

# Performance of Routing Protocols in Very Large-Scale Mobile Wireless Ad Hoc Networks \*

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## Abstract

*As wireless devices become more and more popular, ad hoc networks grow in the number of nodes as well as the complexity of communication among the large number of nodes. However, due to the limitation of simulation technologies, it is either impossible or very hard to investigate the scalability of ad hoc routing protocols in very large-scale wireless networks. In this paper, a comprehensive simulation study is conducted of the performance of an on-demand routing protocol on a very large-scale, with as many as 50,000 nodes in the network. We address the scalability analysis based on various network sizes, traffic load, and mobility. The reasons for packet loss are analyzed and categorized at each layer. Based on the observations, we optimize the parameter selection and try to exhaust the scalability boundary of the on-demand routing protocol for wireless ad hoc networks.*

## 1. Introduction

Mobile ad hoc networks (*MANETs*) are networks without infrastructure and having mobile nodes communicating with each other through multi-hop wireless links. In mobile ad hoc networks, devices are self-organizing, which makes it completely different from other network solutions [1]. Each node in the network can act as a router and forward packets for others. Hence, mobile ad hoc networks can be deployed easily with a high degree of freedom and low cost.

Recent advances in wireless technologies has resulted in a large number of wireless devices participating in the ad hoc networks. Some military applications and sensor networks may involve tens of thousands of nodes. These applications may take advantages of adaptive self-organization

of large-scale ad hoc networks. Scalability is a crucial property under such application environments. Different from *MANETs* operating on small scales, very large-scale *MANETs* face a number of difficulties. To detect and adjust to dynamic network conditions containing routes with nearly 100 hops or more is not an easy task.

In the literature, there has been a substantial amount of research in wireless ad hoc networks, including many proposals for routing protocols [2, 3, 4, 5, 6] as well as performance evaluation and comparison of these protocols [7, 8, 9]. However, the understanding of the performance of such protocols under very large-scale ad hoc networks with tens of thousands of nodes is relatively limited. The lack of understanding of very large-scale ad hoc networks is primarily due to the inability of simulation tools dealing with the excessive CPU and memory requirements needed for such large networks.

We evaluated the potential scalability of an on-demand ad hoc network routing protocol, specifically the Ad hoc On-Demand Distance Vector (AODV) routing protocol. We chose AODV because it is a prominent on-demand routing protocol for ad hoc networks and its scalability is believed to be superior to that of other on-demand routing protocols such as Dynamic Source Routing (DSR) [3]. We ran simulation experiments using the *Georgia Tech Network Simulator (GTNetS)* [10, 11], which is a packet-level simulator designed for efficiency and scale. We used *GTNetS* to analyze networks of up to 50,000 nodes. All the experiments were run based on detailed models at the *MAC* layer, *IP* layer, transport layer, and application layer. Our objective was to investigate the performance of the AODV protocol in very large-scale ad hoc networks and try to find the boundary of the scalability for such networks. The scalability analysis is based on various network size, traffic load, and mobility. Additionally, the reasons for packet loss are analyzed and categorized in detail.

The remainder of this paper is organized as follows. Section 2 gives the related work of performance evaluation of

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wireless ad hoc networks, especially scalability studies. In section 3, a brief description of AODV protocol is given. Section 4 presents the results of our large-scale simulation experiments. Finally, the conclusions and future work are discussed in section 5.

## 2. Related Work

In the literature of mobile ad hoc networks, a major research topic is routing protocols for multihop ad hoc networks. A large number of routing protocols have been proposed. These protocols cover a wide range of design objectives and approaches. The efforts to evaluate and compare the performance of these ad hoc routing protocols using simulation models are presented in [7, 8, 9]. All of these works use the same *ns-2* [12] based simulation environment. Although *ns-2* is widely used, it can only comfortably support simulations with network topologies up to about 1,000 nodes with the popular routing protocols [11]. Therefore, the network topologies in the performance evaluation efforts mentioned earlier are no more than 50 to 100 nodes models.

A recent work evaluating the performance of mobile ad hoc network routing protocols in larger-scale scenarios is presented in [13]. In this work, the *QualNet* [14] simulation environment is used to model network details. This work assesses the scalability of routing protocols by varying one control parameter at a time to stress the network in different directions. It isolates the effects of network size, network density, number of hops from sources to destinations, mobility, number of source and destination pairs, and network load on the performance of routing protocols. The largest network topology investigated was 1,000 nodes. Thus it still leaves some questions on the characteristics of ad hoc routing protocols under larger-scale network scenarios.

As our best knowledge, the largest network topology for mobile ad hoc routing protocols scalability study is illustrated in [15]. In that work, AODV was chosen as the protocol of choice to evaluate the scalability of routing protocols in networks as large as 10,000 nodes. The simulations are based on the models in *GloMoSim*, which is an earlier version of *QualNet*. The objective of [15] is to investigate the effects of the enhancement strategies on the performance of large-scale networks.

Here, we evaluate the ad hoc routing protocols with AODV as an example under very large-scale situation with network sizes up to 50,000 nodes, which is five times larger than the previous efforts. The purpose of this work is trying to exhaust the scalability limits of the on-demand routing protocols for wireless ad hoc networks. Our results provide a guideline for mobile ad hoc network applications and ad hoc routing protocol design consideration.

## 3. Overview of Routing Protocol

We use AODV as a representative to evaluate routing protocols in very large-scale ad hoc networks. AODV [2] is an on-demand distance vector routing protocol. The route discovery is based on a mechanism with broadcast route requests and unicast route replies. One distinguishing feature of AODV is the use of destination sequence number for each route entry. Routing tables are maintained in each node in the network. The operation of AODV consists of route request, route reply, and route maintenance, as shown in Figure 1. The details for the operation of the protocol are briefly discussed in the following paragraphs.

### 3.1. Route Request

A route is needed when a source node sends data packets to a given destination, and no route entry for the specific destination is available. In this case, a route discovery is then initiated by broadcasting route requests (RREQ). Figure 1(a) illustrates the route request flooding procedure. The RREQ includes the destination IP address, the last known sequence number of the destination, the source's IP address, and the source's sequence number. The RREQ also consists of a hop count which limits the broadcast scope, and a broadcast ID which identifies the RREQ uniquely.

When an intermediate node receives a RREQ, it creates a reverse route to the source which will be used for the route reply propagation. If the intermediate node is not the destination and has no valid route to the destination, it rebroadcasts the RREQ with an incremented hop count. In this case, the RREQ floods the network.

An enhancement to the RREQ flood is the expanding ring search. The intention of the expanding ring search mechanism is to find some neighbor nodes with a route to the destination in order to avoid flooding the entire network to search for a route. The operation of the expanding ring search is to set a small time to live (TTL) value to the initial RREQ, and increment for each new RREQ if no route to the destination has been found within the discovery time. This process continues until a TTL threshold is reached. After that, the RREQ is flooded as usual. The expanding ring search introduces a tradeoff between the route discovery latency and the flooding overhead.

When the RREQ reaches the destination or an intermediate node with a valid route (with destination sequence number no less than the sequence number in the RREQ) to the destination, a route reply (RREP) is sent back to the source, which is explained in the next section.

### 3.2. Route Reply

The destination or the intermediate node with an existing route to the destination creates a RREP which consists of the the source and destination IP address, the destination sequence number, and the lifetime of the route. The RREP is unicast back to the source using the reverse route created as the RREQ is forwarded. The RREP unicast process is indicated in Figure 1(b).

The intermediate nodes receiving the RREP create their own route entry to the destination and use the nodes from which they receive the RREP as the next hop toward the destination.

After the source receives the RREP, the route has been established and data packets can be sent to the ultimate destination.

### 3.3. Route Maintenance

Because of the characteristics of mobile ad hoc networks, an active route may break due to node mobility. In this case, a route maintenance action occurs as shown in Figure 1(c). When a link within an active route breaks, the upstream node along the route will detect the broken link and a route error (RERR) message is generated when the neighbors of the upstream node use this route. The RERR consists of a list all the destinations that are no longer reachable because of this breakage. The neighbor nodes receiving the RERR invalidate the broken routes and generate new RERR messages based on their own neighbors using the broken link. When the source receives the RERR, it invalidates the broken routes indicated in the RERR and decides to repair it or not.

In order to detect link failures, a periodic hello message is used. A node participating in routing activities broadcasts hello messages every *Hello\_Interval*. If no response is received from the neighbors, it determines that the link to the neighbor is broken and reacts by invalidating the routes using that link and generating RERR as discussed before.

The periodically transmitted hello messages consumes bandwidth of mobile ad hoc networks. Therefore, an enhancement is provided in the specification to use link layer notifications, such as those provided by IEEE 802.11. When a packet is transmitted to the next hop, the absence of a link layer ACK or failure to receive a Clear-To-Send (CTS) after Request-To-Send (RTS) transmission is the indication of link failure. In this case, the link connectivity can be maintained without the hello message exchange.

Another enhancement of AODV is local repair of broken links. When a link failure occurs, the upstream node detecting the link failure tries to repair the route by transmitting RREQ locally. If the local repair is successful, fewer data packets will be lost and fewer control packets are transmit-

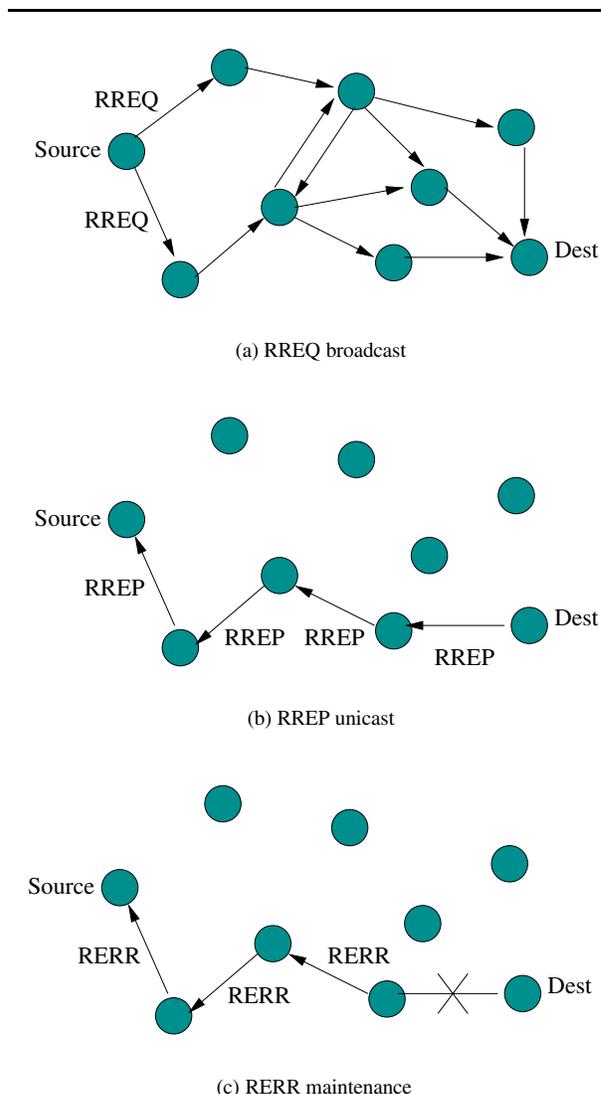


Figure 1. AODV route discovery and maintenance

ted for the repairing. If the local repair fails, the RERR message is generated normally.

In our experiments, we included all of these the enhancements in our simulation model of AODV. In this following section, we will evaluate the performance of AODV under very large-scale ad hoc network scenarios.

## 4. Experiments

### 4.1. Simulation Model

The simulation model used to evaluate the performance of mobile ad hoc networks in very large-scale scenarios

is implemented in *GTNetS* [10, 11]. *GTNetS* is designed specifically for modeling large-scale topologies. It has a number of features that address memory and CPU overhead which enable simulation of larger networks than is possible with other simulation tools, notably the *ns-2* simulator.

**4.1.1. General** Our simulations were performed using network sizes ranging from 10,000 mobile nodes up to 50,000 nodes. The nodes were distributed uniformly within a specified geographic region. The size of the geographic region was varied for different number of nodes in order to keep the node density approximately constant.

The MAC layer protocol used in the simulations is IEEE 802.11 Distributed Coordination Function (DCF) with a channel capacity of 2Mb/s. The IEEE 802.11 model in *GTNetS* includes both RTS/CTS and virtual carrier sense features of the specification. The radio propagation range of each node was 250 meters.

Each simulation was executed for 300 seconds of simulation time. For the largest simulations with network topologies of 50,000 mobile nodes, the running time for a single simulation was about 30 hours. We ran the simulations for each scenario with different seeds and the results are averaged over the multiple runs.

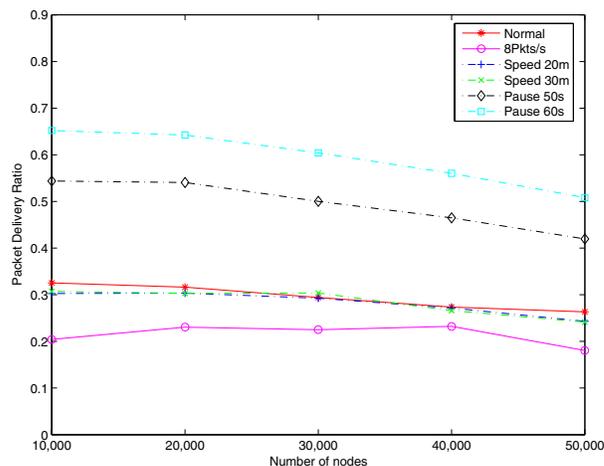
**4.1.2. Traffic Pattern** For all the experiments in this paper, the traffic pattern was a Constant Bit Rate (CBR) data source running on top of UDP. The packet size was 512 bytes. Twenty flows was simulated with randomly selected sources and destinations. The data transmission rate was varied between 4 packets per second and 8 packets per second to investigate the effect of traffic load on the performance.

**4.1.3. Mobility Pattern** The nodes in the simulation move according to the random waypoint model. We varied the mobility scenarios with different maximum speed and pause time. Due to long execution time of the very large-scale simulations, The maximum speed of nodes was varied between 10m/s, 20m/s, and 30m/s. The pause time was varied between 30s, 50s, and 60s.

## 4.2. Simulation Results

This section presents the results achieved for the different simulation scenarios. The metrics used to analyze the performance of AODV in our scenarios were packet delivery ratio, end-to-end latency, control overhead, and average hop count. For each cause of packet loss, we measured their effects on the performance individually. The simulation results are illustrated in the following sections.

**4.2.1. Packet Delivery Ratio** The first set of experiments are designed to evaluate the fraction of successful packet delivery under different traffic loads and mobility scenarios with various number of nodes. The results are shown in Figure 2. The packet delivery ratio is defined as the total number of data packets received at the destination divided by the number of data packets transmitted from the source. In the figures hereafter, we denote the normal simulation scenario as the case with data transmission rate of 4 packets/s, maximum speed 10 m/s, and pause time 30 seconds. The other scenarios are indicated with the parameters varied.



**Figure 2. Packet delivery ratio**

Figure 2 shows that the variation in the packet delivery ratio as a function of topology size is small. This is because it is already very hard to establish and maintain routes in networks with 10,000 nodes. With the normal simulation setting, the packet delivery ratio for 10,000 nodes networks is only 32.5%. The packet delivery ratio in 50,000 nodes networks for the same setting is only 26.3%.

The effect of traffic load on the packet delivery ratio is noticeable however. With the traffic generation rate of 8 packets/s, the packet delivery ratio degrades 31.5% compared to the normal scenario with packet generation rate of 4 packets/s for networks with 50,000 nodes. The reason that high network load plays a significant part on the packet delivery ratio is that more routing control packets are transmitted in the network and competing for access to the channel, which increases the likelihood of collisions.

Mobility is an important issue affecting the performance and scalability of these networks. Frequent link breakage and route recovery due to node mobility limit the scalability of mobile ad hoc networks. To investigate the effect of

node mobility on the packet delivery ratio, we varied both the maximum speed and the pause time. We ran the simulations with maximum speeds of 10m/s, 20m/s, and 30m/s. The packet delivery ratio shown in Figure 2 dictates that the effect of the maximum speed on the packet delivery ratio is not significant. On the contrary, the pause time has a substantial impact on the packet delivery ratio. For higher pause time (low mobility) of 60 seconds, the packet delivery ratio is 50.8% for the network topologies with 50,000 nodes, while it is 42.0% for pause time of 50 seconds and only 26.3% for pause time of 30 seconds. Therefore, as long as the nodes keep moving in such large networks, the chances of link breakage on the long route are high regardless of the speed. The packet delivery ratio only increases when the nodes pause for a long time.

Based on the above analysis, the packet delivery ratio for the very large-scale mobile ad hoc networks with node from 10,000 to 50,000 is very close for the same parameter settings. The traffic load and the pause time have significant effect on the performance whereas the effect of the maximum speed does not.

**4.2.2. End-to-End Latency** The end-to-end latency of each simulation scenario is shown in Figure 3. The end-to-end latency is defined as the difference of the time stamp when a data packet leaves a source node and the time stamp as it arrives at the destination. It is averaged over all successfully received data packets.

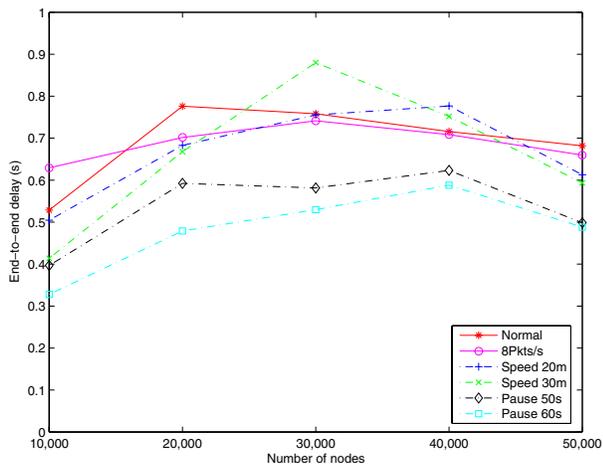


Figure 3. End-to-end latency

It can be observed that the end-to-end delay for all the simulation cases increases sharply when the number of nodes in the networks is increases from 10,000 to 20,000. When the network size grows beyond 20,000 nodes, the

end-to-end delay is fluctuated with small variances for different simulation scenarios. The contributions to the end-to-end latency are the buffering delay experienced by packets waiting for the discovery of a new route, transmission delay of longer route with large number of hops, and the route recovery delay. From Figure 3, it can be observed that the degree of mobility in the term of pause time has a larger effect on the performance of end-to-end delay than any other factors. As an example, the average end-to-end delay for a pause time of 60 seconds is 479ms, whereas it is 776ms for a pause time of 30 seconds with the network size of 20,000 nodes. The effects of traffic load and the maximum speed on the end-to-end latency is not obvious. This is the outcome with the combination of the packet delivery ratio and the total packets arriving at the destinations.

**4.2.3. Control Overhead** One major obstacle for the scalability of mobile ad hoc network routing protocols is too much control overhead due to the very large topologies, high mobility, and frequent route maintenance. Therefore, the control overhead is an important metric to measure the performance of mobile ad hoc routing protocols.

In our simulations, we gathered statistics of the control overhead including route request (RREQ), route reply (RREP), and route error (RERR) messages. Each hop-wise transmission of a control message by a node is considered as one control packet. The results of the control overhead is demonstrated in Figure 4.

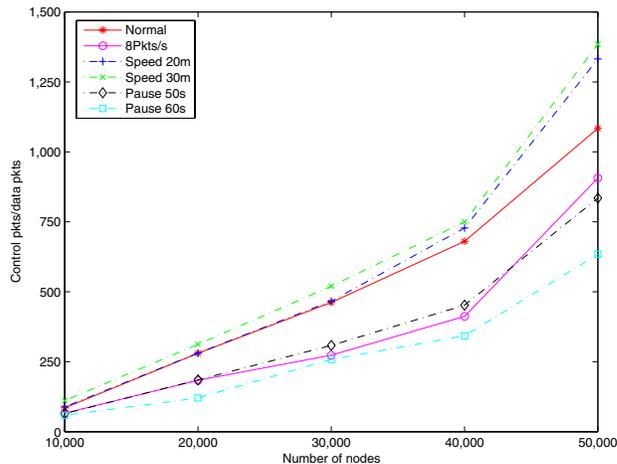


Figure 4. Overhead of control packets

The control overhead measured as the number of control packets sent per data packet received increases as the network size expands. For the network size less than 40,000 mobile nodes, the increase of the control overhead is al-

most linear. When the network size reaches 50,000 mobile nodes, the control overhead rises steeply. In addition, the differences of control overhead under various simulation scenarios are significant for the network size with 50,000 nodes, whereas it is small for the network size with less than 40,000 nodes.

The effect of the traffic load and the mobility on the control overhead is shown in Figure 4. Similar to the trend of the packet delivery ratio discussed in section 4.2.1, the control overhead for the various maximum speeds is not significant. With lower mobility (longer pause time) and higher traffic load, the control overhead is lower than the parameter setting of the normal scenario. This is because lower mobility means fewer link failures, hence fewer route repair messages. When the traffic load is high, more data packets are generated from the same source and have the same destination. In this case, more data packets can share the results of a route discovery and fewer RREQ and RREP are needed.

**4.2.4. Hop Distance** In very large-scale mobile ad hoc networks, the route length from the sources to the destinations can be excessive. It is difficult to maintain such long routes in mobile environments. In addition, the large hop distance also contributes to the packet latency. We measured the average hop distance for the networks with 10,000 to 50,000 nodes and presented the results in Figure 5.

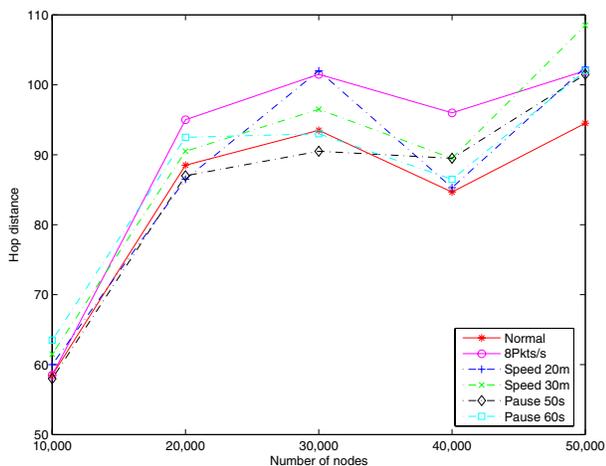


Figure 5. Hop distance

The performance of average hop distance shown in Figure 5 dictates that the hop distance increases steeply from 58.5 hops for the network size of 10,000 nodes to 88.5 hops for the network size of 20,000 nodes. With the network size larger than 20,000 nodes, the average hop distance does not vary too much. This trend is coincident with

the end-to-end delay we discussed in section 4.2.2. This is not by chance. It is because long route with large hop distance means huge transmission delay and high possibility of route failure, leading therefore to large end-to-end latency.

**4.2.5. Packet Loss Categories** In the above sections, we evaluated the performance of mobile ad hoc routing protocols in very large-scale networks from various perspectives including packet delivery ratio, end-to-end latency, control overhead, and hop distance. The factor affecting the performance is the packet loss by origin. In this section, we will discuss the causes for packet losses and break them into detail categories in separate layers.

In the simulations, we considered each of the reasons for packet losses at different network layers and tried to optimize the parameter settings to reduce the packet losses. The optimizations includes the size of the queue for the packets to be buffered when they are awaiting for the route discoveries, and the interface queue size for the packets to be buffered at MAC layer. After the optimizations, the major causes for the packet losses can be categorized as follows:

- **AODV Queue Timeout** In AODV, data packets waiting for a route RREP after sending a RREQ should be buffered. This is a first-in first-out (FIFO) queue. After a route discovery attempt is successful, all the packets using the discovered route are dequeued and sent to the destination.

When the data packets are put into the queue and the queue is full, the first packet in the queue with expired time stamp will be deleted from the queue. In the simulations, the timeout value for the data packets residing in the AODV queue is 30 seconds. The packet drop because of expiration in the AODV queue is categorized as AODV queue timeout.

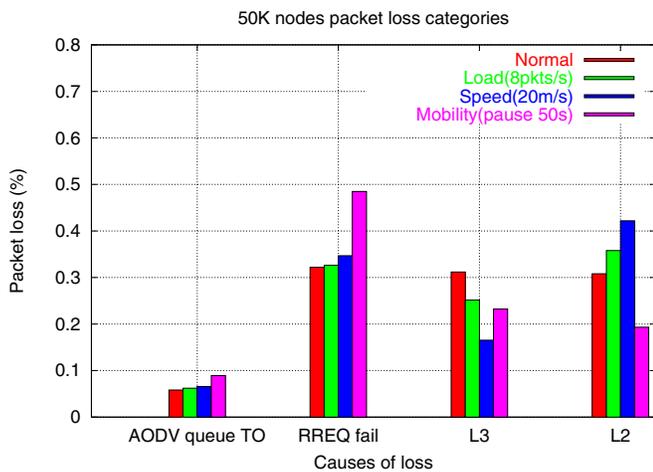
- **RREQ Failure** The route discovery in AODV may not be successful in the first attempt. The maximum number of route discovery retries (*RREQ\_RETRIES*) is specified in AODV with the default setting of 3 times. For every retry, the waiting time for the RREP is binary exponentially increased to reduce congestion in a network. If the route discovery has been attempted for *RREQ\_RETRIES* times without receiving any RREP, all the data packets destined for the corresponding destination should be dropped from the buffer. This is the RREQ failure drop.

- **Network Layer Drop** A data packet dropped in the IP layer is due to node mobility. In very large-scale networks with tens of thousands of mobile nodes, the average hop distance of the routes from the sources to the destinations can be one hundred or more. To maintain the connectivity of such a long route is very difficult. Even with AODV local repair, when several nodes

along a route move out the radio range of their neighbors, it is hard for the local repair to be synchronized and the route to be recovered. Therefore, the network layer drop in the very large-scale mobile ad hoc networks is significant.

- MAC Layer Drop** The MAC layer protocol used in the simulations is IEEE 802.11 Distributed Coordination Function (DCF). The channel access scheme is Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) with acknowledgments. Before unicast data transmissions, Request-To-Send/Clear-To-Send(CTS) messages are exchanged for channel reservation. After successful data transmissions, ACKs are sent for acknowledgments. The MAC layer drops occur due to contention and a neighbor moving out of range, leading to an RTS/CTS failure or unacknowledged data packets.

In the very large-scale simulations, we kept statistics on the packet drops due to the categorized reasons discussed above. We compared the packet drop of networks with 50,000 nodes under various simulation scenarios designed for traffic load and mobility investigation. Figure 6 shows the simulation results.



**Figure 6. 50K nodes packet loss categories**

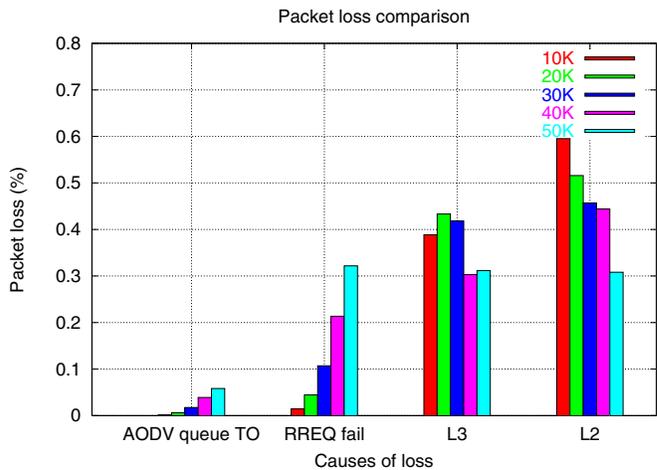
It can be observed from Figure 6 that in all of the four simulation scenarios with various traffic load and mobility, the packet loss due to packet timeout in AODV queue awaiting for the results of route discovery is relatively low (less than 10%). The other three reasons play much important roles resulting in packet drops.

For the scenario with normal parameter setting, the RREQ failure, network layer drop, and MAC layer drop have almost the same effects (around 30%) on the packet

losses. When the traffic load is increased with packet generating rate of 8 packets/s, the MAC layer drop is more significant than the other two. This is because higher traffic load means more collisions at the MAC layer, hence more packet losses. On the contrary, the percentage of packet loss at network layer for higher traffic load reduces due to more data packets sharing the same route discovery.

The effect of node mobility on the packet drop metrics is illustrated with the scenarios of increased maximum speed (20m/s) and large pause time (50 seconds) respectively. When the maximum speed increments to 20m/s, the MAC layer packet loss plays a dominant role (42.4%) whereas the network layer packet drop decreases. Therefore, the packet drop in the MAC layer is very sensitive to the mobility speed of the nodes in the networks. The effect of the other mobility parameter, pause time, is different from the speed. With longer pause time, the majority of packet drops are due to RREQ failure, which is 48.5%. The reason behind this is that there are fewer link breaks with less mobility. So the packet drops in both the network layer and the MAC layer are not significant.

In order to distinguish the effect of different causes of packet drop on the networks of various size, we compared the packet drop categories among networks with size of 10,000 nodes to 50,000 nodes. The result is presented in Figure 7.



**Figure 7. Packet loss comparison**

Figure 7 shows that as the network size increases, the effects of AODV queue timeout and RREQ failure become more and more severe whereas the effects of the network layer drop and the MAC layer drop reduce. This is because for the smaller networks, the average hop distances of the routes is relatively short compared to the networks

with 50,000 nodes. So the possibility of RREQ failure is decreased. For the networks with 40,000 or 50,000 nodes, the same number of data flows spread within larger networks. Therefore, there are fewer collisions in these cases.

## 5. Conclusion

We investigated the scalability of on-demand routing protocols, using AODV as a representative sample, for very large-scale mobile ad hoc networks with up to 50,000 mobile nodes. We designed a set of comprehensive simulations to address the scalability analysis based on the network size, traffic load, and mobility. This unprecedented work was conducted using our *GTNetS* simulation environment, which makes it possible to simulate and study the performance of such large-scale networks in a reasonable time period.

We evaluated the scalability performance of AODV from the aspects of packet delivery ratio, end-to-end latency, control overhead, and hop distance. A detailed analysis of the simulation results is presented from both quantitative and qualitative perspectives. In order to understand the fundamental reasons affecting the performance of these large-scale ad hoc networks, we isolated the causes for packet drops at various network layers and measured them for different network scenarios. This data can provide a guideline for the protocol design and future enhancements.

We provide a methodology to investigate the performance and scalability bounds of mobile ad hoc networks. However, scalability in very large-scale mobile ad hoc networks still leaves many uncovered areas. More scalable and light weight routing protocols for very large-scale mobile ad hoc networks are needed.

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