A Comprehensive Comparison of Routing Protocols for Large-Scale Wireless MANETs

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***Abstract* – Efficient routing protocols can provide significant benefits to mobile ad hoc networks, in terms of both performance and reliability. Many routing protocols for such networks have been proposed so far. Amongst the most popular ones are Dynamic Source Routing (DSR), Ad hoc On-demand Distance Vector (AODV), Temporally-Ordered Routing Algorithm (TORA) and Location-Aided Routing (LAR). Despite the popularity of those protocols, research efforts have not focused in evaluating their performance when applied to large-scale wireless networks. Such networks are comprised of hundreds of nodes, connected via long routes. This greatly affects the network efficiency, since it necessitates frequent exchange of routing information. In this paper we present our observations regarding the behavior of the above protocols, in large-scale mobile ad hoc networks (MANETs). We consider wireless mobile terminals spread over a large geographical area, and we perform extensive simulations, using the QualNet and NS-2 simulators. The results of the simulations yield some interesting conclusions: AODV suffers in terms of packet delivery fraction (PDF) but scales very well in terms of end-to-end delay. DSR on the other hand scales well in terms of packet delivery fraction but suffers an important increase of end-to-end delay, as compared to its performance achieved in small-scale topologies. Also, the effect of maximum connections is severe on TORA, which seems unable to route large amounts of traffic. LAR, seems to scale very well, in terms of all metrics employed.**

***Index Terms* – Wireless Communications, Mobile Ad Hoc Networks, IEEE 802.11, Routing, Performance Evaluation.**

I. Introduction

In order for ad hoc networks to operate as efficiently as possible, appropriate on-demand routing protocols have to be incorporated, to find efficient routes from a source to a destination, taking into consideration the node mobility. Mobility affects ongoing transmissions, since a mobile node that receives and forwards packets may move out of range. As a result, links fail over time. In such cases a new route must be established. Thus, a quick route recovery procedure should be one of the main characteristics of a routing protocol.

Our motivation stems from the fact that, to the best of our knowledge, *the behavior of most of the already proposed routing protocols has not yet been evaluated for large-scale network deployments*. Such networks present a quite different behavior than ordinary networks, in terms of response to connectivity changes. Network scalability implies that distant nodes are likely to connect through long routes. This leads to a larger probability of route failures, since a route now consists of many vulnerable links. One may argue that this depends on the transmission power. Even with high transmission power however, in large scale networks[1] long routes are very likely to exist. As a result, we end up having a reduced neighborhood per node, and a multiple-hop route between a sender and a recipient. Such dynamic topologies are more vulnerable to route failures, since the probability of failure of at least one of the links that comprise the route is now much higher.

As our contribution in this paper we provide a comprehensive performance comparison of four very popular ad hoc routing protocols, in large-scale, variable network topologies. For our studies we utilize two simulators: QualNet and NS-2. We use NS-2 due to its popularity, so that we are able to have a level of comparison to other related studies on routing protocol evaluations especially for smaller scales. We also utilize QualNet, because it is optimized for fast simulations of large-scale networks. We present a set of simulation results, which demonstrates the advantages and the drawbacks of each routing approach. We evaluate the following protocols: AODV [14], DSR [10], LAR [11] and TORA [13].

The rest of this paper is organized as follows. In section II we briefly describe the on-demand routing protocols that we evaluate. In section III we discuss the most important previous studies on the subject and explain our extension to those studies. In Section IV we present our simulation results and observations. Finally, section V concludes the paper.

II. Wireless Ad Hoc Routing Protocols

In this section we briefly describe the on-demand protocols that we investigate. A more detailed description is presented in [3].

AODV: The Ad hoc On-demand Distance Vector routing protocol [14] does not maintain global routing information for the whole network[2]. Nodes that do not belong to a route, do not need to maintain information about that route. Such nodes

[1] We consider that a network is large-scale if it is in the order of hundreds of nodes.

[2] This is a common characteristic of all on-demand routing protocols.

do not send or receive topology-update packets, hence they have information only for their active routes. A node considers a route as active, if it sends, receives or forwards packets for that route and if there is at least one data packet transmitted through this route within a fixed time interval. Hence in AODV, route discovery packets are initiated and broadcasted only when a source desires to contact an intended destination for which is does not have a valid route. Furthermore, changes in network topology must be sent only to those nodes that will need this information. Thus, AODV dynamically establishes route table entries. Every node maintains an increasing counter in order to replace unused or broken routes. A disadvantage of AODV is that it does not support asymmetric links. That is, AODV is capable of supporting only symmetric links between nodes, both of which are able to send packets to each other.

DSR: The Dynamic Source Routing protocol [10] also allows mobile sources to dynamically discover paths towards any desired destination. Every data packet includes a complete list of nodes, which the packet must pass before it reaches the destination. Hence, all nodes that forward or overhear these packets may store routing information for future use. DSR can support fast network topology changes and service even asymmetric links; it can successfully find paths and forward packets in unidirectional link environments. Moreover, like AODV, it has a mechanism for on-demand route maintenance, so there are no periodic topology update packets. When link failures occur, only nodes that forward packets through those links must receive proper routing advertisements. In addition, DSR allows source nodes to receive and store more than one path towards a specific destination. Intermediate nodes have the opportunity to select another cached route as soon as they are informed about a link failure.

A source that desires to send data to a particular destination, first checks to verify that it has a route in its cache for that destination. If it does, it will use that route by placing (in the data packet header) the sequence of hops that the packet must follow to reach the destination. If there is no such route stored in the local cache, then the source will initiate a new path discovery process, by broadcasting a **Route Request** to its neighborhood. This message contains the source and destination addresses, a request ID and an ordered intermediate node address list, through which this message has passed. This node list is initially blank when the message leaves the source node (it has not yet visited any other node). Thereafter, every other node that receives this request message parses it to see if it is the intended destination. If it is, it will reply with a **Route Reply** back to the source, after attaching the list with all intermediate nodes through which the request message passed. If it is not and has already received a similar request with the same ID from the same source, it will discard this request message. If it is not and it sees that its own address is included in the message list, it will discard this request message. Else it will append its own address in this list and then it will further broadcast it to its neighbors.

LAR: Routing overhead can be decreased, by giving location information to the mobile terminals, with use of the Global Positioning System (GPS) for route discovery. Two *Location-Aided Routing* algorithms that use location information have been proposed [11], showing how a route discovery protocol, based on flooding, can be improved. If a node S wants to send data to a node D, for which it knows the previous location L at time t_0 and node D's speed u, then S *expects* that D will be located within an "***expected zone***" at time t_1, a circular area of radius $u(t_1 - t_0)$ and center L. If node S does not know the previous location L, then the "expected zone" for node D will be considered as the whole network geographical region, and the algorithm will follow the basic flooding as in the DSR algorithm.

The two LAR algorithms in [11] use flooding with one modification; the source node S defines a "***request zone***" for the route request. An intermediate node will forward the request message, only if it is located within the request zone. If the request zone includes the expected zone, the probability of finding node D will be increased. The request zone may also include other neighboring request zones. The two schemes give terminals the capability of determining whether they belong to a requested zone or not, so as to know if they should forward certain route request messages. The interested reader may find more details in [11], wherein both schemes are simulated and evaluated.

TORA: Another distributed and loop-free algorithm is the Temporally-Ordered Routing Algorithm (TORA) [13], which quickly provides multiple routes, with less routing overhead, by restricting the generation of routing messages to those terminals located close to the topological changes. Each station needs information about its one-hop neighbors only. This reveals the distributed operation of this routing protocol, which provides multiple routes towards a destination. The protocol includes mechanisms for route discovery, route maintenance and route deletion.

Let us assume a network with N nodes represented by a graph *G = (N, L)*, where L is an initial set of undirected symmetric links (i, j). Each link may be assigned one of three states: *undirected, directed from i to j, and directed from j to i.* For a node i, we define the neighbors N_ig $\in$ g, to the set of nodes j such that $(i, j) \in \quad L$. Mobile nodes establish a directed acyclic graph towards destinations. When topological changes cause link failures, route re-establishment takes place through some "*temporally-ordered"* computations, consisting of a sequence of directed link reversals. TORA discovers routes on demand; however the main goal of the algorithm is to establish routes quickly, while finding the shortest path is of secondary importance. Below we give a brief description of this routing protocol. More details can be found in [12]. Every terminal has a "height" with respect to the destination, calculated by the protocol. Each time a source desires to send data towards an intended receiver, it initiates a *Query* message in which it includes the destination address. The destination, or an intermediate receiver of this message with a route to destination, will reply with an *Update* packet listing its height. Each terminal receiving this *Update* packet sets its height to some value larger than the one contained in the packet. In this way, a set of sequential directed links is created, with edges from the source node to the node that first broadcasted the *Update* packet.

III. Previous Work

In this section we summarize the most relevant previous studies concerning ad hoc on-demand routing performance comparisons. The authors in [2] compare four ad hoc routing protocols using a maximum number of 50 nodes but their traffic load is relatively low, since the data packet size is 64 bytes, the maximum number of sources is 30 and every source node transmits 4 packets / sec. The authors in [7] compare three routing protocols, AODV, DSR and STAR, for which they used two simulators as well: GlomoSim and NS-2. They assume a relatively small geographical region. An interesting approach is also followed in [8], which introduces a new mobility metric: the relative terminal speeds rather than absolute pause times and speeds. A thorough work is presented in [6], in which the authors have performed an extensive performance evaluation between DSR and AODV, in which the basic mobility metric is the node pause times. This work however does not include large-scale networks either. This is also the case with the comparison between AODV, PAODV, CBRP, DSR, and DSDV presented in [1].

Most of the previous work is limited on performing simulations for ad hoc networks with a limited number of nodes deployed in small geographical areas. Our work differs in that we extend our observations to large-scale deployments. We observe and comment on the behavior of each protocol.

IV. Routing Performance Comparisons

In this section we present our simulation efforts to evaluate and compare the performance of the protocols that we described previously in Section II. Additional simulation results are presented in [3].

A. Performance Evaluation Using QualNet

1) The Traffic and Mobility Models: We've used a similar model with [7], [6] to compare the impact of using large-scale topologies (500 nodes) in the performance of the protocols as opposed to the case when a limited number of nodes (50-100) are used. The traffic sources are of continuous bit rate (CBR). The source-destination pairs are chosen randomly from the set of the network's nodes and are the same throughout the duration of the simulation. The data packet is chosen to be 512 bytes and the channel bandwidth 2 Mbps. As a mobility model we utilize the random waypoint in a rectangular field 12000m x 6000m with 500 nodes. Each simulation is run for 200s (simulation time). We've used the same performance metrics as in [7], [6], to be able to directly compare our findings: average end-to-end delay of data packets, normalized routing overhead–the number of routing packets per data packet delivered at the destination and normalized routing load–the number of routing packets transmitted per data packet delivered to the destination.

2) Simulation Results: For our simulations we use 20 sources generating packets with a fixed rate of 4 packets/seconds. In Figure 1, we depict the Packet Delivery Fraction (PDF) for three of the routing protocols upon investigation. As we observe, there is an important degradation of PDF for the AODV as opposed to that of LAR1 and DSR. What is most important is that there is a non-trivial difference between the PDF of AODV measured for 500 nodes and that measured in [6], for 50 nodes. A possible explanation could be that the route discovery process of AODV causes very long delays for large scale networks, due to the amount of control packets transmitted. These delays result in packets (waiting in the queues) being dropped. One should not be surprised by the fact that the end-to-end average delay of AODV appears to be small, as it refers only to delivered packets.

Figure 2 depicts the Average delay in seconds for LAR, DSR and AODV. For this metric, DSR is demonstrating a bad performance as opposed to that achieved for a 50 nodes topology ([6]). A possible explanation for this result could be the aggressive use of route caching in DSR. For a large number of nodes the cache size can increase significantly resulting to increase in delay. Furthermore choosing stale routes can further increase the delay.

For the normalized routing overhead, the results are depicted in Figure 3. There is a dramatic increase in the routing overhead for both DSR and AODV, as compared to the 50 nodes topology, in [6]. This is expected, as many more packets are needed for the route discoveries, especially for AODV, where each of its route discoveries typically propagates to every node. DSR limits the amount of routing packets by making use of cached routes. Another observation is that LAR performs much better than the other two, since it makes use of the nodes' location, decreasing the number of routing packets broadcasted.

B. Performance Evaluation Using NS-2

1) Simulation Model: The simulation model we used was based on the Monarch Project's extensions to NS-2, to support multi-hop ad hoc wireless networks [2]. These include physical, data link, and medium access control layer models. The Distributed Coordination Function (DCF) of IEEE 802.11 is used to model the contention of nodes for the wireless medium. The radio model uses characteristics similar to Lucent's WaveLAN direct sequence spread spectrum radio. The protocols maintain a send buffer of 64 packets, which contains the data packets waiting to be routed. Those are dropped if they wait in the send buffer for more than 30s. All the packets are queued in the interface queue, until the MAC layer can transmit them. The interface queue can hold 50 packets at most.

2) Traffic Model: The source-destination pairs were spread randomly over the network. Constant bit rate (CBR) traffic sources were used. We experimented for different offered loads, by varying the number of source-destination pairs (10 and 20), while keeping the size of the packets and the packet sending rate constant, at 512 bytes and 4 packets/s respectively.

3) Mobility Model: We simulated 50 wireless nodes forming an ad hoc network, moving over a rectangular $1500 \cdot 300$ flat space, with a maximum speed of 20 m/s (average speed 10 m/s). The movement of the nodes was based on the random waypoint model [9]. Each packet starts its journey from a random location to a random destination with a seed of 1 (randomly chosen and uniformly distributed between 0-20 m/s). Once the destination is reached, another random

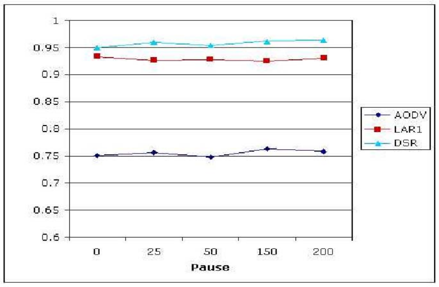

Fig. 1. Packet Delivery Fraction (PDF) for LAR, DSR and AODV.

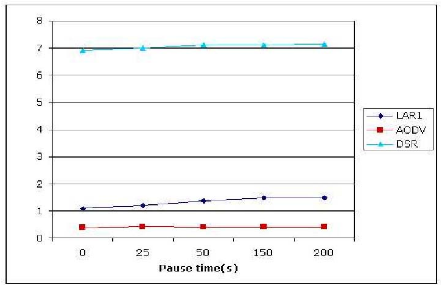

Fig. 2. Average end-to-end delay in seconds for LAR, DSR and AODV.

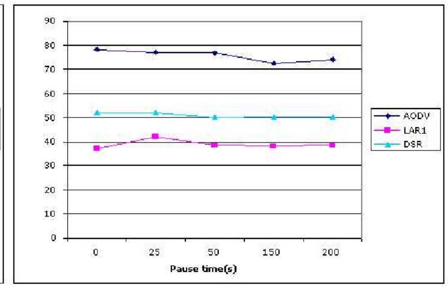

Fig. 3. Normalized routing overhead for LAR, DSR and AODV.

destination is chosen after a pause. The pause time, which affects the relative speed of the nodes is varied, from 0 (constant motion) to the length of the simulation (no motion). We ran this scenario for both 200s and 900s of simulated time.

4) Metrics: Three performance metrics were evaluated:

End-to-end average delay of data packets. This includes the propagation and transfer times, delays at the MAC due to retransmission, and delays at the interface queue and the send buffer.

Packet delivery fraction. The ratio of the packets received by the CBR sinks at the destinations over the packets generated from the CBR sources. The packet delivery fraction describes the loss rate, which shows the maximum throughput the network can support.

Routing overhead. The total number of routing packets transmitted. The routing overhead does not include MAC or ARP packets, since each routing protocol could be run over different medium access or address resolution protocols, each having different overhead. The routing overhead measures the degree to which the protocol will function in networks with many nodes, under heavy load, or in low-bandwidth environments. Large numbers of routing packets can increase the delays in the network interface transmission queues, the probability of packet collisions, and the power consumption in the nodes.

5) Simulation Results: In order to test the ability of the protocols to successfully deliver data packets, while adapting to network topology changes, we varied the workload, by using 10 and 20 maximum connections. By experimenting with different pause times, we were able to measure the performance of the protocols for different degrees of mobility.

To compare the routing protocols fairly, identical mobility and traffic scenarios were used for all of them. In order to achieve that, each run of the simulator was given two scenario files, describing the exact motion of each node and the exact sequence of packets originated by each node, together with the exact time at which each change in motion or packet origination occurs. We generated 21 scenario files altogether.

We also run the simulations for 900s of simulated time, apart from 200s, to make sure that this does not greatly affect the results.

Effect of Maximum Connections on AODV: We determine the behavior of AODV when doubling the number of maximum connections, hence increasing the network load. As we can see in Figure 4, the average delay did –as expected– increase, but to a reasonable extent. This increase can be justified by the additional bandwidth consumed by the data packets that are dropped, as well as by the extra routing and MAC control packets. MAC control packets (RTS, CTS, etc.) have also to be retransmitted often, due to collisions or link loss.

Figure 5 shows the drop in the packet delivery fraction, when doubling the maximum connections. The amount of packets received has decreased significantly, especially for low pause times, (higher mobility). These results agree with the results presented in [5].

Figure 6 shows the significant increase in routing packets when the maximum connections double. This is to be expected, since AODV is an on-demand routing protocol and as the number of sources increases, more routing packets have to be transmitted, for working routes to more destinations to be maintained. The results agree with those presented in [9], even though the number scales are different, since 64-byte, instead of 512-byte, packets are used.

Effect of Maximum Connections on TORA: The effect of maximum connections was more severe on TORA. Taking into account the packet size (512 bytes), TORA seemed unable to route that amount of traffic, and dropped the major part of the packets, as shown in figure 8. This is an extreme case of the phenomenon described in [9], occurring for 30 sources and only 64-bytes packet size. TORA fails to converge, because of increased congestion. TORA is layered on top of IMEP, the Internet MANET Encapsulation Protocol [4], which is required to provide reliable, in-order delivery of all routing messages from a node to each of its neighbors, as well as notification to the routing protocol whenever a link to one of its neighbors is created or broken. The congestive collapse observed is most probably happening due to a positive feedback loop developed in TORA/IMEP, wherein the number of routing packets sent cause numerous collisions in the MAC-layer, which in turn cause data, *ACK*, and *HELLO* packets to be lost. The loss of these packets cause IMEP to erroneously believe that links to its neighbors are breaking. TORA reacts to the perceived link breakages by sending more *UPDATE* messages, which in turn cause more congestion. Moreover each *UPDATE* requires reliable delivery, which increases the exposure to additional erroneous links failure detections, since the failure to receive an *ACK* from retransmitted *UPDATEs* is treated as a link

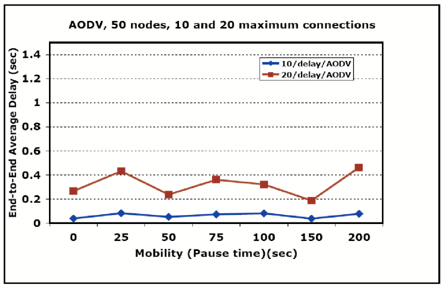

Fig. 4. Increase in the average end-to-end delay for AODV, when doubling the number of maximum connections.

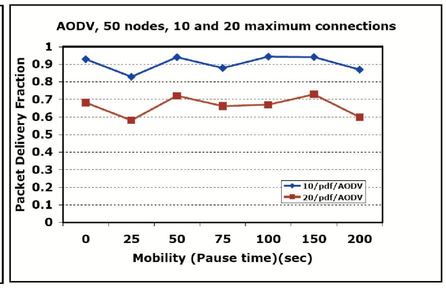

Fig. 5. Drop in the packet delivery fraction for AODV, when doubling the number of maximum connections.

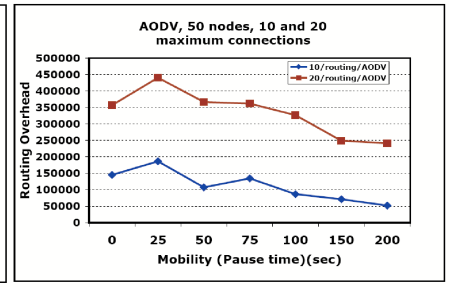

Fig. 6. Increase in routing information exchange for AODV, when doubling the number of maximum connections.

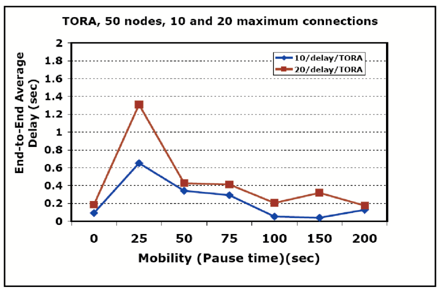

Fig. 7. Increase in the average end-to-end delay for TORA, when doubling the number of maximum connections.

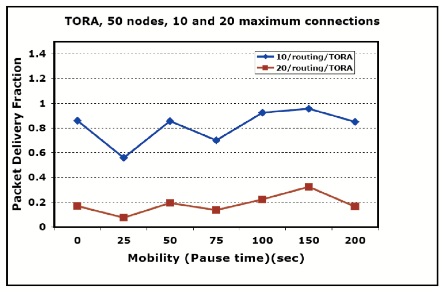

Fig. 8. Drop in the packed delivery fraction for TORA, when doubling the number of maximum connections.

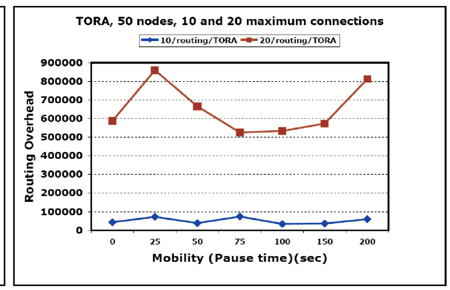

Fig. 9. Increase in routing information exchange for TORA, when doubling the number of maximum connections.

failure indication.

Figure 9 shows the tremendous increment in routing packets, which is also responsible for the congestion. These packets are the ones used to create and maintain routes, multiplied by the number of retransmission and acknowledgment packets IMEP uses to ensure reliable and in-order delivery. To that amount of packets is also added a substantial amount of traffic generated as a result of IMEP's neighbor discovery mechanism, which requires each node to transmit at least 1 *HELLO* packet per *BEACON* period.

Comparison of AODV and TORA: AODV provides less end-to-end average delay compared to TORA. The difference is however bigger, when taking into account the reaction of TORA to congestion, which causes it to drop a major amount of traffic. Therefore the average delay presented for TORA (Figure 7) is not accurate, as a lower delivery fraction means that the delay metric is evaluated with fewer samples. The longer the path lengths, the higher the probability of a packet drop. Thus with a lower delivery fraction, samples are usually biased in favor of smaller path lengths and therefore have less delay.

Again AODV outperforms TORA in terms of packet delivery. For 10 maximum connections the packet delivery fraction is approaching 1 and is in accordance with results presented in [9]. The size of the packets (512 bytes) does not allow AODV to reach maximum packet delivery for 20 maximum connections, which is the case in [9], where the packets are only 64 bytes long. For 10 maximum connections TORA has relatively lower packet delivery fraction than that presented in [9], due to the bigger packet size, and of course the situation gets much worse for 20 maximum connections, as described earlier. For bigger pause times (less mobility), the packets delivered are -as expected- more, for both protocols. However TORA is not able to recover from the positive feedback loop happening for 20 maximum connections, even when all nodes are stationary.

The routing packets transmitted give us information regarding the ability of the protocols to function in networks with many nodes, heavy load or low-bandwidth. Figure 9 shows that TORA is not suitable for such environments. For high degrees of mobility, both protocols produce a significant amount of control packets, especially for 20 maximum connections, where there are many working routes to be maintained. For TORA the situation then is extreme, as already described. TORA produces less packets than AODV for 10 maximum connections, in contrast to what presented in [9]. This is explained, if we take into account that we use 512-bytes packets, instead of 64, and that IMEP aggregates many TORA and IMEP control messages together into a single packet before transmission.

C. Comparison of QualNet and NS-2 results for AODV

In order to evaluate both simulators, we also present comparative results of a simulation of a network of 50 nodes, for 10 flows, with the previous setup. The graphs in Figures 10, 11, and 12 show the comparative results for the packet delivery fraction, average end-to-end delay, and the number of routing packets respectively. As we can see, the results are very similar, proving the simulators to be relatively reliable. The minor differences, such as the ones of Figure 12, can be

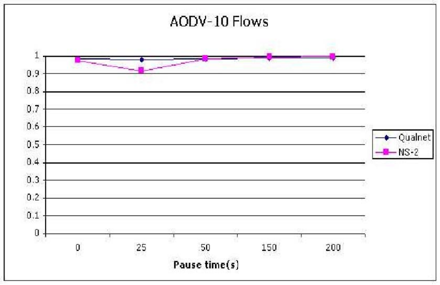

Fig. 10. Packet Delivery Fraction (PDF) for AODV.

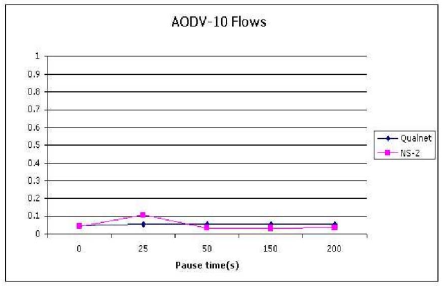

Fig. 11. Average end-to-end delay in seconds for AODV.

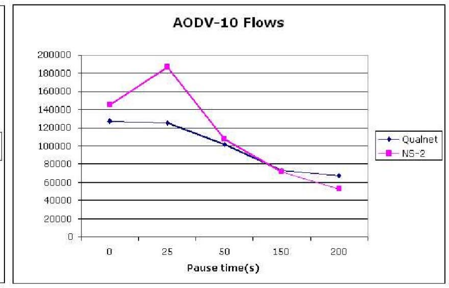

Fig. 12. Number of routing packets transmitted for AODV.

explained by the fact that the simulations are based on different random scenarios for traffic and topology.

V. Conclusions

We have presented a detailed performance comparison of important routing protocols for mobile ad hoc wireless networks. All four protocols have some kind of route maintenance mechanisms, which store the routing information until sources do not need it anymore or until routes becomes invalid; that is, some intermediate nodes become unreachable. LAR extends the on-demand approach making use of physical location of the nodes provided by global positioning systems (GPS). Hence, a significant decrease in routing overhead is achieved. Using NS-2 we simulated wireless ad hoc networks of 50 nodes, employing AODV and TORA as the routing protocols. In order to test the behavior of the two protocols under increased workload, we performed simulations with 10 and 20 maximum connections. AODV managed to handle the increased load, even though more packets are dropped and more routing packets are generated. TORA on the other hand was unable to route that amount of traffic, and dropped the major part of it, while producing a tremendous amount of routing packets. The cause of the congestion collapse lies most probably in a positive feedback loop between the loss of data packets and the creation of routing packets. This observations lead us to conclude that TORA most probably would not be suitable for networks with many nodes, heavy load, or low-bandwidth. Using QualNet we were able to analyze the performance of AODV, DSR (both of them are Internet drafts) and LAR using large-scale topologies with 500 nodes. To the best of our knowledge, in all previous studies the performance evaluation has been limited to a small number of nodes, usually 50.

The results of the simulations yield some interesting conclusions: AODV suffers in terms of packet delivery fraction (PDF) but scales very well in terms of end-to-end delay. DSR on the other hand scales well in terms of packet delivery fraction (PDF) but suffers an important increase of end-to-end delay, again as compared to the performance achieved in small-scale topologies. The last protocol we evaluated, LAR, seems to scale very well in terms of all metrics used but it requires additional hardware for getting the nodes location.

From the results obtained one can come to the conclusion that both major routing protocols, AODV and DSR, have important drawbacks when it comes to scalability. Therefore this work can motivate further research on improving the current protocols and/or create new ones to meet the challenges of large-scale wireless networks.

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