Combining Cooperative Link Layer Protocols with Distributed Routing Protocols in Mobile Ad Hoc Networks – Perspectives and Performance Analysis

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***Abstract*— In cooperative link layer protocols the use of relay nodes may increase the capacity of the radio links. The study in this paper investigates what (if any) performance gain may be passed onto the routing protocol of a mobile ad hoc network. Two popular routing protocols are considered, AODV and OLSR, as each provides a unique route acquisition mechanism. A distributed procedure to choose the relay node at the link layer is combined with the two routing protocols. Analysis via simulation confirms some expected (and perhaps some other less expected) benefits when using a cooperative link layer protocol in place of a non-cooperative one, e.g., improved delivery ratio, end-to-end delay, and reduced signaling overhead.**

I. Introduction

Most routing protocols in wireless mesh networks use hop count as the metric to optimize when computing the route between two nodes. This often leads to a route built on many wireless links that are stretched, i.e., close to their maximum transmission range. Some of these links may become a potential bottleneck, as their low signal to noise ratio (SNR) values at the receiver may cause multiple retransmissions of the same data packet. In order to avoid such weak links, metrics other than hop count have been suggested [1], [2], e.g., expected number of transmissions (ETX) and expected transmission time (ETT). Incorporating these metrics into the existing routing protocols would require some modifications of the same, and is under investigation [3], [4].

In this paper, a different approach is investigated, which does not require any modification of the routing protocol. A cooperative medium access control (MAC) is used to mitigate the aforementioned drawbacks of poor route selection. The cooperative MAC is a variant of IEEE 802.11b, termed cooperation based relay aided (COBRA)[1] MAC [5]. In COBRA MAC, the sender makes the first attempt to send a data frame directly to the next hop destination. If the packet needs to be retransmitted due to low SNR at the destination, the retransmission is performed by a third node (relay), which is near by. The advantage of this procedure is to provide space diversity and therefore improve the delivery ratio of the packet to the destination. While other cooperative MAC protocols have been proposed in the literature [6], [7], [8], COBRA MAC is chosen in this study due to its unique characteristic. For example, it is the only cooperative MAC protocol reported so far to yield up to 20% throughput gain in (static) multi-hop networks [9], when compared to a non-cooperative MAC.

The rationale of the presented approach is that COBRA MAC may strenghten the quality of the wireless links chosen by the routing protocols. The routing protocol need not be involved with the relay selection, which is fully performed at the MAC layer. In turn, the increased quality of the links used by the route may improve the delivery ratio of both the data and control frames. The former may then be delivered more reliably across the route. The latter may offer more robust signaling to the routing protocol against unforeseeable fluctuations of the link quality due to both the node mobility and channel fading. A more robust signaling may facilitate the procedure of both computing and maintaining an active route.

Many routing protocols are available for wireless ad hoc networks. Examples are dynamic source routing (DSR), ad hoc on demand distance vector routing (AODV), destination sequenced distance vector routing (DSDV), and optimized link state routing (OLSR). While COBRA MAC can be adapted to work with any of these routing protocols, the study reported in this paper focuses on AODV and OLSR only, as they are widely used [10], [11]. AODV uses an (reactive) on-demand approach. OLSR uses a (proactive) table exchange approach in selecting the routes.

II. COBRA MAC Protocol

The COBRA MAC protocol is a variation of the IEEE 802.11b in ad hoc mode. When two nodes exchange (data and control) frames over one hop, other nodes within transmission range may overhear the ongoing frame transmissions. One of these nodes may act as a relay as shown in Fig. 1. The relay stores a copy of the received data frame and then senses the channel after a timeout RIFS (relay inter frame space) defined in [5]. If the channel is sensed free, the relay makes the assumption that the intended destination has not received the data frame successfully and retransmits the same frame. On the contrary, if the channel is sensed busy, it indicates that the destination is responding with a positive acknowledgement,

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[1]COBRA MAC was previously referred to as UTD MAC.

hence the local data frame copy at the relay is discarded. Since the relay sends the data frame through a statistically independent channel and it may be at a more vantage position, it increases the probability of successful reception at the destination. More details about the COBRA MAC are available in [5].

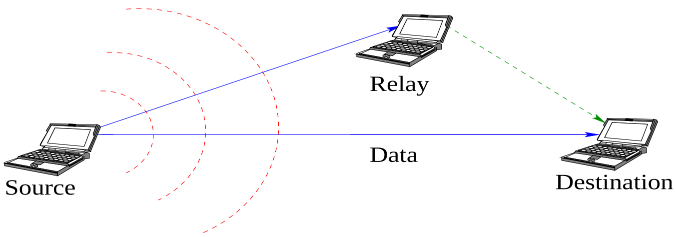

Fig. 1. Relay node cooperating in the unicast data frame transmission from source to destination.

It is possible to adopt COBRA MAC in the more general multi-hop case, by which packets are transmitted along a computed route to reach the end destination. Note that only unicast packets may be transmited with the help of a relay. On the other hand, broadcast packets (which may be required by the routing protocol to function properly) are transmitted without the help of any relay.

A. Relay Selection Algorithm

An essential function of the COBRA MAC is the selection of the relay to be used while transmitting a data frame over a given link. The following protocol is used to accomplish this task.

When a node receives a frame from one of its neighbors, the hardware measures the corresponding SNR and provides the measured information to the MAC layer. The MAC layer maintains a table with the SNR values of all its current neighbors. The node then periodically broadcasts the SNR table using a link quality (LQ) message every LQ_TIME_OUT. When a node does not receive a LQ message for more than $MAX\_LQ\_TIME\_OUT$, it considers that neighbor to have moved away and removes the corresponding entry from its table. Upon completion of the SNR table exchange, every node can perform the following calculation. Let the node that performs the calculation be the sender of a data frame. The sender computes the *harmonic mean* of the SNR levels of the sender-relay and relay-destination channels as defined in [12]. Only those nodes that have a harmonic mean greater than the SNR between the sender and destination are considered as potential relays nodes. Among these, the node with the maximum harmonic mean of SNR is chosen as the relay.

The relay (if any) chosen by the sender is then explicitly indicated in the transmitted data frame header. For example, the third or fourth address field of IEEE 802.11b header may be used to carry the relay address, as these two fields are not used in regular data transmissions. With this mechanism, it is possible for the sender to specify a particular relay for each transmitted data frame. The MAC data frame format is shown in Fig. 2.

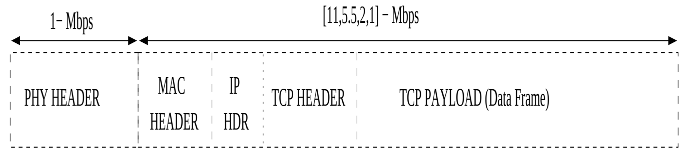

Fig. 2. MAC frame format.

When the relay is required to transmit a copy of the data frame, the MAC header contains the sender address, the destination address, and the frame subtype field is set to 1000 (reserved) as shown in Fig. 3. This is to inform the destination that the frame is being sent by the relay, not the original sender. The destination can then correctly attribute the measured SNR of the received frame to the relay. Since a node is chosen as relay only if a LQ message is received from it, any node can stop sending its LQ messages if it does not wish to be considered as relay.

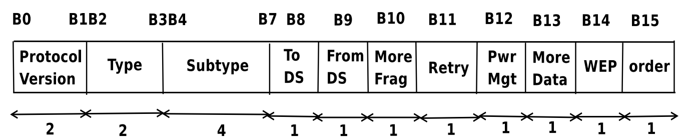

Fig. 3. Frame control field.

III. COBRA MAC IN TWO ROUTING PROTOCOLS

The following two sections explain how COBRA MAC may be combined with AODV and OSLR, respectively.

A. AODV

AODV is a type of on-demand routing protocol [10], [13], in which a node initiates a route discovery process only when it requires a route. Route discovery is performed by flooding route request (RREQ) frames to reach the intended destination. The expanding ring technique may be used, each time with an increased time-to-live (TTL) value to expand the scope of the search incrementally. If a node receiving such a RREQ is either the destination or a node with a valid routing table entry, it responds with a route reply (RREP) frame. Else it broadcasts the RREQ packet with a decremented TTL value, provided TTL is not zero.

The RREP is a unicast packet (thus relay aided) sent to the upstream hop towards the source. The relay aided RREP reduces the probability of failing to acquire a path within the maximum RREQ retry limit. This also decreases the average path acquisition latency defined as the average time required for a route discovery process to find a new route. The source decides the next hop towards the destination as the node from which it received the RREP with the least hop count. If the source does not receive a RREP after a timeout, it reattempts with a higher TTL. A TTL maximum value may be set after which the source considers the destination as unreachable, and drops all packets buffered for the destination. Each node maintains a table with the next hop to a destination and a corresponding life time. The life time of a route to the end destination is refreshed each time a successful packet is sent to the next hop of the destination. That includes packets that may be delivered over a link with the help of a relay.

In order to detect link breaks AODV uses both hello messages and link level feedback. In IEEE 802.11b the link level feedback informs that a link is lost when a packet is dropped after maximum retry limit. In this case AODV invalidates all routes that include that link as a next hop. It then initiates a route error (RERR) message to inform the source about the lost link. RERR is a unicast packet and it may be relay aided, thereby increasing the probability of promptly delivering the information about the lost link to the source, and saving the source from sending further packets along the lost link.

As already mentioned, the route found by AODV tends to use long range (weak) links, as its objective is to minimize the number of hops. A weak link is more likely to cause AODV to think that the route is lost and initiate a RERR, which in turn requires the initiation of a new route discovery procedure. The use of COBRA MAC is essential to reduce the probability of losing an active route by increasing the packet delivery ratio over that link. This reduces both AODV signaling overhead and time spent performing route discovery.

Finally, as any successful data frame transmission helps prolong the life time of an active route in AODV, relay aided unicast data frames may help maintain the active route for a longer time, thus enabling the source to deliver more packets to the end destination.

B. OLSR

OLSR is a popular table driven routing protocol, in which each node broadcasts periodic hello messages and topology control messages to proactively find routes to all reachable destinations [11], [14]. The hello message contains the information about the one hop neighbors. By exchanging hello messages, the nodes come to know about their two hop neighbors. Based on the one hop and two hop neighbors, every node computes a smallest set of one hop neighbors called MPRs (multipoint relays[2]) that can cover all its two hop neighbors. The fundamental difference between OLSR and other table driven routing protocols is the use of MPRs in exchanging topology information. MPRs have been shown to reduce the amount of routing overhead required in the network. The information about MPRs is also exchanged in the hello messages. Topology control (TC) messages are used by a node to disseminate information about itself to other nodes that are not within two hops. TC messages of a node contain the list of its multipoint selectors, i.e., nodes that chose the TC message sender as a MPR. The TC message sender is like a gateway to the multipoint selectors. The TC messages are rebroadcasted only by the MPRs of the node, thereby minimizing the overhead. It is also suggested that redundancy in MPRs helps OLSR perform better in terms of route acquisition [14]. The above feature, i.e., MMPR (M redundant multipoint relays) is used in obtaining the simulation results presented in the paper. Since the route discovery in OLSR is only through control messages, which are broadcast, cooperation at MAC layer cannot help in this process. However, once a route is established, relay aided data frames may be transmitted.

[2]The multipoint relay in OSLR should not be confused with the relay in COBRA MAC.

TABLE I

PARAMETERS USED IN SIMULATION

Path Loss Exponent β = 4	Fading is Flat Rayleigh
Average Transmitter Power = 100 mW	PHY Header = 192 bits
SIFS = 10 μs	RIFS = 30 μs
DIFS = 50 μs	Slot Time = 20 μs
Vulnerable Period = 20 μs	Max Retrans. Attempts = 6
Frame Size = 1023 bytes	CWmin = 31 slots
CWmax = 255 slots	MAC Header = 34 bytes
MAC ACK = 14 bytes	Sensitivity = -107 dBm

IV. RESULTS

This section discusses some of the assumptions used to obtain simulation results for the performance comparison. The results obtained for delivery ratio, end-to-end delay and Routing overhead are discussed.

A. Simulation Setup

Implementations of AODV and OLSR routing protocols closely match their specifications in [13], [14]. Control Packets are given priority over data packets at internet protocol (IP) layer. In OLSR, packets that do not have a next hop towards the destination are buffered for a fixed time equal to 6 seconds (three hello messages or one TC message). If a route is not found after 6 s, packets are discarded at the IP layer. In AODV, packets that do not have a next hop are stored in a no-route buffer and route discovery process is initiated. If route is found, all packets buffered for that particular destination that are present in the no-route buffer are allowed to enter the IP transmit buffer. The buffer size was limited to 16 control packets and 48 data packets (including transit packets). The buffers are drop tail (packets finding the buffer full will be discarded). Transit packets are given preference over node's own packets. The parameters used in IEEE 802.11b and cooperative MAC for simulation are tabulated in Table I. The LQ_TIME_OUT and $MAX\_LQ\_TIME\_OUT$ used by the relay selection algorithm are set to 2 s and 6 s respectively. The channel is assumed to have a flat Rayleigh fading that remains constant for the duration of a data frame. The channel model is described in detail in [15].

The sensing threshold is set to -107 dBm. Whenever a node senses a power level that is higher than -107 dBm, it assumes the channel to be busy. Spatial reuse is possible because of the finite sensitivity range value[3].

Data rate is fixed to 1 Mbps to improve the packet delivery ratio. Each node transmits 1003 byte UDP packets. Both regular (line of nodes) as well as random (with mobility characterized by random waypoint (RWP) model) topologies

[3]-107 dBm sensing range with a transmitted power of 100 mW correspond to about 150 m in a nonfading channel where the path loss exponent β is 4.

have been used to analyze the performance. In the regular topology the nodes are placed along a line maintaining a constant inter-node distance, with the source S and destination D at the extremes. For the RWP mobility model, the minimum speed is kept greater than zero to avoid non uniformity in simulations [16]. The nodes are allowed to move for an initial 1000 s (settling time) before activating the protocols, in order to allow the nodes to reach a steady state [17].

When using RWP model, two cases are considered.

- *Uniformly distributed pause time* - The pause time is assumed to vary uniformly between zero and a specified value.
- *Fixed pause time* - The pause time is assumed to be a fixed value.

Uniformly distributed pause time implies that a node will stay fixed after reaching a destination position, for a uniformly distributed time. In steady state this leads to a distribution of nodes that is almost uniformly distributed. However when pausetime is 0 s, the nodes are always in movement. Since a node chooses a position uniformly distributed over the simulation area, there is a higher probability for it to choose a position that is in the opposite direction to its previous movement. This is because area on the other side will be higher. Thus nodes tend to cross the center frequently, causing a bell shaped probability distribution function of the position of nodes as shown in Fig. 4. This implies that all nodes will converge to the center of the simulation area most of the time. Thus nodes will be at most one hop distance from each other leading to an increase in delivery ratio when compared to other pause times. This is counter to the intuition that an increase in pause time will cause a decrease in mobility and an increase in delivery ratio.

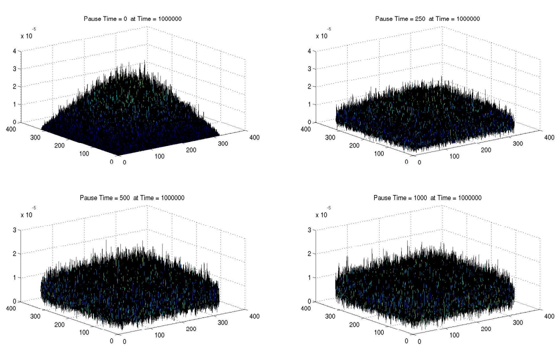

Fig. 4. Distribution of nodes for pause time 0 s at various instances of time.

In the next two sections, the simulation results showing the performance of AODV and OLSR combined with IEEE802.11 and COBRA MAC are presented. Each point reported in the graphs is an average of ten independent simulation runs. The performance metrics analyzed in this study are defined as follows:

- *Delivery ratio:* The ratio of the number of data packets received at the final destination(s) to the number of packets sent by the original source(s).
- *End-to-end delay:* The average time delay between the transmission of a data packet at the application layer of the source and its reception at the application layer of the destination in seconds.
- *Routing overhead ratio:* The ratio of the total number of control bytes spent by the routing protocol to the total number of data bytes received at the destination during the entire simulation time.
- *Percentage of active path time:* The percentage of total simulation time for which a path between a source and destination remained active in AODV.
- *Average path acquisition latency:* The average time delay between the broadcasting of a RREQ and the reception of a corresponding RREP in AODV.
- *Number of path breaks:* The number of times an active link is invalidated causing a path break, requiring reinitiation of a route discovery process in AODV.
- *Percentage of packets dropped as no route found:* The percentage of the number of data packets dropped by all nodes with respect to the number of packets sent by the original source(s), after failure to find a route to the destination(s) within the maximum retry limit.
- *Average number of packets buffered as no route found:* Average number of data packets buffered in all the nodes while waiting for a route to be established.

V. AODV SIMULATION RESULTS

The performance of AODV routing protocol combined with COBRA MAC was studied in both static and mobile scenarios. Two methods of relay selection were used for the COBRA MAC protocol, crystal ball (CB) and link quality estimator (LQE). CB finds the relays assuming the availability of global knowledge about exact node positions. LQE is the relay selection algorithm proposed in II-A. CB is used as a reference to compare the efficiency of the LQE protocol. Since it assumes the global knowledge of nodes, CB performs better than LQE.

A. Static scenario

In this scenerio nodes are assumed to be stationary. Such a scenario was targeted, as it helps understand the operation of the protocol and the reasons for the better performance of cooperative MAC. A linear topology is assumed with a constant inter-node distance. The source and destination are chosen to be at the extremes of the line of nodes. All the simulations were run for a total simulation time of 2000 s.

1) Effect of end-to-end distance: In order to study the effect of increase in end-to-end distance, the source to destination distance was varied from 160 m to 640 m with the inter-node distance being 40 m. Increase in end-to-end distance implies an increase in the number of intermediate nodes effectively increasing the average number of hops required to reach the destination. The source transmits data packets at a rate of 2 kilobytes per second (kBps). The delivery ratio for IEEE 802.11b in this scenario shown in Fig. 5 falls steeply with increase in the end-to-end distance. This is because AODV finds paths with minimum hop count increasing the chances of weak links when the end-to-end distance is increased. COBRA MAC helps deliver more packets even with weak links by the use of relays for each link. Use of link layer feedback prevents AODV from sending further packets into a broken path and reinitiate a route discovery process instead. Fig. 6 shows the advantage of using COBRA MAC. The relays help in delivering the packets faster by avoiding retransmissions in weak links thus decreasing the number of attempts to deliver packets. Each attempt taken by MAC to deliver a frame costs an extra backoff time apart from other transmission delays. The delay is also partly attributed to the path acquisition latency. Use of cooperation aids in the delivery of RREP packets which are unicast and thus helps in lowering the path acquisition latency as shown in Fig. 10. This factor also relates to the decrease in average number of data packets dropped or buffered when no route is found with COBRA MAC, as seen in Figs. 11 and 12. As successful transmission of data packets increases the life expectancy of paths in AODV, cooperation increases the average active path time by reducing the number of path breaks, observed in Figs. 8 and 9. Thus use of COBRA MAC decreases the routing overhead ratio as shown in Fig. 7 by minimizing path breaks avoiding reinitiation of route discovery processes. It can be observed that CB performs better than LQE. This is because CB always picks the best relay with its knowledge of exact node positions while LQE may not be able to do so due to its dependencies on link level uncertainties. The difference in performance however is low, which implies that LQE is as good as CB. Similar simulations were run with the inter-node distance set to 30 m and the distance between the source and destination varied from 150 m to 600 m. The delivery ratio, end-to-end delay and routing overhead ratio are shown in Figs. 13, 14 and 15 respectively. Here again the COBRA MAC outperforms IEEE 802.11b. It is observed that the active path time for COBRA MAC is higher than IEEE 802.11b as shown in Fig. 16.

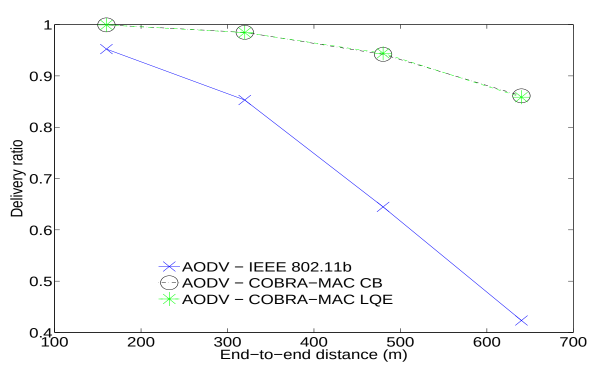

Fig. 5. Delivery ratio vs. End-to-end distance, linear topology, inter-node distance is 40 m.

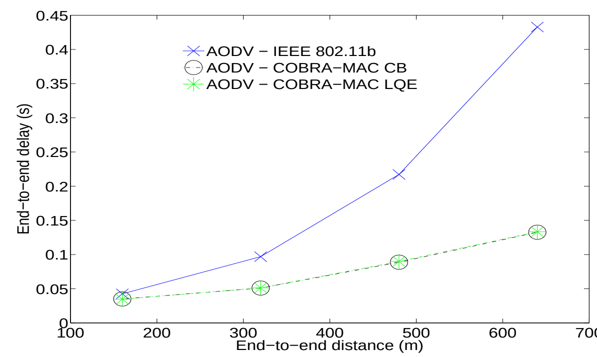

Fig. 6. End-to-end delay vs. End-to-end distance, linear topology, inter-node distance is 40 m.

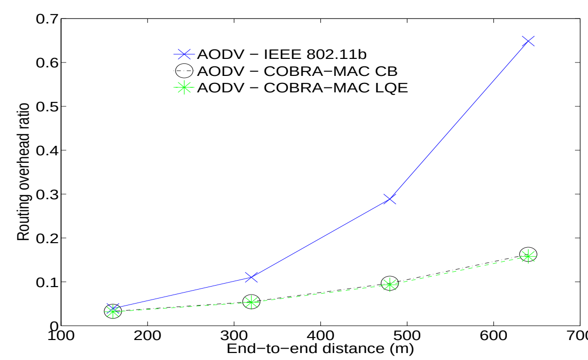

Fig. 7. Routing overhead ratio vs. End-to-end distance, linear topology, inter-node distance is 40 m.

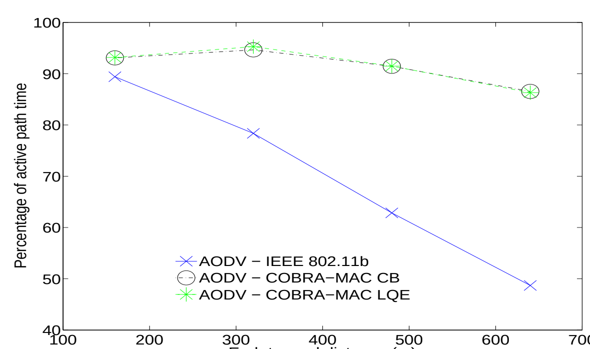

Fig. 8. Percentage of active path time vs. End-to-end distance, linear topology, inter-node distance is 40 m.

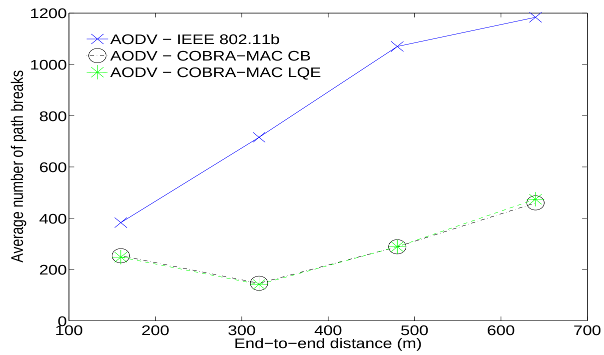

Fig. 9. Average number of path breaks vs. End-to-end distance, linear topology, inter-node distance is 40 m.

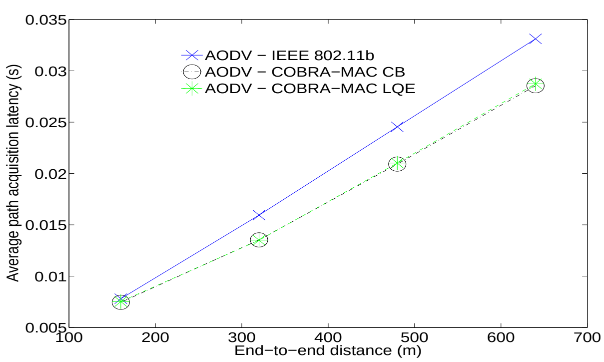

Fig. 10. Average path acquisition latency vs. End-to-end distance, linear topology, inter-node distance is 40 m.

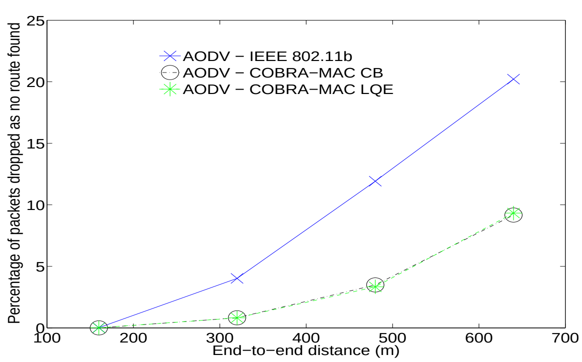

Fig. 11. Percentage of packets dropped as no route found vs. End-to-end distance, linear topology, inter-node distance is 40 m.

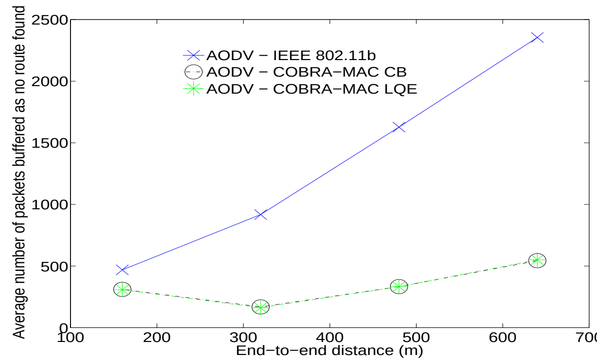

Fig. 12. Average number of packets buffered as no route found vs. End-to-end distance, linear topology, inter-node distance is 40 m.

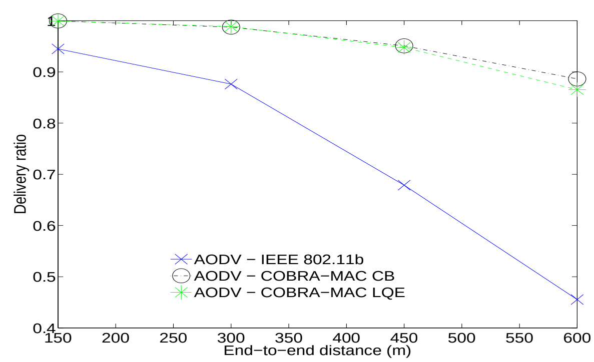

Fig. 13. Delivery ratio vs. End-to-end distance, linear topology, inter-node distance is 30 m.

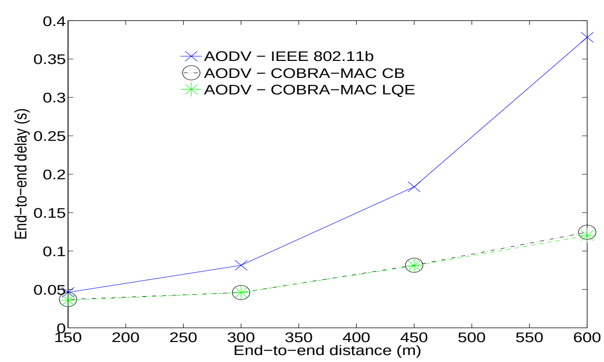

Fig. 14. End-to-end delay vs. End-to-end distance, linear topology, inter-node distance is 30 m.

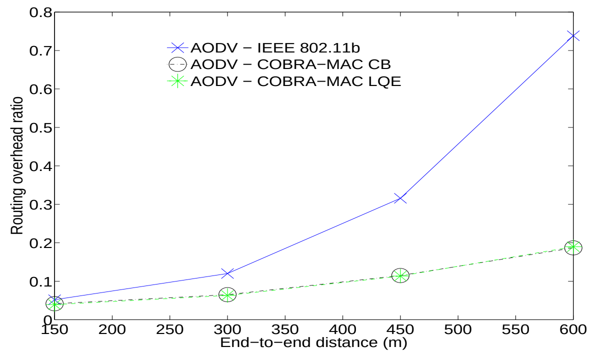

Fig. 15. Routing overhead ratio vs. End-to-end distance, linear topology, inter-node distance is 30 m.

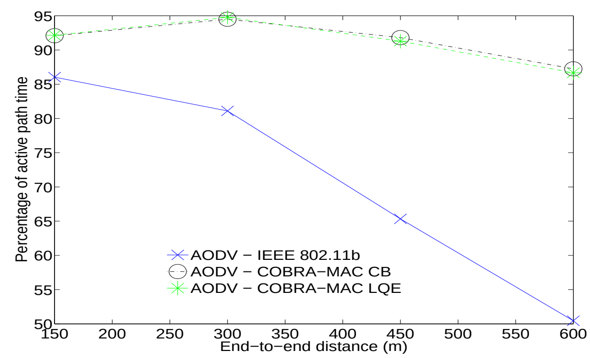

Fig. 16. Percentage of active path time vs. End-to-end distance, linear topology, inter-node distance is 30 m.

2) Effect of offered load: To see the effect of increase in traffic load, simulations were run for a linear topology with end-to-end distance and inter-node distance set to 600 m and 40 m respectively and the arrival rate of data packets was varied from 1 to 25 kBps. Increase in offered load rises the congestion in the network. This affects the successful delivery of control packets and thus affects the routing. Due to the link layer feedback, each time a packet gets dropped after maximum retry limit, AODV assumes to have lost the link. All routes that use this link are invalidated. Whenever a route is lost at an intermediate node, all packets buffered for the corresponding destination are discarded. With increase in arrival rate, there is an increase in the number of link failures, thus more number of packets are dropped at higher arrival rates. This causes a drop in delivery ratio with rise in offered load, as shown in Fig. 17. COBRA MAC outperforms IEEE 802.11b in delivering packets and also keeps the end-to-end delay low as seen in Fig. 18. The steep fall in delivery ratio and rise in delay for IEEE 802.11b for higher arrival rates suggest that the network may be saturated. COBRA MAC helps in delaying this saturation. In this scenerio again it can be observed that LQE performs as good as CB. The routing overhead ratio shown in Fig. 19 has an initial fall because with lower arrival rates, a greater number of control packets are spent in route discovery processes for lesser number of packets delivered. Also there may be loss in control packets. COBRA MAC partially alleviates the loss of control packets by the use of relays in transmission of RREP packets. For higher arrival rates, COBRA MAC performs better than IEEE 802.11b by keeping the path alive for a longer time, hence requiring less routing overhead. This fact is also visible from Fig. 20 which shows that COBRA MAC keeps the paths active for about 90% of the time while IEEE 802.11b can manage only for less than 55% of the time. The average number of path breaks, shown in Fig. 21 has an initial rise because with higher arrival rate, i.e more data packets, the probability of failure after maximum transmission attempts is higher, causing greater number of path breaks due to link layer feedback. COBRA MAC reduces the probability of such failures.

Similar simulations were run with an end-to-end distance of 320 m. The delivery ratio, end-to-end delay and routing overhead ratio plots are shown in Figs. 22, 23 and 24 respectively. Though the delivery ratio is improved by COBRA MAC, the end-to-end delay is higher for both the variants of COBRA MAC, CB and LQE, when compared to IEEE 802.11b. This is because with an end-to-end distance of 320 m and internode distance of 40 m, the COBRA MAC tries to keep weak links upto 200 m alive for a longer time. These weak links always rely on the help of relays for transmission. This can result in greater number of retransmissions increasing the end-to-end delay. The IEEE 802.11b on the other hand, causes immediate path breaks for such paths and finds shorter links. It is also seen that of the two variants of COBRA MAC, CB performs slightly better than LQE as it chooses better relays with the knowledge of exact node positions. The number of path breaks gets reduced when COBRA MAC is used. This is because cooperation helps maintain a link for a longer time by successfully delivering packets before maximum retry limit, preventing unnecessary link breaks. By maintaining individual links longer, cooperation is able to maintain a path for more time when compared to IEEE 802.11b. The average number of path breaks and percentage of active path time are shown in Figs. 26 and 25 respectively.

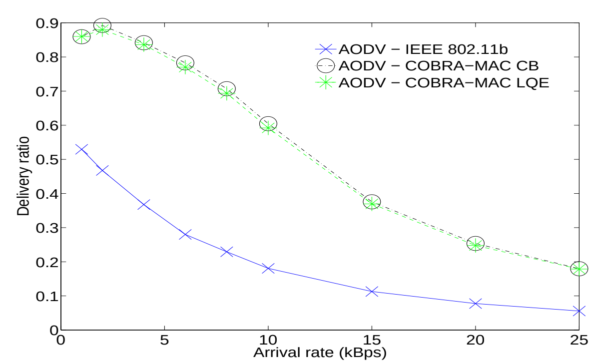

Fig. 17. Delivery ratio vs. Arrival rate, linear topology, end-to-end distance is 600 m, inter-node distance is 40 m.

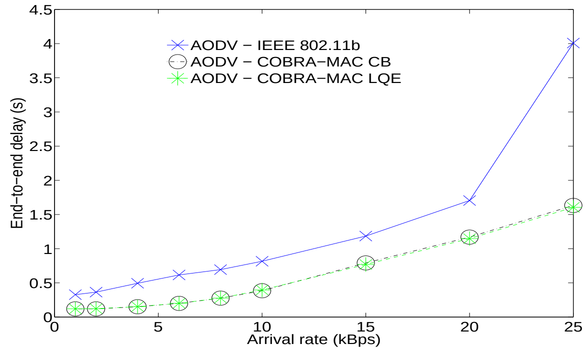

Fig. 18. End-to-end delay vs. Arrival rate, linear topology, end-to-end distance is 600 m, inter-node distance is 40 m.

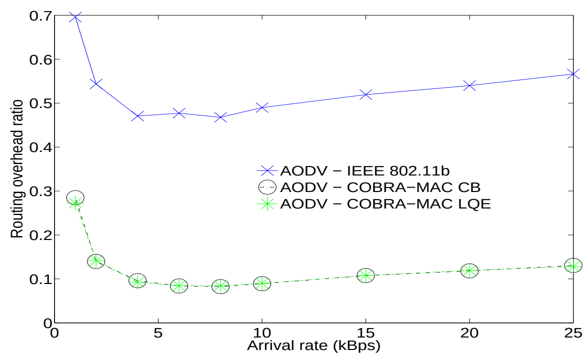

Fig. 19. Routing overhead ratio vs. Arrival rate, linear topology, end-to-end distance is 600 m, inter-node distance is 40 m.

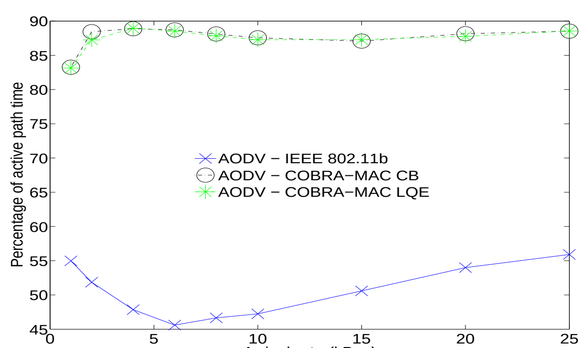

Fig. 20. Percentage of active path time vs. Arrival rate, linear topology, end-to-end distance is 600 m, inter-node distance is 40 m.

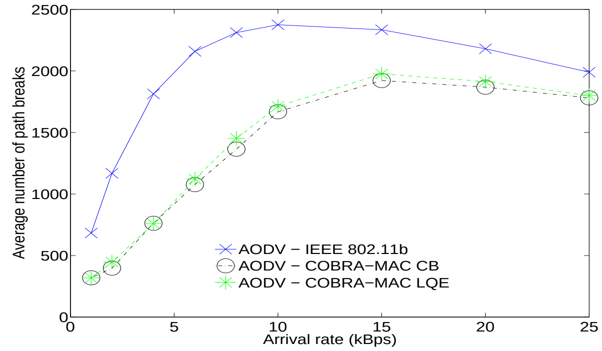

Fig. 21. Average number of path breaks vs. Arrival rate, linear topology, end-to-end distance is 600 m, inter-node distance is 40 m.

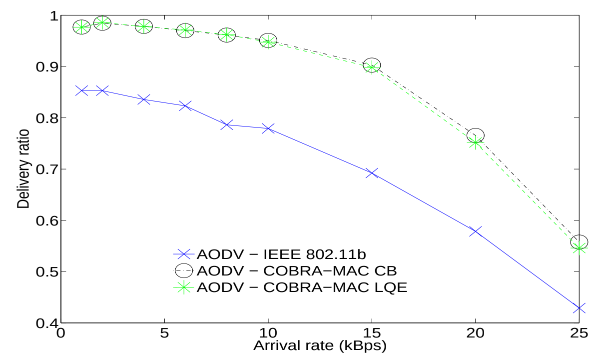

Fig. 22. Delivery ratio vs. Arrival rate, linear topology, end-to-end distance is 320 m, inter-node distance is 40 m.

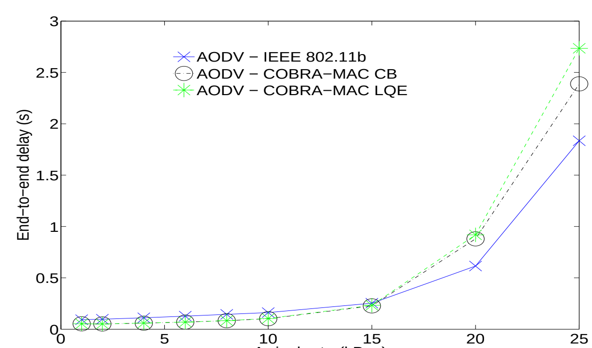

Fig. 23. End-to-end delay vs. Arrival rate, linear topology, end-to-end distance is 320 m, inter-node distance is 40 m.

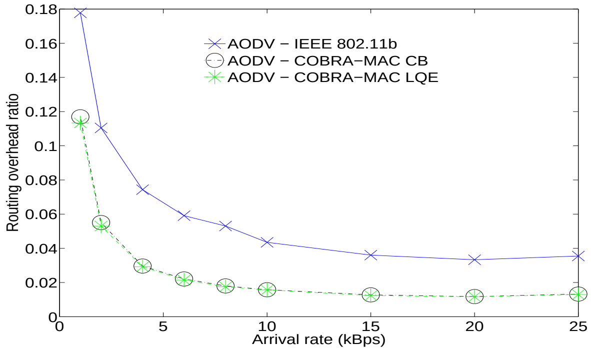

Fig. 24. Routing overhead ratio vs. Arrival rate, linear topology, end-to-end distance is 320 m, inter-node distance is 40 m.

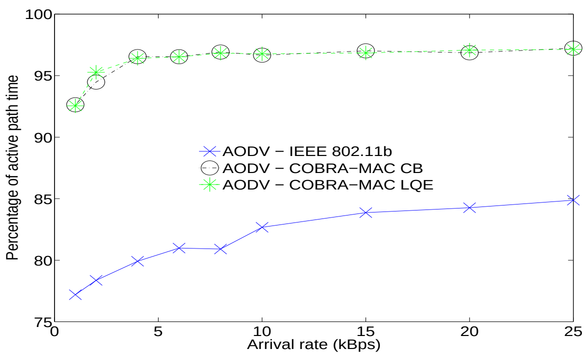

Fig. 25. Percentage of active path time vs. Arrival rate, linear topology, end-to-end distance is 320 m, inter-node distance is 40 m.

B. Mobile scenario

In this scenerio, nodes are assumed to move according to the random way point mobility model.

1) Unlimited buffer capacity at IP: IP is assumed to have an infinite storage capacity. This increases the queuing delay but prevents loss of packets due to buffer overflow. In the following simulations the pause time is assumed to be uniformly distributed between zero and the value reported.

A grid topology of size 320 m X 320 m with 15 nodes is assumed. One source transmits data with an arrival rate of 2 kBps. The pause time for the nodes is varied from 0 to 2000 s with the total simualtion time being 2000 s. Figs. 27, 28 and 29 show the delivery ratio, end-to-end delay and routing overhead ratio for this scenario. COBRA MAC performs better than IEEE 802.11b. The relay search area for COBRA MAC CB is the circle that has source and destination on the circumference of the circle whose center is the midpoint of the line joining source and destination and radius equal to half the source-destination distance. In this scenerio however when LQE and CB are compared there is no clear winner unlike the static scenario. This is because in a static scenario, a relay is always present at a vantage position and CB finds it. In a mobile scenario, CB will not choose a relay if it is not at a vantage position however, LQE may choose one. Since the data rate is only 1 Mbps, a relay at a bad position can also help sometimes.

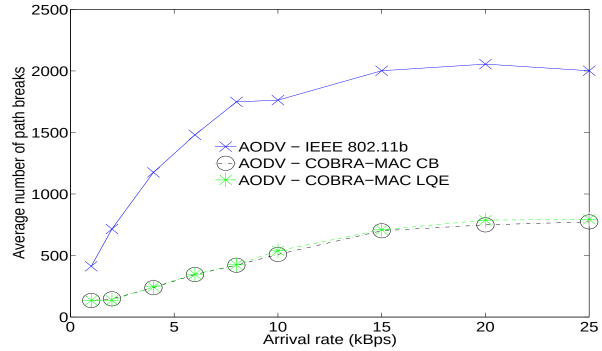

Fig. 26. Average number of path breaks vs. Arrival rate, linear topology, end-to-end distance is 320 m, inter-node distance is 40 m.

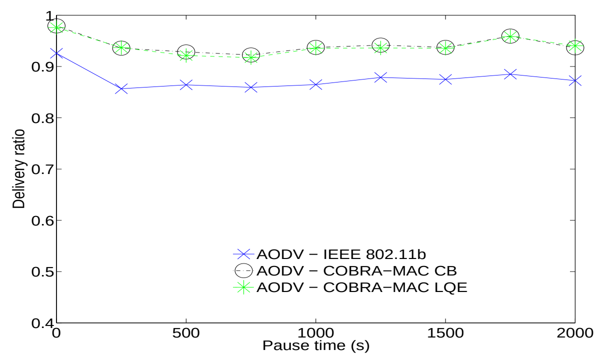

Fig. 27. Delivery ratio vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 15 nodes.

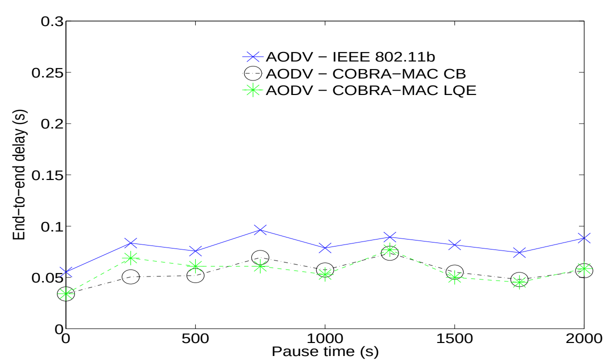

Fig. 28. End-to-end delay vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 15 nodes.

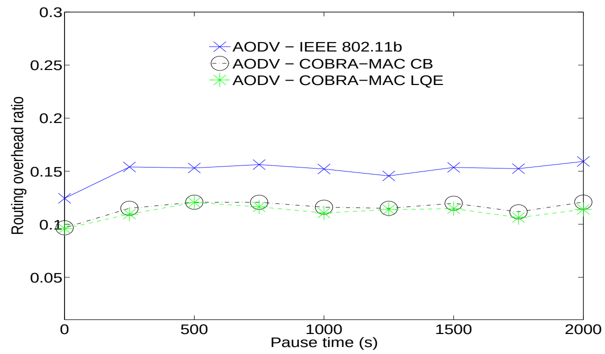

Fig. 29. Routing overhead ratio vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 15 nodes.

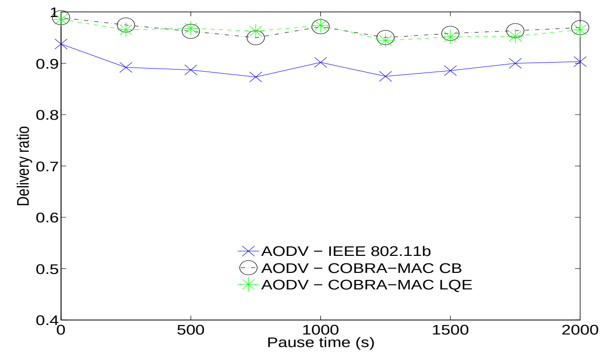

Fig. 30. Delivery ratio vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 20 nodes.

The simulations are repeated with 20 nodes. The delivery ratio, end-to-end delay and routing overhead ratio are shown in Figs. 30, 31 and 32. It is seen that the delivery ratio is relatively greater for all three MAC implementations when compared to the 15 nodes simulation. This is due to the better connectivity with the help of intermediate nodes and a higher possibility to find relay nodes in the case of cooperation.

In order to see the effect of increasing traffic in the network, number of source destination pairs was increased to 5. The corresponding delivery ratio, end-to-end delay and routing overhead ratio plots are shown in Figs. 33, 34 and 35. There is a slight decrease in the delivery ratio and increase in the end-to-end delay due to the increased congestion. The routing overhead ratio is not comparable because it is a ratio depending on the total number of data packets received which is greater when there are 5 sources.

When compared with the results obtained with one source, it can be seen that the delivery ratio has decreased for both the techniques. This shows that the use of cooperation at MAC layer is not affected by this increase in traffic. The cooperative MAC protocol is still able to deliver more packets compared to IEEE 802.11b. If the number of sources is now increased to 10, the overall arrival rate becomes 20 kBps and there is an increase in congestion in the network. This inhibits the routing protocol and MAC protocol from delivering packets which can be infered from the decrease in delivery ratio shown in Fig. 36. However AODV with COBRA MAC, is able to perform well even under such conditions. This is because of increased number of transmissions of the same packet from more vantage positions with the help of a relay. Since these transmissions take place at the same data rate as that of the sources, they occupy the channel for the same amount of time. This makes the network more congested, preventing other nodes from transmitting. This causes a marginal increase in the end-to-end delay seen in Fig. 37. However a gain in terms of routing overhead ratio is seen as shown in Fig. 38.

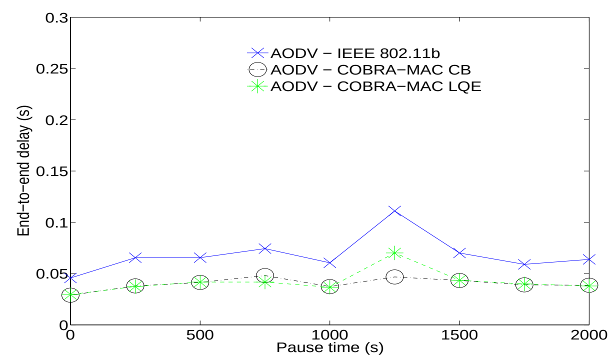

Fig. 31. End-to-end delay vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 20 nodes.

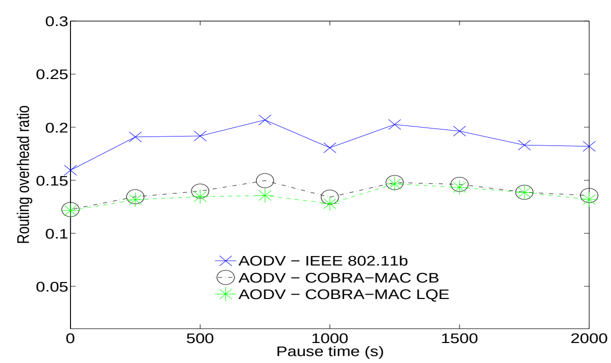

Fig. 32. Routing overhead ratio vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 20 nodes.

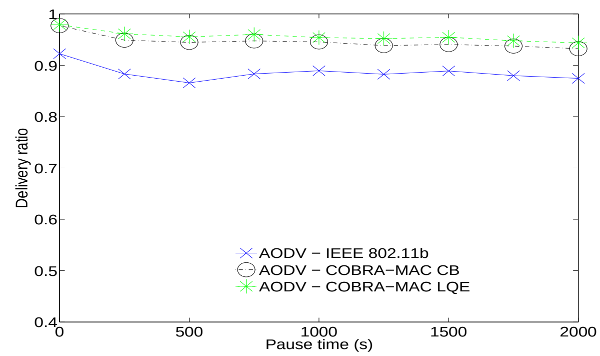

Fig. 33. Delivery ratio vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 20 nodes, 5 sources.

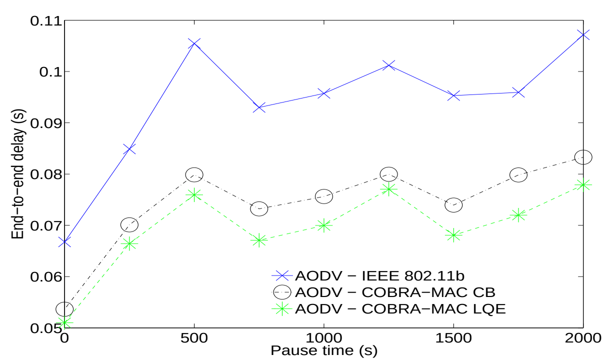

Fig. 34. End-to-end delay vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 20 nodes, 5 sources.

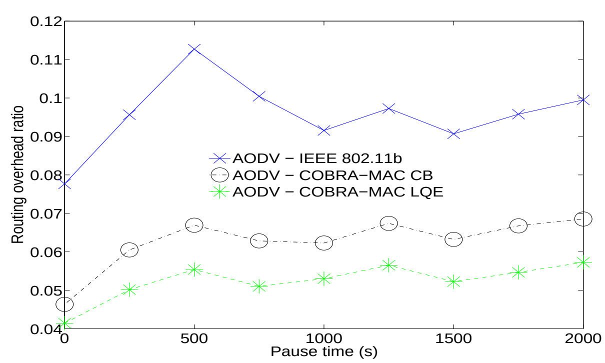

Fig. 35. Routing overhead ratio vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 20 nodes, 5 sources.

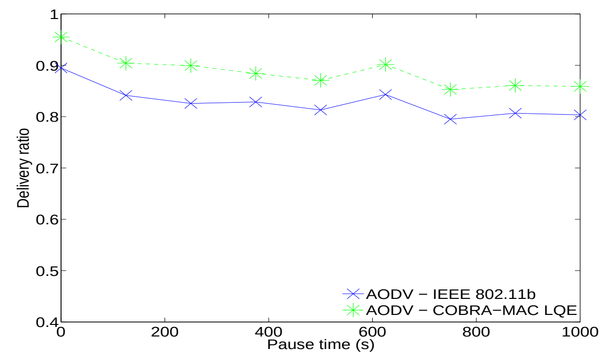

Fig. 36. Delivery ratio vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 20 nodes, 10 sources.

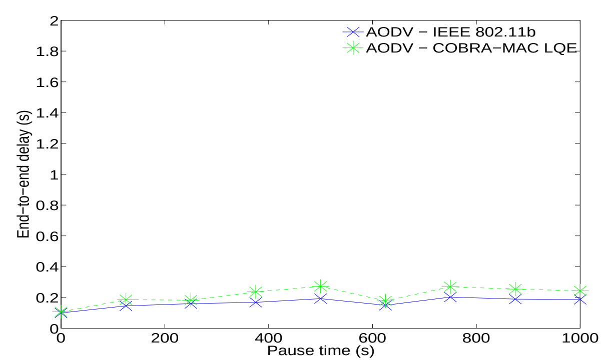

Fig. 37. End-to-end delay vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 20 nodes, 10 sources.

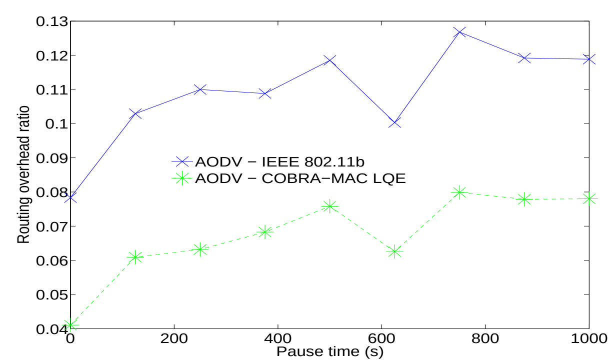

Fig. 38. Routing overhead ratio vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 20 nodes, 10 sources.

2) Limited buffer capacity at IP: The assumption made in the earlier set of simulations was that there is an unlimited buffer size at the IP. This was made to obtain the maximum delivery ratio. The loss in packets was either because AODV was unable to find the route in time or the packets were dropped at the MAC layer. The buffer does not build up much in the simulation with one source, as the network has only one flow of traffic with an arrival rate of 2 kBps. The buffer size is now limited to 64 packets at the IP, with preference for control packets. The simulation results with one source and limited buffer show that this change does not affect the results as infered from Figs. 39, 40 and 41. Simulations are performed with the number of sources as 5 with each source generating traffic at the rate of 2 kBps giving an overall arrival rate of 10 kBps. Since this also does not saturate the network, the results are similar to the ones presented with unlimited buffer size. The corresponding delivery ratio, end-to-end delay and routing overhead ratio are shown in Figs. 42, 43 and 44. When the buffer size is limited, packets get dropped when the buffer at IP build up. This effect, which occurs only when the network is congested, is seen when the number of sources is increased to 10. Now the delivery ratio decreases slightly when compared to the case of unlimited buffer size as shown in Fig. 45. However the end-to-end delay and routing overhead ratio are reduced as shown in Figs. 46 and 47 respectively.

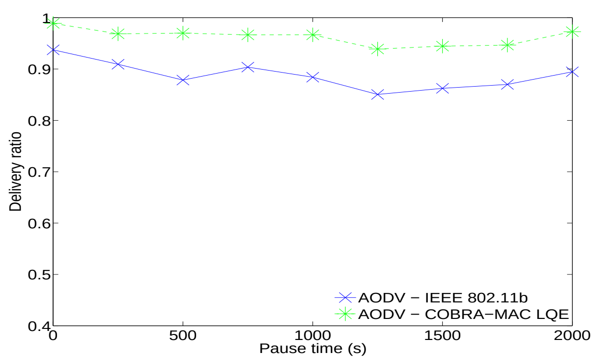

Fig. 39. Delivery ratio vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 20 nodes, 1 source, IP buffer size is 64.

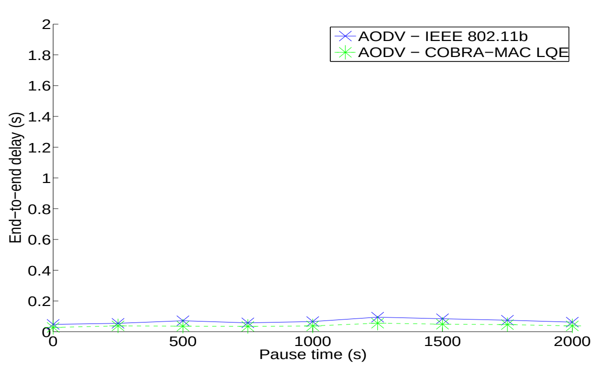

Fig. 40. End-to-end delay vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 20 nodes, 1 source, IP buffer size is 64.

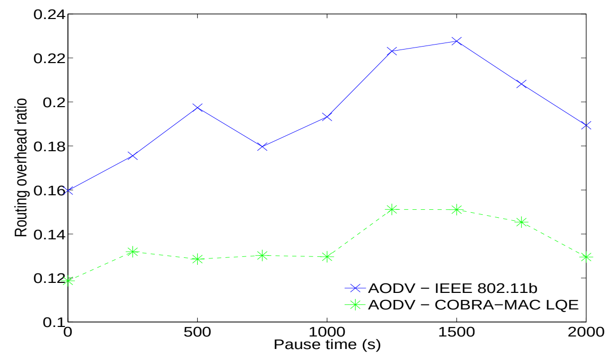

Fig. 41. Routing overhead ratio vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 20 nodes, 1 source, IP buffer size is 64.

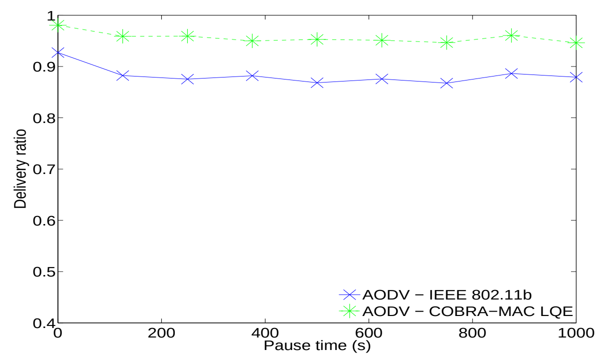

Fig. 42. Delivery ratio vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 20 nodes, 5 sources, IP buffer size is 64.

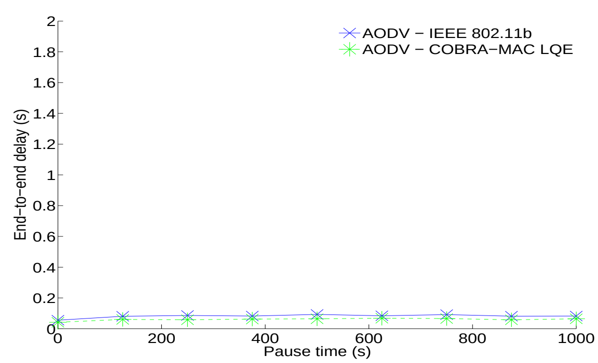

Fig. 43. End-to-end delay vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 20 nodes, 5 sources, IP buffer size is 64.

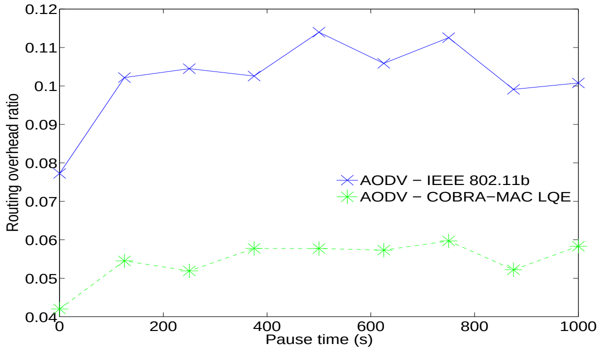

Fig. 44. Routing overhead ratio vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 20 nodes, 5 sources, IP buffer size is 64.

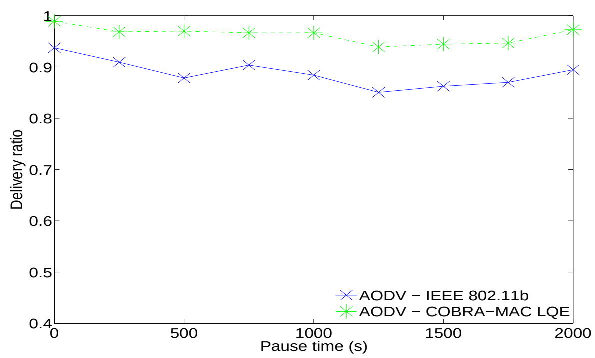

Fig. 45. Delivery ratio vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 20 nodes, 10 sources, IP buffer size is 64.

3) Effect of increasing number of nodes: The number of nodes in the network is varied from 10 to 20. The buffer size at IP is limited to 64 packets. The simulation area is 320 mX320 m and the pause time is fixed to 0 s with the total simulation time being 1000 s. COBRA MAC performs better than IEEE 802.11b in terms of delivery ratio, end-to-end delay routing overhead ratio and average active path time even when the number of nodes is less, as shown in Figs. 48, 49, 50 and 51.

This implies that routing with cooperation helps achieve the same amount of connectivity as that obtained with IEEE 802.11b, with lesser number of nodes.

Now to see if such gains can still be achieved when the overall network load is increased, the number of sources is increased to five. Even under this increased traffic load, it can be seen that the use of cooperation helps obtain a conectivity that can be achieved by IEEE 802.11b only with a higher number of nodes. The corresponding results are shown in Figs. 52, 53, 54 and 55.

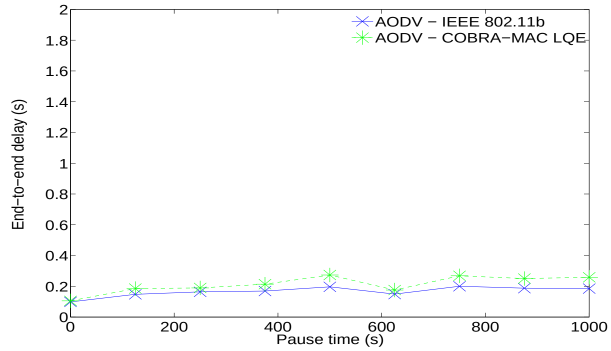

Fig. 46. End-to-end delay vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 20 nodes, 10 sources, IP buffer size is 64.

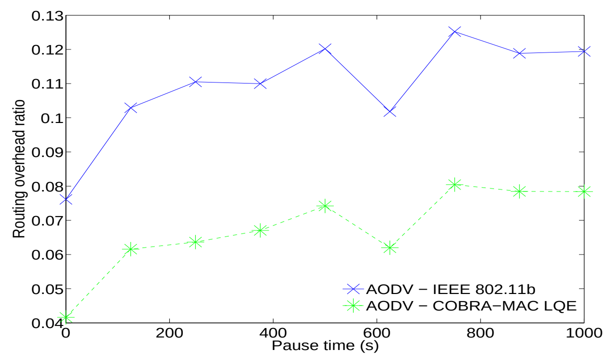

Fig. 47. Routing overhead ratio vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 20 nodes, 10 sources, IP buffer size is 64.

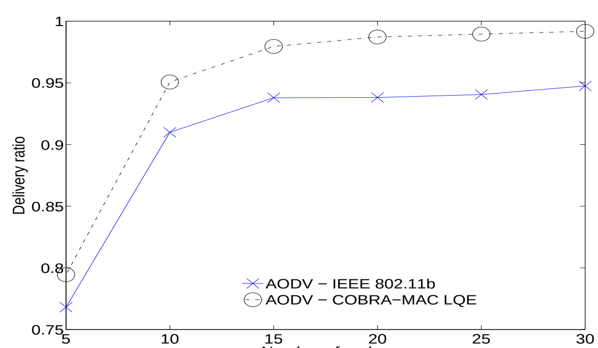

Fig. 48. Delivery ratio vs. Number of nodes, random waypoint mobility model, area is 320 m X 320 m, 1 source, IP buffer size is 64.

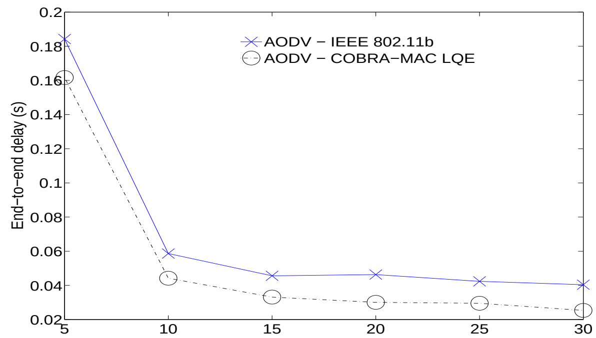

Fig. 49. End-to-end delay vs. Number of nodes, random waypoint mobility model, area is 320 m X 320 m, 1 source, IP buffer size is 64.

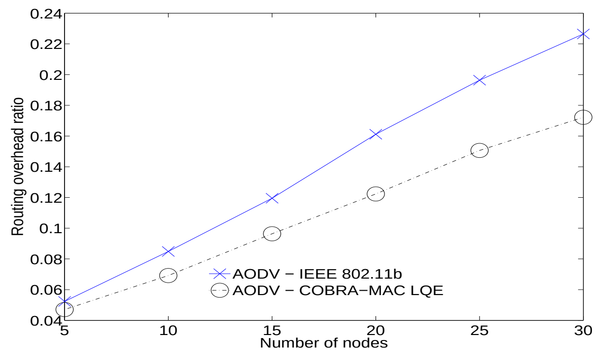

Fig. 50. Routing overhead ratio vs. Number of nodes, random waypoint mobility model, area is 320 m X 320 m, 1 source, IP buffer size is 64.

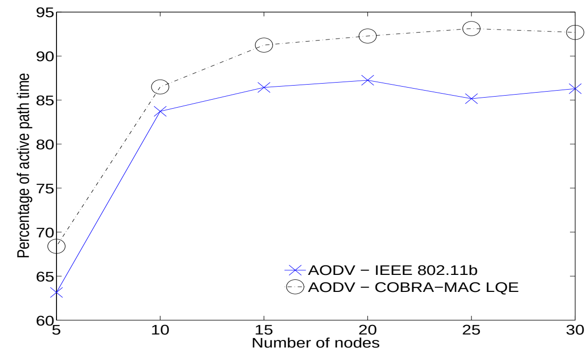

Fig. 51. Percentage of active path time vs. Number of nodes, random waypoint mobility model, area is 320 m X 320 m, 1 source, IP buffer size is 64.

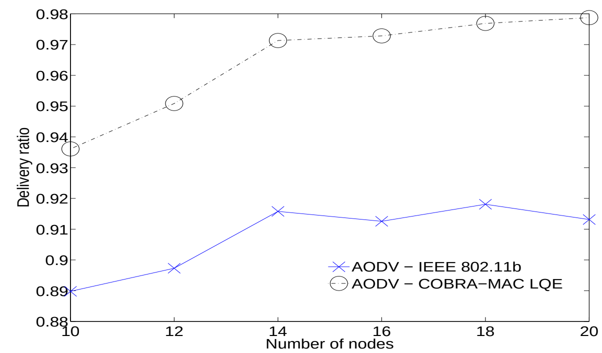

Fig. 52. Delivery ratio vs. Number of nodes, random waypoint mobility model, area is 320 m X 320 m, 5 sources, IP buffer size is 64.

4) Effect of mobility: Mobility plays an important role in route selection. Increase in mobility causes nodes to move away from the transmission range of its neighbors.

To study this phenomenon, the mobility is increased by increasing the average velocity. A grid of area 320 m X 320 m with 20 nodes moving according to a random waypoint mobility model is considered. Five sources generate traffic at a rate of 2 kBps each to randomly chosen destinations. The pause time for the nodes is fixed at 0 s, i.e., the nodes are always moving. The total simulation time is 1000 s.

With IEEE 802.11b, when a node moves towards the end of transmission range, the link gets lost, which happens frequently at high mobility. However when COBRA MAC is used, the relay is able to keep a link active for a longer time by delivering packets even when the destination moves away from the transmission range of the source, as long as the source is within the reach of the relay. This prevents unnecessary link breaks unlike IEEE 802.11b.

COBRA MAC achieves higher delivery ratio as shown in Fig. 56 and is more robust to increase in velocity. The corresponding end-to-end delay and routing overhead ratio are shown in Figs. 57 and 58 respectively. Since COBRA-MAC delivers much more in terms of number of packets (greater throughput) compared to IEEE 802.11b, the comparison of end-to-end delay is not fair. There is a marginal increase in routing overhead ratio with increase in average velocity for AODV. This is due to increase in number of path breaks at high mobility causing reinitiation of route discovery. COBRA-MAC helps lowering the routing overhead ratio by keeping the paths active for a longer time.

VI. OLSR SIMULATION RESULTS

The results for OLSR have been split into two parts. In the first section, results for static network are presented. A regular linear topology was considered for study. The second part of the results section includes mobility for which random waypoint mobility model was used.

A. Static scenario

A bunch of nodes was placed along a straight line. The source node is the one that is in the beginning of the line and destination is always the last node in the line. The source node generates poisson arrivals and is the only generator of packets. The other nodes just aid in forwarding traffic or act as relays.

Figs. 59, 60 and 61 show the delivery ratio, end-to-end delay and routing overhead ratio when the source and destination nodes were placed at distances specified along the X-axis of the graphs. The inter-node distance in this case was 40 m. Each point reported in the graph is an average of ten independent simulation runs. We see that as the end-to-end distance is increased, the delivery ratio (across both the MAC variants) steeply falls. As the end-to-end distance increases, the routing protocol is unable to find paths. If at

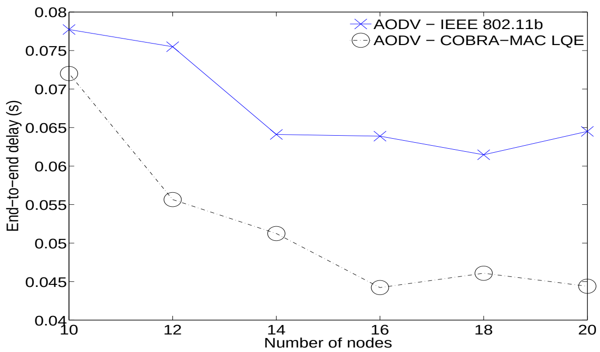

Fig. 53. End-to-end delay vs. Number of nodes, random waypoint mobility model, area is 320 m X 320 m, 5 sources, IP buffer size is 64.

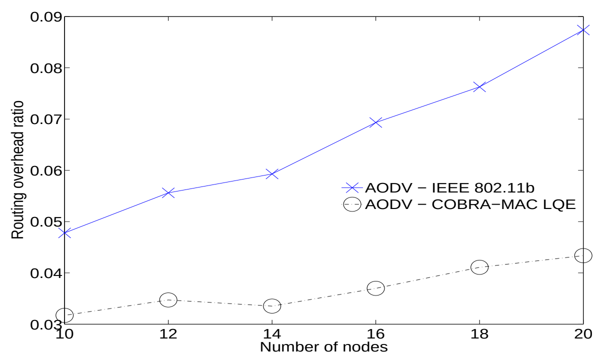

Fig. 54. Routing overhead ratio vs. Number of nodes, random waypoint mobility model, area is 320 m X 320 m, 5 sources, IP buffer size is 64.

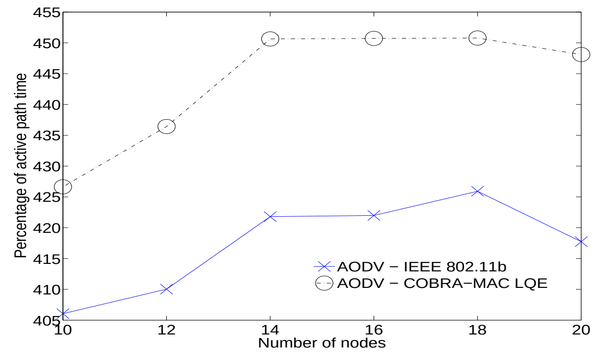

Fig. 55. Percentage of active path time vs. Number of nodes, random waypoint mobility model, area is 320 m X 320 m, 5 sources, IP buffer size is 64.

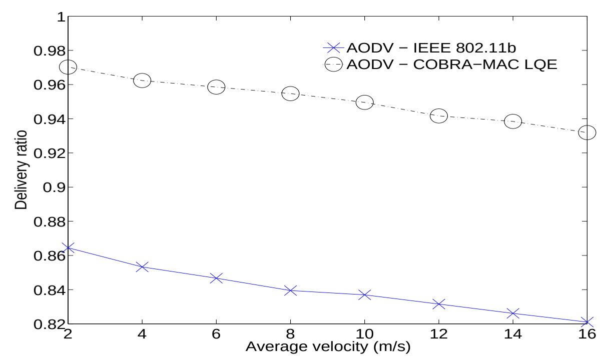

Fig. 56. Delivery ratio vs. Average velocity, random waypoint mobility model, area is 320 m X 320 m, pause time is 0 s, five sources, destinations picked in a uniformly distributed manner.

all the routing protocol obtains a path, there will be many weak links as OLSR tries to minimize the number of hops to the destination. The cooperative MAC performs better as it uses the relay available between the intermediate sender and receiver in each hop. Fig. 60 shows that the delay incurred by the cooperative MAC is less compared to that seen by IEEE 802.11b. Though COBRA MAC does not help in routing, we see an improvement in routing overhead in Fig. 61. This is because routing overhead is counted as the ratio of number of bytes of control frames sent to the number of bytes of data successfully received. Since cooperative MAC delivers more data bytes compared to IEEE 802.11b, the routing overhead ratio for cooperative MAC appears better. COBRA MAC CB uses the perfect knowledge of node positions in deciding the relay for the cooperative MAC whereas LQE uses the link quality based relay selection algorithm to pick relays. We see from the figures that LQE performs as good as CB.

Figs. 62, 63 and 64 show the delivery ratio, end-to-end delay and routing overhead ratio when the source and destination nodes were placed at distances specified by points along the X-axes. The inter-node distance in this case was set to 30 m. Here again, we see that increase in end-to-end distance decreases the delivery ratio. COBRA MAC CB and LQE perform very similar and they outperform IEEE 802.11b in terms of delivery ratio and routing overhead ratio. At most points, the cooperative MAC variants perform better compared to IEEE 802.11b. Since the transmission rate used is 1 Mbps, mostly the sender MAC can deliver the frame in six attempts (maximum retry limit set in the simulator). The actual number of attempts taken to deliver a frame in cooperative MAC depends on the position of the relays. If LQE does not select the relay properly, it would consume much more delay compared to CB which would pick the right relay. An extra attempt to deliver a packet would cost the MAC an extra backoff time apart from other transmission times. This increases the delay when number of nodes is 11.

Figs. 65, 66 and 67 show the plot of delivery ratio, end-to-end delay and routing overhead ratio when the end-to-end distance between the source and destination was set to 320 m. The inter-node distance is 40 m in this case. IEEE 802.11b performs almost the same way even while increasing the arrival rate. Even for high arrival rates, the delivery ratio for IEEE 802.11b remains fairly constant suggesting that the MAC is not saturated. COBRA MAC CB and LQE perform better compared to IEEE 802.11b. The performance improvement is consistent in terms of delivery ratio, end-to-end delay and routing overhead ratio.

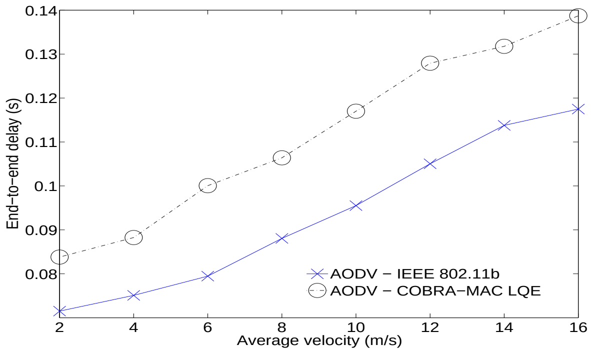

Fig. 57. End-to-end delay vs. Average velocity, random waypoint mobility model, area is 320 m X 320 m, pause time is 0 s, five sources, destinations picked in a uniformly distributed manner.

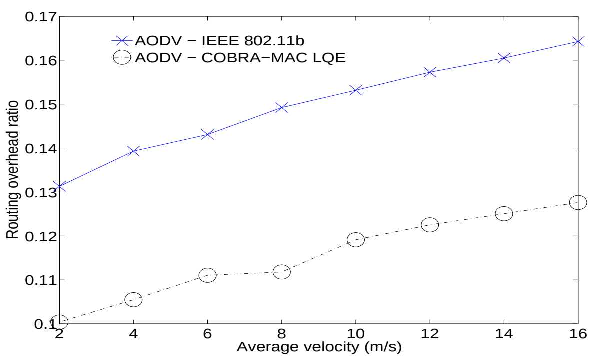

Fig. 58. Routing overhead ratio vs. Average velocity, random waypoint mobility model, area is 320 m X 320 m, pause time is 0 s, five sources, destinations picked in a uniformly distributed manner.

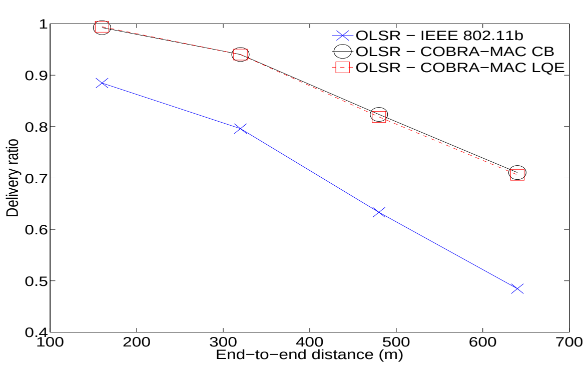

Fig. 59. Delivery ratio vs. End-to-end distance, linear topology, inter-node distance is 40 m, offered load is 2 kBps.

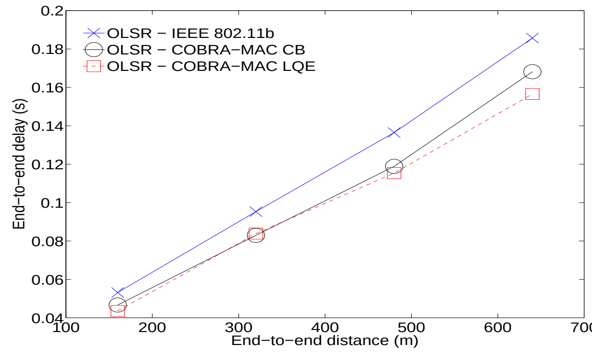

Fig. 60. End-to-end delay vs. End-to-end distance, linear topology, inter-node distance is 40 m, offered load is 2 kBps.

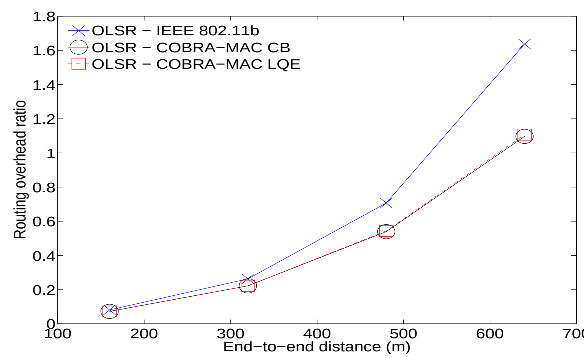

Fig. 61. Routing overhead ratio vs. End-to-end distance, linear topology, inter-node distance is 40 m, offered load is 2 kBps.

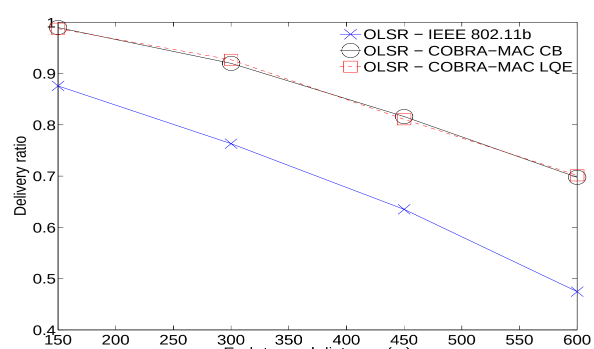

Fig. 62. Delivery ratio vs. End-to-end distance, linear topology, inter-node distance is 30 m, offered load is 2 kBps.

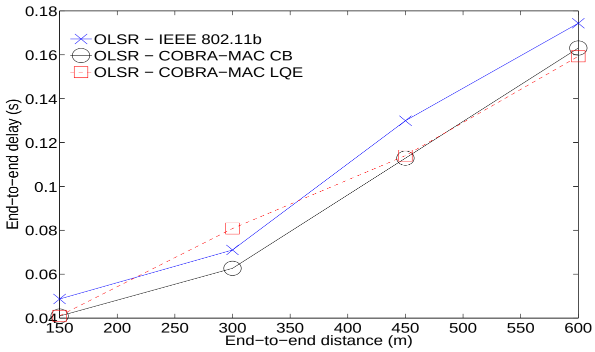

Fig. 63. End-to-end delay vs. End-to-end distance, linear topology, inter-node distance is 30 m, offered load is 2 kBps.

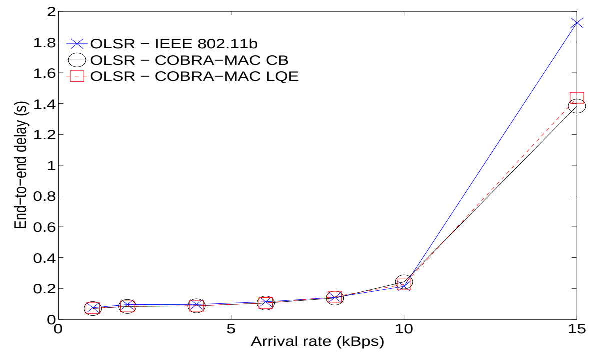

Fig. 66. End-to-end delay vs. Arrival rate, linear topology, end-to-end distance is 320 m, inter-node distance is 40 m.

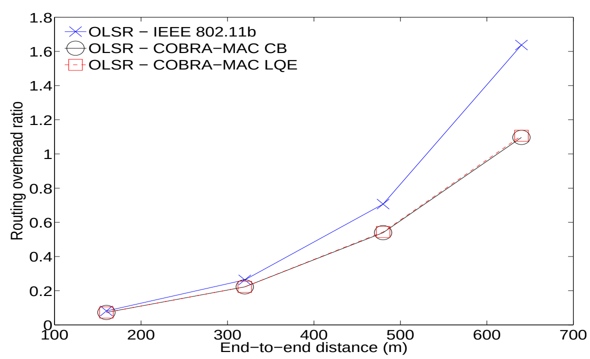

Fig. 64. Routing overhead ratio vs. End-to-end distance, linear topology, inter-node distance is 30 m, offered load is 2 kBps.

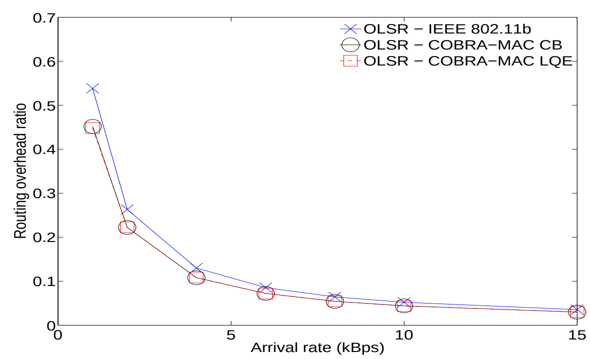

Fig. 67. Routing overhead ratio vs. Arrival rate, linear topology, end-to-end distance is 320 m, inter-node distance is 40 m.

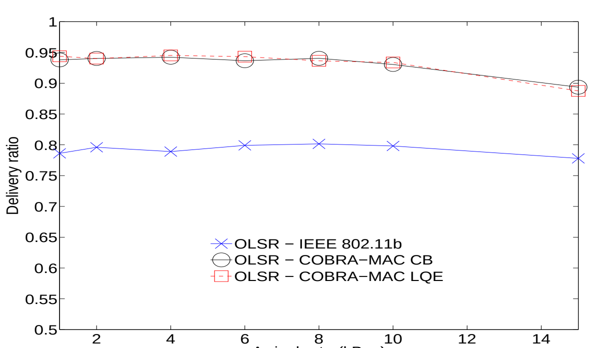

Fig. 65. Delivery ratio vs. Arrival rate, linear topology, end-to-end distance is 320 m, inter-node distance is 40 m.

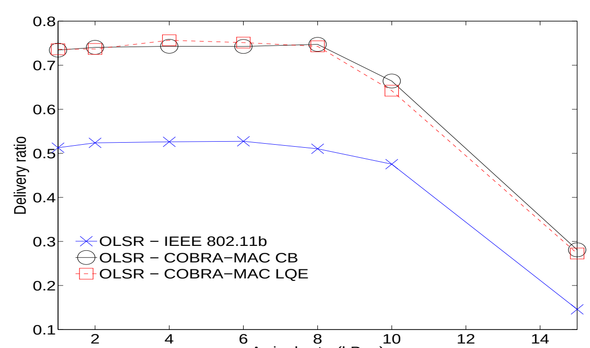

Fig. 68. Delivery ratio vs. Arrival rate, linear topology, end-to-end distance is 600 m, inter-node distance is 40 m.

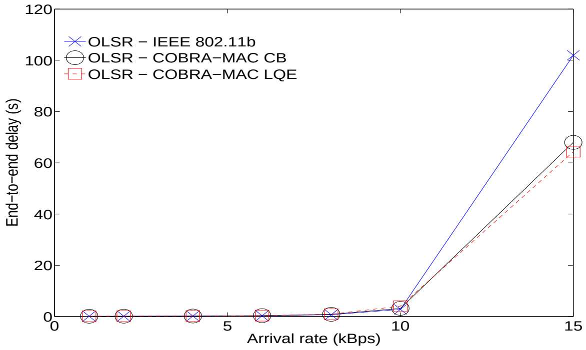

Fig. 69. End-to-end delay vs. Arrival rate, linear topology, end-to-end distance is 600 m, inter-node distance is 40 m.

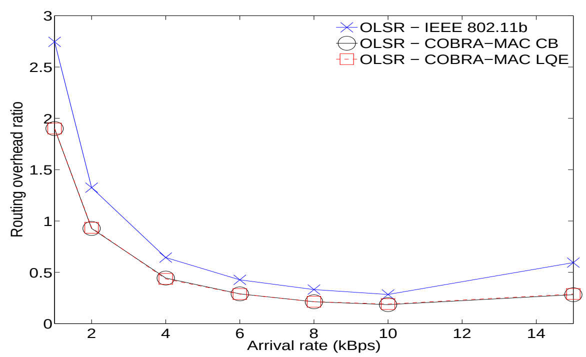

Fig. 70. Routing overhead ratio vs. Arrival rate, linear topology, end-to-end distance is 600 m, inter-node distance is 40 m.

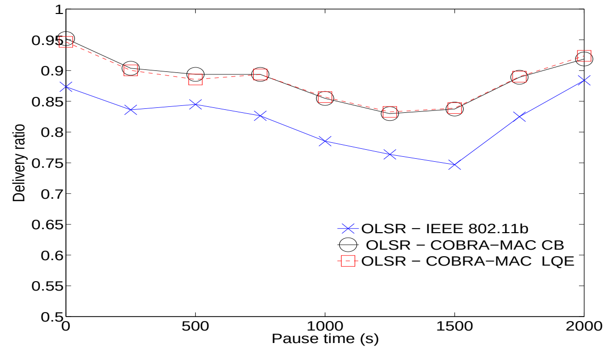

Fig. 71. Delivery ratio vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 15 nodes, 1 source.

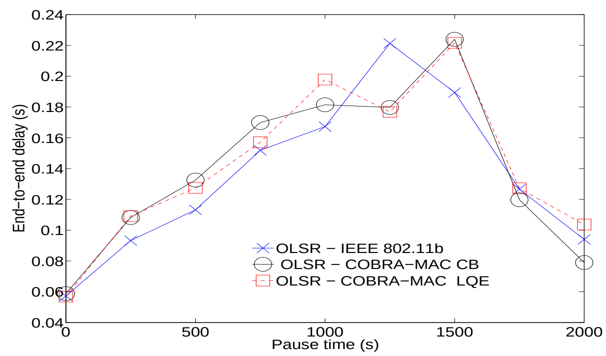

Fig. 72. End-to-end delay vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 15 nodes, 1 source.

Figs. 68, 69 and 70 show the delivery ratio, end-to-end delay and routing overhead ratio when the end-to-end distance between the source and destination was set to 600 m. The inter-node distance is 40 m in this case. IEEE 802.11b performs almost the same way till an arrival rate of 10 kBps. When arrival rate is further increased, IEEE 802.11b MAC is saturated. This is justified by the trend in the end-to-end delay. Also, the number of packets that are dropped as no route was available would increase. Any route failure would take non-negligible time to be reestablished. In OLSR, for a multi-hop destination (greater than two hops), the minimum time required is 5 s (equal to the TC message interval). This would mean that the number of packets dropped is 75 packets in a 5 s interval which is high. Also, a packet that does not have a valid next hop at the source would be buffered for a fixed time of 6 s (3 hello messages interval). It is seen that COBRA MAC can alleviate the problems caused by MAC saturation but could not fix the issues caused by routing.

B. Mobile scenario

1) Unlimited buffer capacity at IP: Figs. 71, 72 and 73 show the delivery ratio, end-to-end delay and routing overhead ratio in a mobile scenario. One source always generates the packets and the destination is kept the same across all simulations. The total time of simulation was 2000 s and the pause time of the nodes is varied along the x-axis. Each point is again an average over 10 independent simulation runs. COBRA MAC LQE performs almost the same as CB even in mobile scenarios. The relay search area for COBRA MAC CB is the circle that has source and destination on the circumference of the circle whose center is the midpoint of the line joining source and destination and radius equal to half the source-destination distance. The trend in end-to-end delay is mixed. There is no clear winner. This is because of using a fixed transmission rate of 1 Mbps. Also, in static networks a relay is always present and in advantageous positions. In mobile scenarios, we cannot guarantee vantage positions for the relays. It should also be noted that not all the individual hops can have relays in mobile scenario. Hence the path consists of heterogeneous mixture of IEEE 802.11b and COBRA MAC link protocols.

Figs. 74, 75 and 76 show the delivery ratio, end-to-end delay and routing overhead ratio when the number of nodes in the network is increased to 20. One source always generates the packets and the destination is kept the same across all simulations. The total time of simulation was 2000 s and the pause time of the nodes is varied along the X-axis. If we compare Figs. 71 and 71, it can be seen that increasing the node density would increase delivery ratio. This is because the routing protocol can use the extra nodes for route discovery. The comparison of IEEE 802.11b and COBRA MAC variants leads to similar conclusions as described previously.

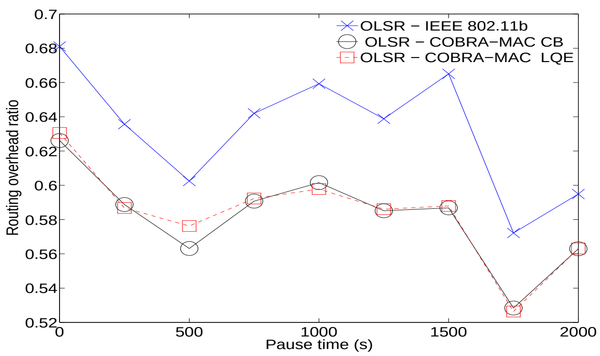

Fig. 73. Routing overhead ratio vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 15 nodes, 1 source.

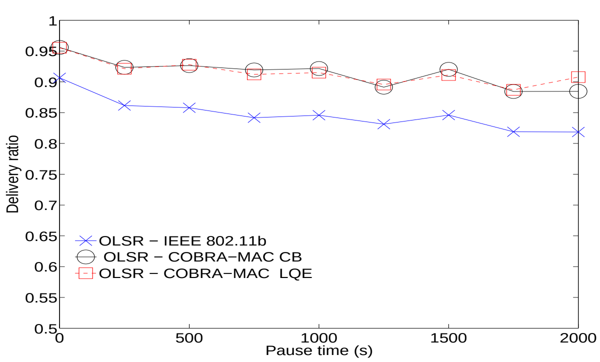

Fig. 74. Delivery ratio vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 20 nodes, 1 source.

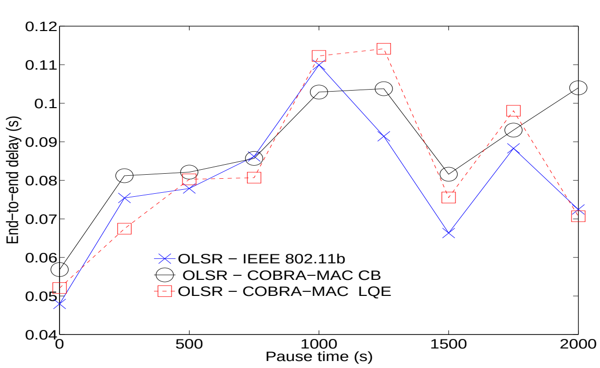

Fig. 75. End-to-end delay vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 20 nodes, 1 source.

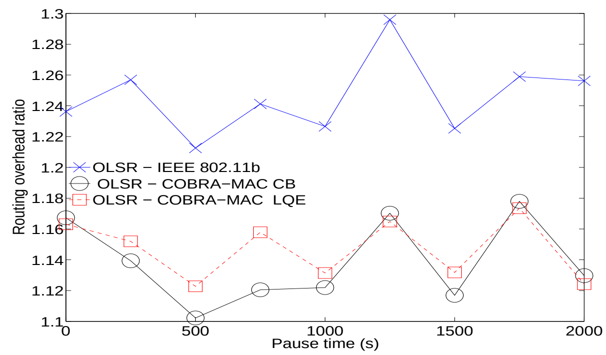

Fig. 76. Routing overhead ratio vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 20 nodes, 1 source.

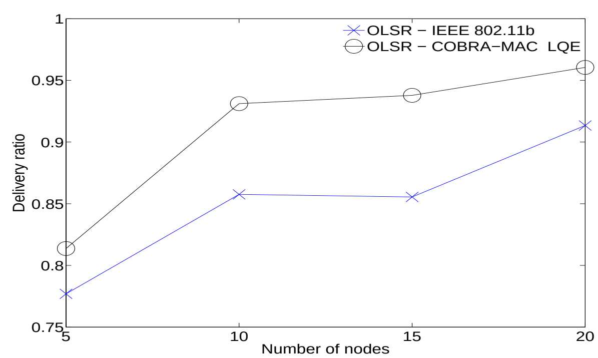

Fig. 77. Delivery ratio vs. Number of nodes, random waypoint mobility model, area is 320 m X 320 m, 1 source, pause time is 0 s.

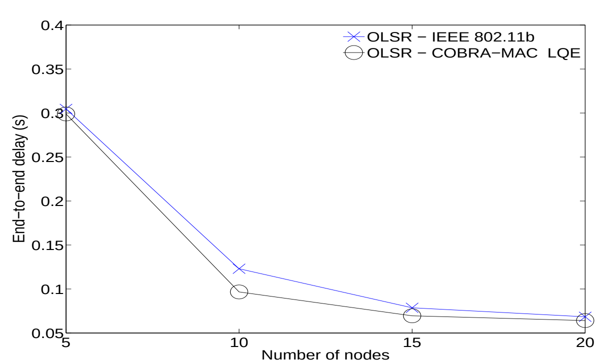

Fig. 78. End-to-end delay vs. Number of nodes, random waypoint mobility model, area is 320 m X 320 m, 1 source, pause time is 0 s.

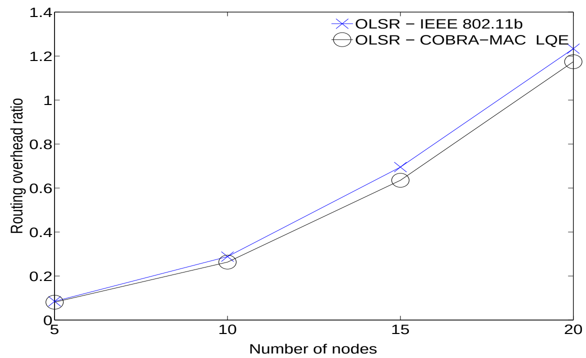

Fig. 79. Routing overhead ratio vs. Number of nodes, random waypoint mobility model, area is 320 m X 320 m, 1 source, pause time is 0 s.

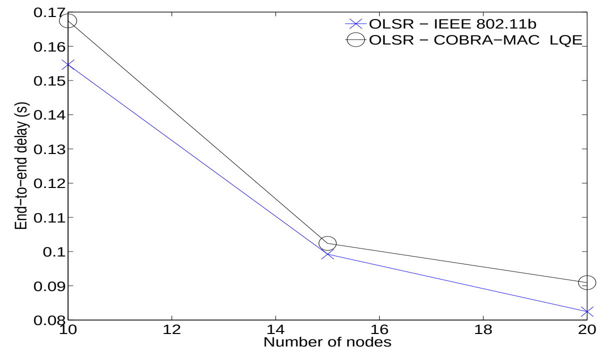

Fig. 81. End-to-end delay vs. Number of nodes, random waypoint mobility model, area is 320 m X 320 m, 5 sources, pause time is 0 s.

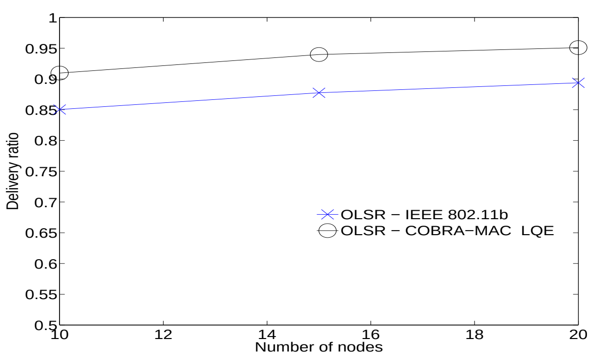

Fig. 80. Delivery ratio vs. Number of nodes, random waypoint mobility model, area is 320 m X 320 m, 5 sources, pause time is 0 s.

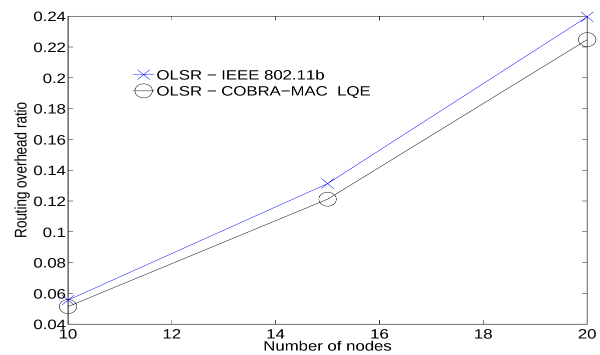

Fig. 82. Routing overhead ratio vs. Number of nodes, random waypoint mobility model, area is 320 m X 320 m, 5 sources, pause time is 0 s.

Figs. 77, 78 and 79 show the delivery ratio, end-to-end delay and routing overhead ratio in a mobile scenario when the number of nodes in the network is varied. One source always generates the packets and the destination is kept the same across all simulations. The total time of simulation was 1000 s and the pause time of the nodes was fixed to 0 s. This corresponds to relatively high mobility. As we increase the number of nodes, the delivery ratio increases. This is because the routing layer exploits the nodes to discover better paths. The performance of COBRA MAC in terms of delay is better compared to IEEE 802.11b.

Figs. 80, 81 and 82 show the delivery ratio, end-to-end delay and routing overhead ratio when the number of sources is increased to 5. There are five pairs of source-destination chosen before simulation and they perform as a source-sink pair across all simulations. The total time of simulation was 1000 s and the pause time of the nodes was fixed to 0 s. Figs. 77 and 80 present identical scenarios except that the number of flows is increased. This results in a decrease in delivery ratio across both the MAC variants. This is because of congestion in the network. This is justified by the delay comparison as reported in Figs. 78 and 81. COBRA MAC performs bad compared to IEEE 802.11b in Fig. 81. The increase in number of sources is congesting the network already. When relays try to help, they occupy the medium for a time equal to the transmission time of a packet. The delivery ratio improvement shows that the relays are successful in their attempts but it comes at a price with increase in delay. The delivery ratio plots in Figs. 77 and 80 show that COBRA MAC requires almost half the number of nodes to provide same or better connectivity than IEEE 802.11b.

Figs. 83, 84 and 85 show the delivery ratio, end-to-end delay and routing overhead ratio when there are five source-destination pairs and the pause time is varied from 0 s to 1000 s along the x-axis. There were 20 nodes in the network. Figs. 74 and 83 represent identical scenarios except that the number of sources is 5 in the latter. The gain in delivery ratio with COBRA MAC is seen to be less when the number of sources is 5. Also there is an increase in the delay when the number of sources is 5.

Keeping the same area, the number of sources was increased to 10. This means that there are no spare nodes which can act as a relay alone. A relay is either a source or a destination. We see from Figs. 86, 87 and 88, the gain with COBRA MAC reduces in terms of delivery ratio. The corresponding delay seen in Fig. 87 shows that COBRA MAC has already reached saturation. This is because of the infinite buffer size at the IP transmit queues. Because the channel is always busy, some nodes may not get the opportunity to transmit. This results in building up of IP queues which leads to enormous delays.

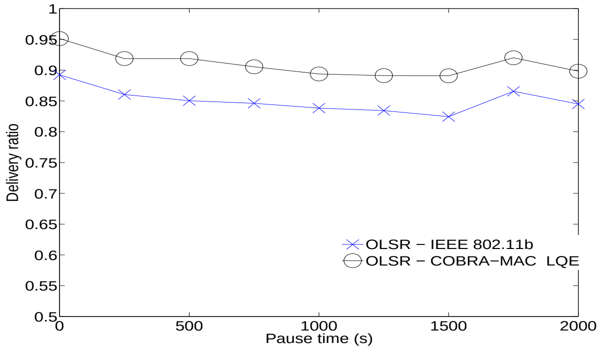

Fig. 83. Delivery ratio vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 20 nodes, 5 sources.

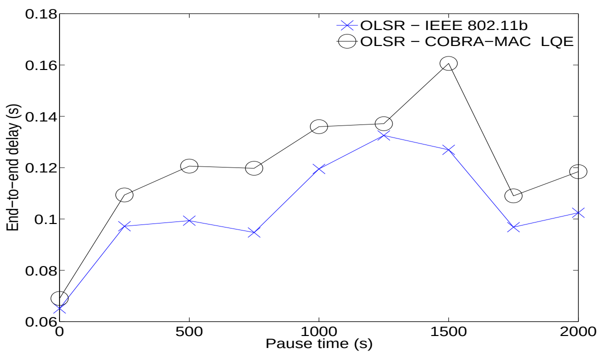

Fig. 84. End-to-end delay vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 20 nodes, 5 sources.

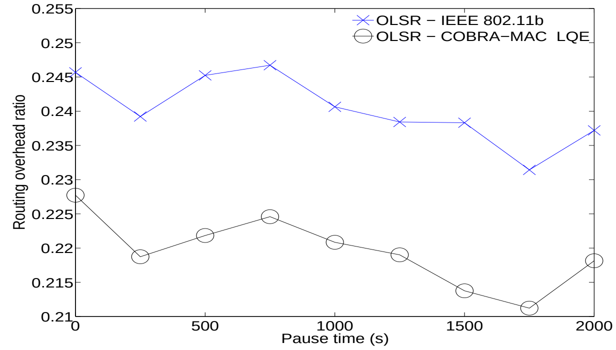

Fig. 85. Routing overhead ratio vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 20 nodes, 5 sources.

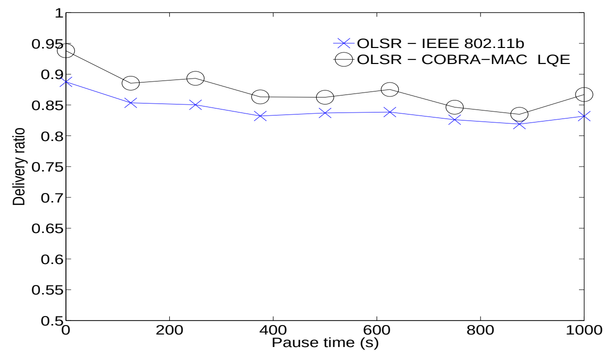

Fig. 86. Delivery ratio vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 20 nodes, 10 sources.

Figs. 89, 90 and 91 show the delivery ratio, end-to-end delay and routing overhead ratio when the number of sources was increased to 20. COBRA MAC performs inferior compared to IEEE 802.11b because it gets saturated quickly. A relay's transmission stops other nodes from transmitting their packets. With IEEE 802.11b already saturated, relay transmissions are extra transmissions that congest the network. The choice of giving preference to transit packets over the transmit packets does not work in favor of COBRA MAC. The probability of finding the transit packet queue empty decreases with cooperation. This means that the nodes are not transmitting their own packets instead they are transmitting the transit packets. This makes the transmit packets stay in the queue for a long time and when they finally get a chance to be transmitted, the queued packets significantly increase the delay which is seen in Fig. 90.

Thus we see that as we increase the number of active senders in the network, the network starts to get congested. Any transmission in the network causes the neighbors to sense the channel as busy making them unable to transmit their packets. Also if there is a node that is in the path of many flows in the network, the node's transit queue is never empty. This would mean that due to this particular node alone, the end-to-end delay for the packets forwarded by it would be very high. This is seen in 20 sources case.

2) Limited buffer capacity at IP: Figs. 92, 93 and 94 show the delivery ratio, end-to-end delay and routing overhead ratio in a mobile scenario when number of nodes was varied and the number of sources was 5. The pause time was fixed to be 0 s. The number of control packets that could be buffered at any node was set to a maximum of 16 packets and the number of data packets (including the transit packets) that could be buffered was set to 48 packets. Control packets get preference over data packets. Also, the transit packets are given preference over a node's own data packets. The end-to-end delay comparison of Figs. 93 and 81 confirms that the limit on queue size did not have an effect. This is because the queues do not get full in this scenario. Also, the delivery ratio remained fairly the same as shown in Figs. 92 and 80.

Figs. 95, 96 and 97 show the delivery ratio, end-to-end delay and routing overhead ratio when pause time was varied. The number of nodes in the network was 20 and there were 5 source-destination pairs. The plots look similar to the case with unlimted buffer size as shown in Figs. 83 and 84. The variance in delay disappeared when buffer size was limited.

Figs. 98, 99 and 100 show the delivery ratio, end-to-end delay and routing overhead ratio when pause time was varied with the number of sources being 10. The number of nodes in the network was 20. The comparison between Figs. 87 and 99 shows the advantage of using limited buffer size. This significantly reduces the delay for both the MAC variants. By limiting the buffer size, more packets are dropped due to buffer overflow which is reflected in Fig. 98.

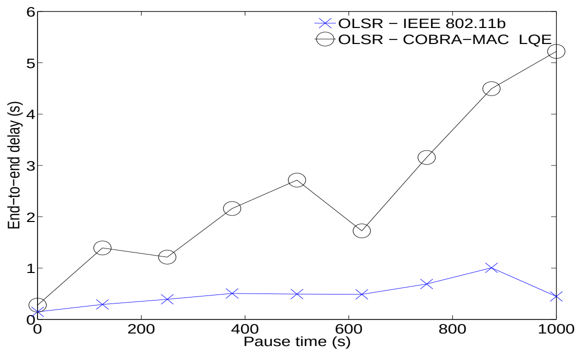

Fig. 87. End-to-end delay vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 20 nodes, 10 sources.

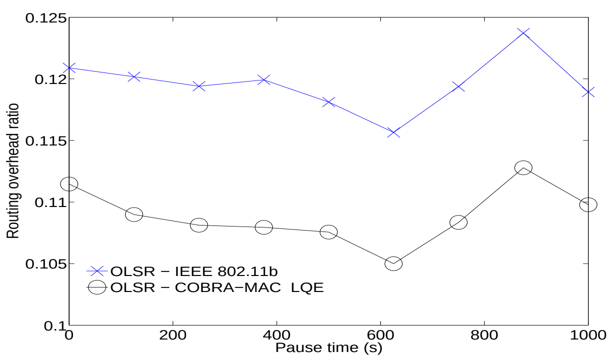

Fig. 88. Routing overhead ratio vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 20 nodes, 10 sources.

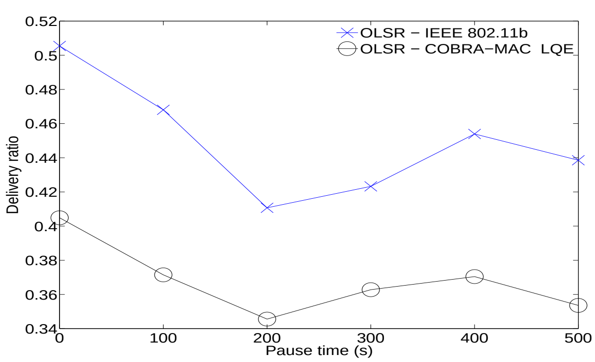

Fig. 89. Delivery ratio vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 30 nodes, 20 sources.

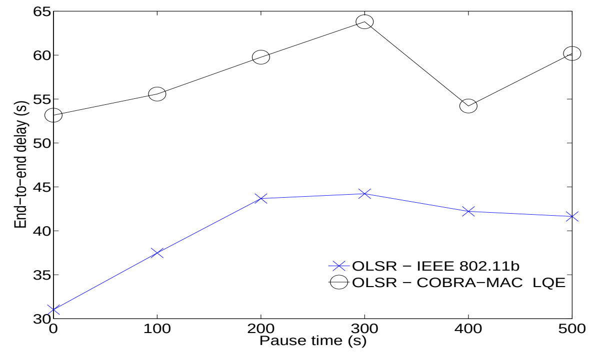

Fig. 90. End-to-end delay vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 30 nodes, 20 sources.

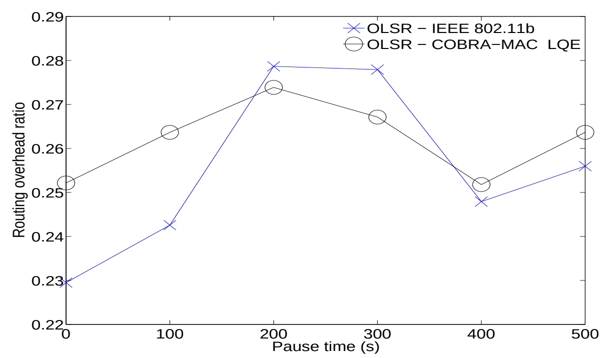

Fig. 91. Routing overhead ratio vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 30 nodes, 20 sources.

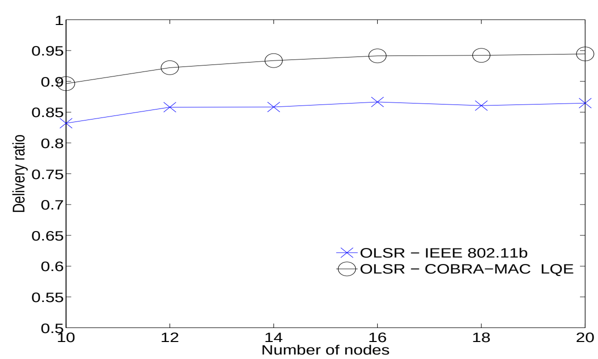

Fig. 92. Delivery ratio vs. Number of nodes, random waypoint mobility model, area is 320 m X 320 m, 5 sources, pause time is 0 s.

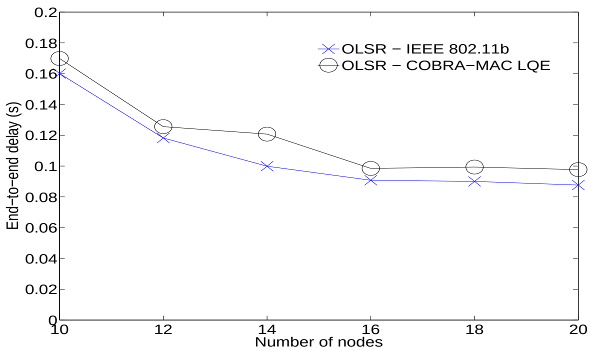

Fig. 93. End-to-end delay vs. Number of nodes, random waypoint mobility model, area is 320 m X 320 m, 5 sources, pause time is 0 s.

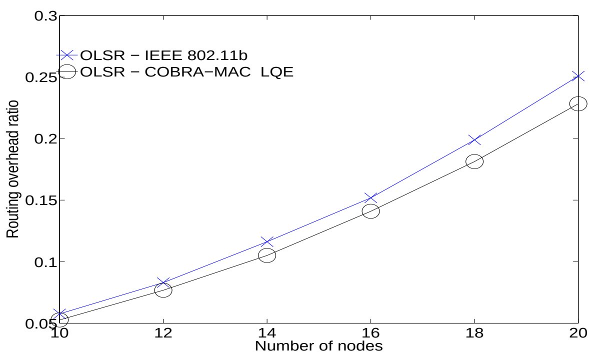

Fig. 94. Routing overhead ratio vs. Number of nodes, random waypoint mobility model, area is 320 m X 320 m, 5 sources, pause time is 0 s.

Figs. 101, 102 and 103 report the delivery ratio, end-to-end delay and routing overhead ratio in the limited buffers case when the number of nodes in the network is 30 and the number of sources is 20. When compared to the plots Figs. 89, 90 and 91 with unlimited buffer size, the delay is much lesser in the limited buffers case. This is because packets that are dropped when the queues are full do not contribute to the delay. However, the delivery ratio for COBRA MAC is less compared to IEEE 802.11b. This is because COBRA MAC gets saturated much faster compared to IEEE 802.11b. Thus cooperation is not a suitable option when the network is really congested. Use of relays would be beneficial when the network is suitably dense but not congested.

3) Rectangular grid results: In section VI-B, the nodes were allowed to roam inside a square area. In this subsection, results for nodes moving around in a rectangular area are presented. All results presented henceforth would have limited buffers as it appears practical and beneficial to all protocol variants. Also in results presented so far for mobile scenario, the pause time of a node was uniformly distributed. In results that follow, the pause time is fixed.

Figs. 104, 105 and 106 show the delivery ratio, end-to-end delay and routing overhead ratio for both IEEE 802.11b and COBRA MAC when nodes were moved in a rectangular area of 360 m X 180 m. The delivery ratio, end-to-end delay and routing overhead ratio maintain similar trends. The pause time was fixed.

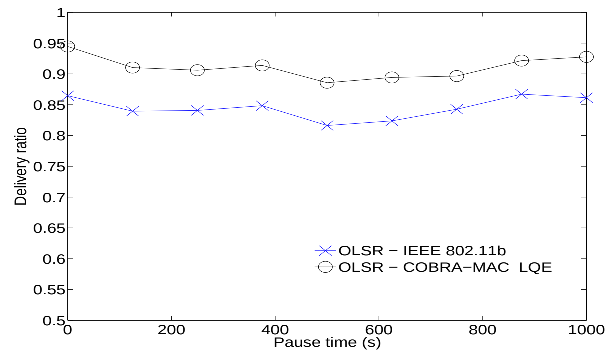

Fig. 95. Delivery ratio vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 20 nodes, 5 sources.

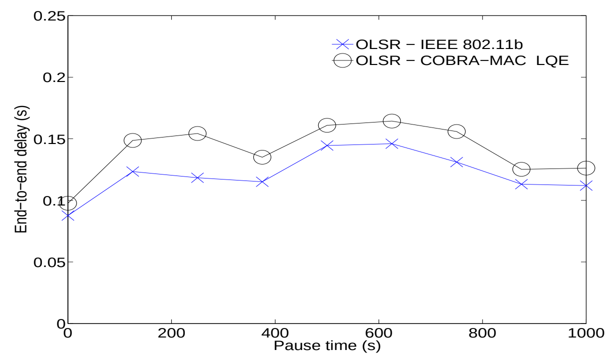

Fig. 96. End-to-end delay vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 20 nodes, 5 sources.

4) Effect of mobility: To better depict the effect of mobility on protocol performance, velocity was chosen as the controlling parameter. Figs. 107, 108 and 109 show the delivery ratio, end-to-end delay and routing overhead ratio when average velocity was varied along the x-axis. There are five sources in the network generating traffic to destinations uniformly chosen among the set of available nodes. The pause time was fixed to 0 s which corresponds to highly mobile case. The delivery ratio for IEEE 802.11b falls steeply due to frequent link breaks. COBRA MAC is robust to change in node positions as seen in the graph. The gain of COBRA MAC over IEEE 802.11b at high mobility is about 23%. COBRA MAC has higher delay compared to IEEE 802.11b but at the same time COBRA MAC delivers more number of packets. Thus the comparison of delay is not fair. The increase in delivery ratio also affects the routing overhead ratio positively. COBRA MAC requires the same amount of routing overhead ratio as IEEE 802.11b to deliver more number of packets.

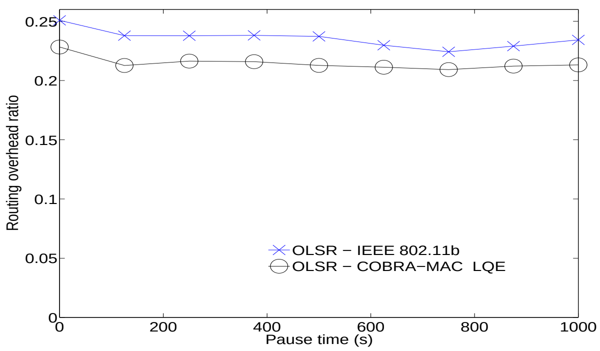

Fig. 97. Routing overhead ratio vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 20 nodes, 5 sources.

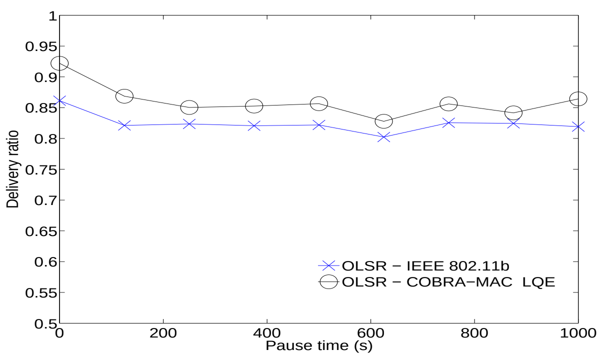

Fig. 98. Delivery ratio vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 20 nodes, 10 sources.

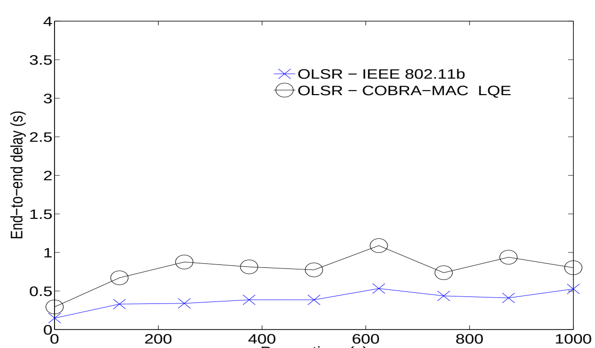

Fig. 99. End-to-end delay vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 20 nodes, 10 sources.

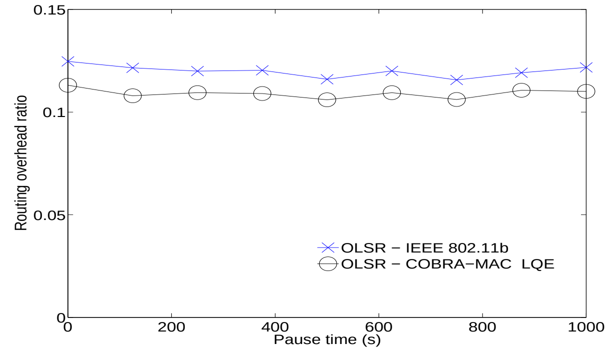

Fig. 100. Routing overhead ratio vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 20 nodes, 10 sources.

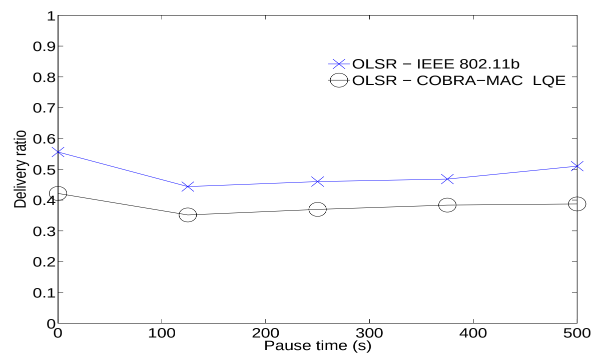

Fig. 101. Delivery ratio vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 30 nodes, 20 sources.

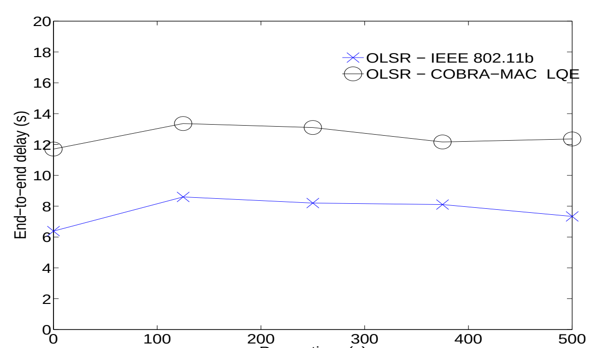

Fig. 102. End-to-end delay vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 30 nodes, 20 sources.

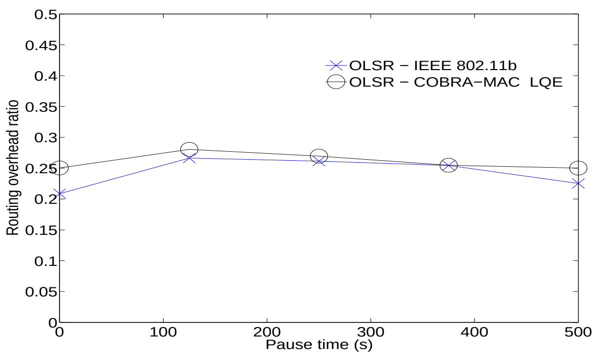

Fig. 103. Routing overhead ratio vs. Pause time, random waypoint mobility model, area is 320 m X 320 m, 30 nodes, 20 sources.

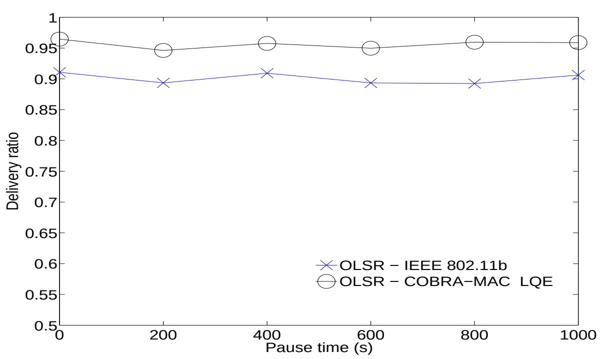

Fig. 104. Delivery ratio vs. Pause time, random waypoint mobility model, area is 360 m X 180 m, 20 nodes, 5 sources.

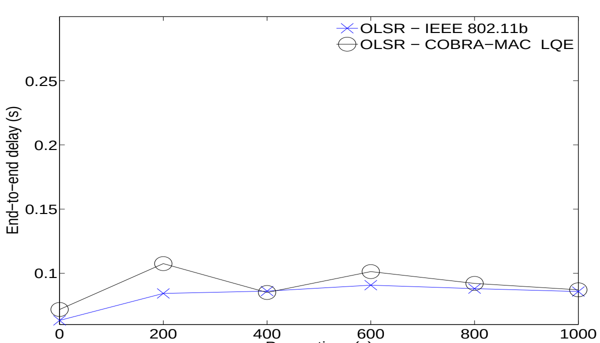

Fig. 105. End-to-end delay vs. Pause time, random waypoint mobility model, area is 360 m X 180 m, 20 nodes, 5 sources.

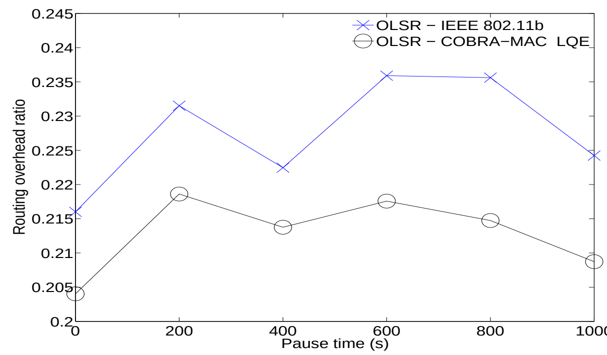

Fig. 106. Routing overhead ratio vs. Pause time, random waypoint mobility model, area is 360 m X 180 m, 20 nodes, 5 sources.

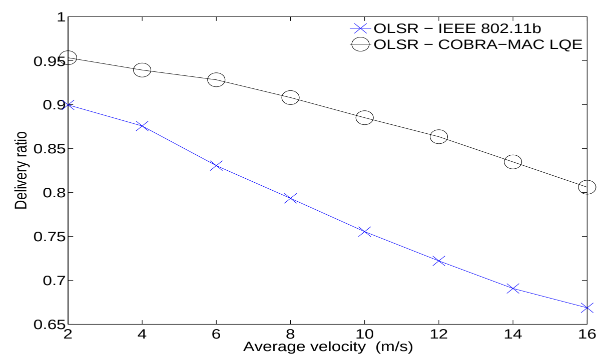

Fig. 107. Delivery ratio vs. Average velocity, random waypoint mobility model, area is 320 m X 320 m, pause time is 0 s, five sources, destinations picked in a uniformly distributed manner.

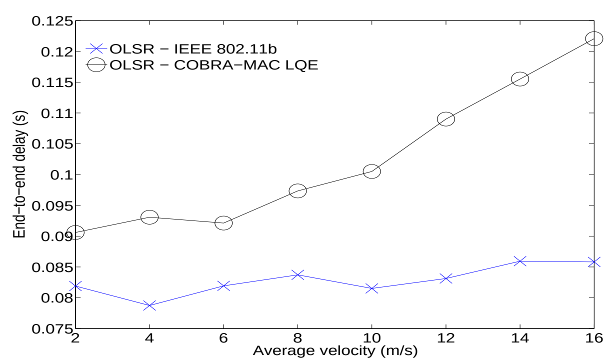

Fig. 108. End-to-end delay vs. Average velocity, random waypoint mobility model, area is 320 m X 320 m, pause time is 0 s, five sources, destinations picked in a uniformly distributed manner.

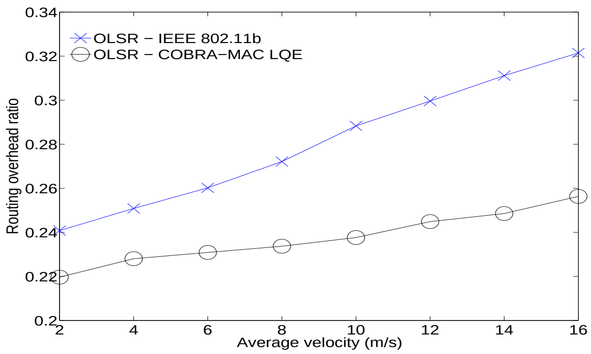

Fig. 109. Routing overhead ratio vs. Average velocity, random waypoint mobility model, area is 320 m X 320 m, pause time is 0 s, five sources, destinations picked in a uniformly distributed manner.

VII. CONCLUSION

COBRA — a cooperative MAC protocol — may be instrumental to overcome some drawbacks of today's mobile routing protocols. COBRA MAC was found to improve various performance metrics of routing protocols (in the study AODV and OLSR), i.e., packet delivery ratio, end-to-end delay, and routing overhead. No changes are required in the routing protocol, as the cooperative mechanism is fully implemented in the MAC layer, including the dynamic selection of the relay for every individual link transmission. Future studies on the subject will address end-to-end throughput gains of the routing protocol, which may be obtained when using multiple transmission rates at the MAC.

REFERENCES

[1] D. D. Couto, D. Aguayo, J. Bicket, and R. Morris, "A High-Throughput Path Metric for Multi-hop Wireless Routing," in *Proc. ACM/MobiCom 2003*, San Diego, September 2003.

[2] R. Draves, J. Padhye, and B. Zill, "Routing in Multi-Radio, Multi-hop Wireless Mesh Networks," in *Mobicomm 2004*, Philadelphia, Pennsylvania, USA, 2004.

[3] K. N. Ramachandran, M. M. Buddhikot, G. Chandramenon, S. Miller, E. M. B. Royer, and K. Almeroth, "On the Design and Implementation of Infrastructure Mesh Networks," in *IEEE Workshop on Wireless Mesh Networks (WiMesh)*, California, USA, sep 2005.

[4] [Online]. Available: http://www.olsr.org/docs/README-Link-Quality.html

[5] N. Agarwal, D. ChanneGowda, L. N. Kannan, M. Tacca, and A. Fumagalli, "IEEE 802.11b cooperative Protocols:A performance study," in *IFIP/TC6 NETWORKING 2007*, Atlanta, GA, USA, May 2007.

[6] M. Janani, A. Hedyat, T. Hunter, and A. Nosratinia, "Coded Cooperation in Wireless Communications: Space-time Transmission and Iterative Decoding," in *IEEE Trans. on Signal Processing*, Feb 2004, vol. 52, no. 2, pp. 362–371.

[7] P. Gupta, I. Cerutti, and A. Fumagalli, "Three Transmission Scheduling Policies for a Cooperative ARQ protocol in Radio Networks," in *Proc. WNCG conference*, Oct. 2004.

[8] P. Liu, Z. Tao, and S. Panwar, "A Co-operative MAC Protocol for Wireless Local Area Networks," in *Proc. IEEE International Conference on Communications (ICC)*, Seoul, Korea, may 2005.

[9] L. Kannan, K. Vijayasankar, D. Channegowda, N. Agarwal, M. Tacca, and A. Fumagalli, "Cooperative Communications in Multi-hop Networking: a Case Study Based on the IEEE 802.11 Protocol." [Online]. Available: http://opnear.utdallas.edu/publications/reports/UTD-EE-03-2007.pdf

[10] C. E. Perkins and E. M. Royer, "Ad-hoc On-demand Distance Vector Routing," in *Proceedings of the 2nd IEEE Workshop on Mobile Computer Systems and Applications*, New Orleans, LA, USA, February 25–26 1999.

[11] T. Clausen, P. Jacquet, A. Laouiti, P. Muhlethaler, a. Qayyum, and L. Viennot, "Optimized Link State Routing Protocol," in *IEEE INMIC Pakistan*, 2001, best paper award.

[12] A. Bletsas, A. Lippman, and D. P. Reed, "A Simple Distributed Method for Relay Selection in Cooperative Diversity Wireless Networks Based on Reciprocity and Channel Measurements," in *Vehicular Technology Conference, 2005. VTC 2005-Spring. 2005 IEEE 61st*, 2005, Vol. 3, pp. 1484–1488.

[13] C. E. Perkins, E. M. Belding-Royer, and S. R. Das, "Rfc3561 – ad hoc on-demand distance vector (aodv) routing," July 2003. [Online]. Available: http://www.ietf.org/rfc/rfc3561.txt

[14] T. Clausen and P. Jacquet, "Optimized Link State Routing Protocol (olsr)," United States, 2003. [Online]. Available: http://www.ietf.org/rfc/rfc3626.txt

[15] N. Agarwal, "Cooperative MAC Protocols for IEEE 802.11 Ad Hoc Networks," Master's thesis, The University of Texas at Dallas, 2006.

[16] P. S. Christian Bettstetter, Giovanni Resta, "The node distribution of the random waypoint mobility model for wireless ad hoc networks," *IEEE Transactions on Mobile Computing*, 2003.

[17] S. S. Ghanta Ravikiran, "Influence of mobility models on the performance of routing protocols in ad-hoc wireless networks," *IEEE 2004*, 2004.