interest bound, destination label and source label* for the enclave and broadcasts it within the region of interest by setting the bounds. The node receiving this message updates its routing table with a new next hop if the sequence number is higher than its current sequence number or if the MA has a lower destination label than its current next hop. The update travels one-hop and each neighbor on receiving the update sends its own MA update. The source sends MR with a data packet on a periodic basis to refresh the S-labels at the intermediate nodes.

When a node moves, it gets assigned new labels by MA updates if it still is in the region of interest. The node chooses a node from its new one-hop neighbors with the lower D-label as its next hop and assigns its label accordingly. If *S* moves it gets a new next hop through the updates. If it doesn't get a new next hop, it gets a link failure. In that case *S* sends a new MR, gets a new D-label and re-assigns the bounds of the region of interest. The new bounds are propagated by the update MAs. If *D* moves and gets a link failure, it sends an update MA immediately. If it still has one enclave member as its neighbor, the D-labels re-adjust by the MA updates. The neighbor accepts the new D-label because it has a higher sequence number. If *D* moves further away, the updates from *D* are ignored by its one-hop neighbors because the enclave conditions don't satisfy. So *S* has to re-discover *D* by sending MR. If there is a change in bounds, it re-adjusts by updates.

If data is transmitted in broadcast mode, the route failures are detected by a mechanism of implicit acks where the sender hears the next hop retransmit the data packet. An absence of three consecutive implicit acks is detected as route failure and the node tries to re-establish the route by local repair. Local repair is done by sending a neighbor request MA to

TABLE I
NOTATION

s_D^A	Set of next hops for dest D at node A
sn_D^A	Destination sequence number at node A
L_D^A	The label stored for dest D at node A
L_S^A	The label stored for src S at node A
c_A^B	The cost of link from A to B
$L_{D,x}^A$	The label reported by next hop x for dest D known at node A
$L_{D,x}^{*A}$	Min value of $L_{D,x}^A$
L_D^{MR}	D-label carried in MR
L_S^{MR}	S-label carried in MR
L_D^{MA}	D-label carried in MA
L_S^{MA}	S-label carried in MA
k_D	Max spacing between D-labels
k_S	Max spacing between S-labels

its neighbors indicating the minimum D-label at the node and next hop as nil. The neighbor on receiving this, updates its route table and sends an MA if it has a route to *D* that satisfies the ordering conditions with the successor nodes. If the implicit acks do not detect the route failure, the new routes are discovered by the periodic MA updates with the higher sequence number.

The nodes are spaced in terms of destination labels so that the max number of nodes can be allowed to join in the path without a re-ordering which can serve as backup paths in case of route failures. The elliptical region of interest has been chosen as it has been shown by Sampath and Garcia-Luna-Aceves [6] to be more efficient than the conventional circular search region. The bound for the elliptic region of interest is calculated from the largest existence or interest bound and is propagated with the MA. The epsilon value of the elliptical enclave is varied to adjust the size of the enclave depending on the network congestion.

B. Information Stored and Exchanged between nodes

The information stored at each node and exchanged between nodes is shown in Table I.

The messages exchanged 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 $< S, D >$ and L_S^D is the existence Bound for $< S, D >$.
- Mesh Announcement, MA which consists of $\{dst, src, L_D^{MA}, L_S^{MA}, L_D^S, L_S^D\}$.

C. Conditions for Loop Freedom using Labels

Feasible Label Condition(FLC) A node A makes node B its successor on receiving an input event from B if either of these conditions are satisfied:

$$sn_D^B > sn_D^A$$
$$sn_D^B = sn_D^A \wedge L_{D,B}^A < L_D^{*A}$$

Minimum Label Condition(MLC) The label for *D* at node *A* never increases if the sn_D^A stays the same. If the node does not have a feasible successor that satisfies this, it should discover a new successor. The label can increase if the sequence number for *D* increases. If $sn_D^{'A}$ and $L_D^{'A}$ are the new sequence number and label then either one of the following is satisfied:

$$sn_D^{'A} > sn_D^A$$
$$sn_D^{'A} = sn_D^A \wedge L_D^{'A} \leq L_D^{*A}$$

Since the D-label never increases till it is reset with a higher sequence number, L_D^{*A} corresponds to the recent value of L_D^A. *Advertised Label Condition(ALC)* When a node transmits an advertisement *a*, it should make sure the following satisfies: $L_D^a > max\{L_{D,x}^A | x \in s_D^A\}$

D. Condition for Proactive Route Maintenance

Elliptic Enclave Condition(EEC) A node is a member of an Enclave if it satisfies the condition:

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

The δ parameter is adjusted to allow for a hysteresis zone of nodes inside the enclave.

E. Procedures

PROCEDURE 1 (NODE INITIALIZATION) The successor table s_D^A is empty at init. For each $< S, D >$ pair

$$s_D^A = \{\}, sn_D^A = 0$$
$$L_S^A = 0, L_D^A = L_D^{*A} = \infty$$
$$L_{S,x}^A = \infty, L_{D,x}^A = 0$$

If the *A* node reboots or loses the routing state for a destination *D*, it finds its new labels through the update MA from its neighbors following FLC and MLC. This ensures the new D-label with higher sequence number or D-label that is smaller than the older one if the sequence number is the same. So no loops are formed.

PROCEDURE 2 (INITIATING MR) A source node *S* initiates MR on demand the first time it has to send data to a destination *D*. Then it keeps sending MR on a periodic basis to continue showing interest in *D*. Once *S* does not have any more data to send to *D*, it stops sending the MR. The MR has *ttl* set from the existence bound when it is available.

The node sending MR sets

$$L_D^{MR} \leftarrow L_D^{*A}$$
$$L_S^{MR} \leftarrow L_S^A$$

PROCEDURE 3 (RECEIVE MR) The node *B* receiving the MR first checks if the MR is acyclic from the mr_id of the message. If not, it drops the MR. Otherwise it checks if it satisfies the existence bound if that is available. If not, it drops the packet. If *B* has a route to *D*, it might send MA as per Procedure 5. Else it relays the MR considering the *ttl* value in the MR. The D-labels are shared by all the nodes in the region of interest, so if there is another MR for the same $< S, D >$

which satisfies $L_D^B < L_D^{MR}$ then the second one is not relayed. The new sequence number of MR or MA is set as follows:

$$sn_D^{'MR} \leftarrow \begin{cases} sn_D^B & \text{if } sn_D^B > sn_D^{MR} \\ sn_D^{MR} & \text{otherwise} \end{cases}$$

PROCEDURE 4 (RELAY MR) If the MR is relayed by node *B*, the new labels are set as follows:

$$L_D^{'MR} \leftarrow \begin{cases} L_D^{*B} & \text{if } sn_D^B > sn_D^{MR} \\ min(L_D^{*B}, L_D^{MR}) & \text{if } sn_D^B = sn_D^{MR} \\ L_D^{MR} & \text{otherwise} \end{cases}$$

If $L_S^B \leq L_S^{MR}$ then set

$$L_S^{'B} \leftarrow L_S^{MR} + k_S$$
$$L_S^{MR} \leftarrow L_S^{'B}$$

PROCEDURE 5 (INITIATE MA) Case 1: A node *B* receiving MR can send MA if either one of the following are satisfied:

$$sn_D^{MR} < sn_D^B$$
$$sn_D^{MR} = sn_D^B \wedge L_D^{*B} < L_D^{MR}$$

If $L_S^B \leq L_S^{MR}$ then set new label $L_S^{'B} \leftarrow L_S^B + k_S$

Case 2: At the expiry of a timer, *D* sends out an MA for each active $< S, D >$ pair incrementing the sequence number sn_D^{MA} by 1.

Case 3: MA is also sent by a node *B* in the region of interest on receiving an update MA. This process sets the route at *B* as per procedure 6 before sending the new MA.

The new MA in all three cases has

$$L_S^{MA} \leftarrow L_S^{'B}$$
$$L_D^{MA} \leftarrow L_D^{'B}$$
$$sn_D^{MA} \leftarrow sn_D^B$$

PROCEDURE 6 (SET ROUTE) Node *A* sets or updates its route to *D* via successor *B* on receiving an MA. If the node *A* is *D*, it sets $L_D^A \leftarrow 1$, else it finds a value of k_D such that new label $L_D^{'A} \leftarrow max\{L_{D,x}^B, x \in s_D^A\} + k_D$ and $L_{D,x}^A < L_D^{'A} < L_D^{MR}, x \in s_D^A$

Node *A* sets the following:

$$s_D^A \leftarrow s_D^A \cup \{B\}$$
$$L_D^{*A} \leftarrow \begin{cases} min(L_D^{*A}, L_D^{'A}) & \text{if } sn_D^A = sn_D^{MA} \\ L_D^{'A} & \text{if } sn_D^A < sn_D^{MA} \end{cases}$$
$$sn_D^A \leftarrow sn_D^{MA}$$

PROCEDURE 7 (RECEIVE MA) The MA received by node *A* from node *B* is accepted if any of the two conditions below holds:

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

If the MA is accepted *B* is added to s_D^A. *A* also sets $L_{D,B}^A \leftarrow L_D^{MA}$ and $sn_D^A = sn_D^{MA}$.

A checks if EEC holds. If *A* lies in the region of interest it broadcasts a new MA as per Procedure 5. This ensures that MA is propagated within the region of interest and hysteresis zone outside it.

When *S* receives the MA for the MR it sent, it updates the existence bound, L_S^D from the MA and the interest bound, L_D^S from the value of L_D^{MA} as described above. After the initial route setup, *S* sends the interest and existence bounds in the periodic MR.

IV. EXAMPLE

Figure 1(a) shows the network for source *S* and destination *D*. Initially *S* does not have a route to *D*. So it broadcasts an MR with S-label of 0. The nodes *A*, *B*, *C*, *E*, *J* and *V* relay the MR and set their S-labels. In this example, for simplicity, we have assumed distance based labels with a default k-skip value of 100 for the label spacing. *D* sets its S-label and the existence bound (EB) to 300. Now *D* sets its D-label at 1 and does a limited broadcast of the MA with the EB of 300. Only the nodes that satisfy the EEC with δ value of k (*E, V, B, C, J, A*) rebroadcast the MA on receiving it. All the nodes that receive the MAs (*E, V, J, A, B, C, M, K* and *P*) set their D-labels according to the maximum feasible ordering. When the MA reaches *S*, it sets the D-label and interest bound(IB) to 300 and next hop to *B*. It also stores the next hop *A* in the routing table as an alternate path with D-label 400. The EB and IB define the enclave for $< S, D >$. The subsequent MAs are limited broadcast in this ROI. All the other nodes set the next hop to the node from which it receives a valid MA. For example, Node *B* sets next hop to node *E*. For node *A*, there are two possible next hops, nodes *C* and *J*, each with the same D-label 200. In this case, *A* selects *C* based on smaller node id and stores *J* in the routing table as alternate path.

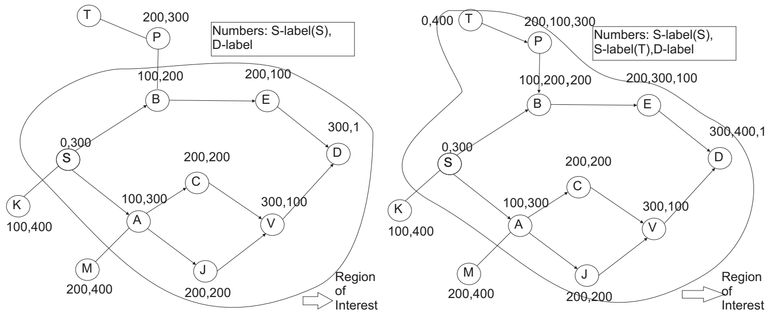
In Figure 1(b), a new source *T* wants to initiate a flow to *D*. *T* sends an MR that reaches node *P*. *P* is one hop away from the ROI and therefore has a D-label and a route to *D*. *P* sends an MA to *T*. The MR, which also has a data packet, travels along the route $B \rightarrow E \rightarrow D$ and sets the S-labels of these nodes. The enclave for $< T, D >$ is set as before. The ROI now has all the nodes of the two enclaves. All the nodes in the ROI have a path to *D*.

If the node *B* goes down, *S* finds the route through node *A* in its routing table and sets the D-label and interest bound to 400. When *B* comes back up, if *B* sends an update MA with the same sequence number as *A*, *S* sets *B* as the next hop again. But if *B* has a lower sequence number, *S* ignores the MA from *B* and continues to use *A* as a next hop till it receives an update MA from *B* with a higher sequence number than *A*.

For QoS routing, the labels could be derived from a QoS metric and a lexicographic ordering relation has to be defined based on the values of the metric. In that case the ROI would be based on the QoS metric.

V. PERFORMANCE EVALUATION

We present simulation results comparing OPERA with AODV and OLSR. AODV and OLSR have been selected



(a) Source S creates ROI

(b) Source T joins ROI

Fig. 1. Example showing OPERA ROI setup

because they are the standard baselines for performance comparisons.

The Qualnet simulator version 3.9.5 has been used for the simulations. We have IEEE 802.11 DCF as the MAC protocol at 2 Mbps bandwidth. Random way point mobility with pause time of 10s and speed of 1-10 m/s has been used. 100, 200 and 400 nodes have been simulated in an area of 1800m x 1800m. 10 simulations with random seeds have been run. The mean performance with 95% confidence interval, assuming a normal distribution, has been reported.

The metrics used are delivery ratio, end to end delay and network load. The delivery ratio is the ratio of number of CBR packets received by the destinations to the number of CBR packets sent by the sources. End to end delay is the one-way delay between the time a CBR source sending the packet and the destination receiving it. Network load is the per node control overload. For OPERA the control overload is the MR and MA packets. For AODV it is the RREQ, RREP and RERR and for OLSR it is the Hello and TC packets.

A. Increasing number of concurrent flows

In this test the size of the network is 100 nodes and the number of concurrent flows has been increased from 5 to 35. Each flow is between a different pair of source and destination nodes. Each source sends 1000 packets of size 256 bytes. The rate is 10 packets/sec. Up to 25 concurrent flows, AODV shows slightly better performance than the OPERA in terms of delivery ratio and end-to-end delay. At around 25 flows we see that AODV network load increases sharply and delivery ratio falls well below OPERA. The delay is more than OPERA at this load onwards. The performance of OPERA is much better than OLSR at all loads. The lower delay and delivery ratio of OPERA can be attributed to using elliptical region of interest and better local repair. The low network overload of OPERA shows the effect of using region of interest for limiting the propagation of control packets.

B. Increasing network size with exponential flows

In this experiment, CBR flows have exponential arrival times. The mean inter-arrival times for flows is 10 sec and mean flow duration is 200 sec which one-third of the simulation duration of 600 sec. At any instant we have about 20 CBR flows between different source and destination pairs. Each CBR flow generates 256 byte packets at 5 packets/sec. The network size is varied from 100 to 400 nodes while the concurrent load is kept more or less constant.

While OLSR has the lowest delivery ratio and highest delay at all network sizes, OPERA shows very little increase of delay and decrease of delivery ratio with increase of network size. although AODV shows a better performance for smaller network size, it shows a steep degradation at around 200 nodes. At 400 nodes it delivers about the half the packets that OPERA delivers. The network load graph shows a sharp increase in the network traffic for AODV at this network size. OPERA shows a lower end to end delay due to elliptical regions of interest and better local repair. The network load of the OPERA is the lowest due to use of the regions of interest.

VI. Conclusion

We presented OPERA which maintains a source and destination label at each node. The destination label is global across all sources that have interest in the destination. The source label is unique for each source. OPERA establishes loop-free routes based on the destination label and limits propagation of the proactive updates in the elliptical region of interest based on source and destination labels.

Qualnet simulations show that OPERA performs better than AODV and OLSR with increasing load and network sizes.

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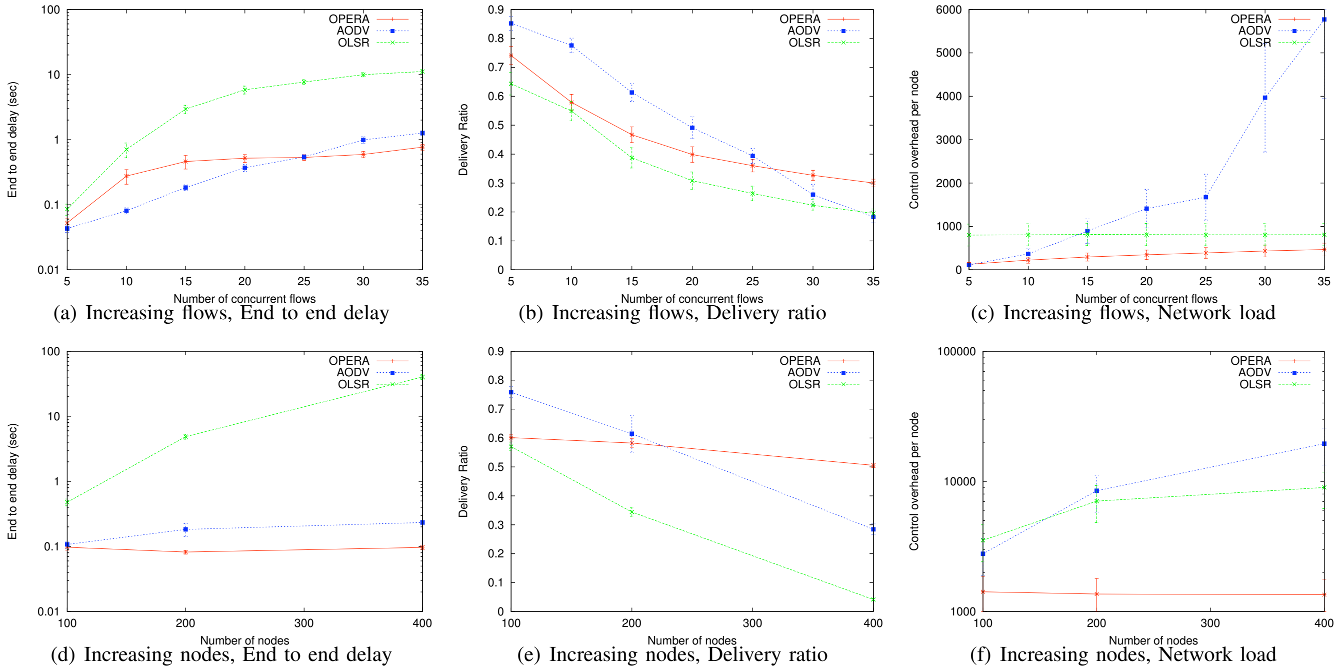

(a) Increasing flows, End to end delay
(b) Increasing flows, Delivery ratio
(c) Increasing flows, Network load
(d) Increasing nodes, End to end delay
(e) Increasing nodes, Delivery ratio
(f) Increasing nodes, Network load

Fig. 2. Performance with increasing number of flows and increasing number of nodes with exponential flows

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