Sustaining Performance Under Traffic Overload

Saman DeSilva   Rajendra V. Boppana
Computer Science Department
The Univ. of Texas at San Antonio, San Antonio, TX 78249
sdesilva@cs.utsa.edu   boppana@cs.utsa.edu

Abstract— **In this paper, we investigate the performance of wireless ad hoc networks with traffic loads beyond saturation. While it is desirable to operate a network below saturation, an ad hoc network should be designed to degrade its performance gracefully under severe loads. Using AODV (ad hoc on-demand distance vector) and 802.11 as example routing and MAC (Medium Access Control) level protocols, we show that the throughput of an ad hoc network drops off rapidly beyond saturation. The reasons for this behavior are high route maintenance overhead and increased radio interference. We propose modifications to the protocols to mitigate these negative factors and provide graceful degradation of performance under heavy loads.**

Keywords:. ad hoc networks, performance degradation, network overload.

I. Introduction

Recent advances in wireless communication technology and portable devices have generated a lot of interest in mobile ad hoc networks (MANETs). A MANET is a collection of wireless devices moving in seemingly random directions and communicating with one another without the aid of an established infrastructure. Communication protocols for MANETs are designed to work in peer-to-peer networking mode. To extend the normal coverage of the node, neighboring nodes act as routers. Thus, the communication may be via multiple hops from a source to its destination. Since mobility of the nodes may break communication links frequently, designing ad hoc networks to repair these routes and sustain the performance is more challenging than the traditional cellular wireless network.

As the number of nodes increase, the bandwidth available per user decreases proportionately. On the average, an ad hoc network with, say, 100 nodes moving in a $1200 \times 1200\ m^2$ field and a random mobility pattern with 2 Mbps links will be able to achieve a maximum throughput of 400 Kbps for UDP/CBR (Constant Bit Rate) traffic. The maximum throughput may vary depending on the number of nodes and total number of connection established within the ad hoc network. Therefore, a typical ad hoc network could archive only a maximum of 20% of single wireless channel bandwidth. If there are 20 senders, then each sender achieves an average of 1% of the channel BW. Since the bandwidth is a scarce commodity, ad hoc network is likely to operate in saturated state. Lack of flow control for UDP and real-time streaming data makes it impossible for the network attempt to operate below the point of saturation. While the 802.11 MAC protocol [4] is designed to give a node a fair share of the bandwidth within the its neighbors, it generally does not work well when the network is saturated. Therefore, the routing layer and routing algorithm must to ensure that throughput degrades gracefully when the network is overloaded.

There have been few studies on the behavior of ad hoc networks beyond the saturation. Most techniques in literature attempt to reduce routing overhead to reduce congestion and facilitate higher throughput prior to saturation. In Castaneda et al. [3] query localization technique is use on on-demand routing protocol to reduce network congestion and to improve end-to-end delay. Similarly, Geral et al. [6] use passive clustering to reduce routing overhead. Gu et al. [7] an embedded mobile backbone is dynamically constructed to form a 2-level physical heterogeneous multihop wireless network to eliminate network wide route broadcast. Das et al. [8] use route caches to reduce the congestion.

An alternative approach to reduce the routing overhead is to reduce the need for route discovery. When the network is at or beyond saturation, the 802.11 MAC protocol causes frequent false route breaks [5]. (If the next hop does not respond even when it is within the radio range of a transmitting node, then it makes the latter to falsely conclude that the route is broken. Such route breaks are termed false route breaks.) Reducing these false route breaks reduce the need for route discovery. For example, in [11], the number of packet drops are reduced by using RTS validation. Xu et al. [13] use different technique to reduce false route breaks. CTS responses are restricted to shorter distance than normal communi-

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cation range such that it will minimize the collisions due to hidden nodes. However, we have not come across any specific studies to make MANET behave gracefully on traffic loads beyond saturation.

In this paper, we analyze the performance of MANETs beyond the saturation point. Using AODV and 802.11 as routing and MAC protocols, we investigate the reasons for sharp drop off in throughput for traffic loads beyond saturation. We show that the route discovery mechanism used in protocols such as AODV is responsible for bandwidth losses beyond saturation. We propose a simple modification to mitigate this. Using simulations we show the proposed modification to AODV with that of our earlier modifications to on 802.11 MAC protocol to mitigate false route breaks [5] will let a MANET perform gracefully under traffic overloads.

In section 2, we present the background material. Section 3, we analyzed in detail the ad hoc network in saturation. The proposed IP layer modification for Ad hoc network is presented and analyzed in Section 4. In section 5, we conclude with our findings.

II. Background

A. 802.11 MAC protocol

The IEEE 802.11 protocol [4] provides peer-to-peer networking using distributed coordinate function (DCF) based on a carrier sense multiple access with collision avoidance (CSCM/CA) protocol. To implement CSMA/CA, the 802.11 MAC protocol uses both physical carrier sense and virtual carrier sense. A mobile node can physically sense the carrier when the noise level is higher than a preset limit. To maintain virtual carrier sense, each transmission at MAC level maintain the duration of the channel usage for the current communication. A mobile node can begin to use the radio channel only when both physical sense and virtual sense indicate that the channel is idle.

To overcome the inherent problems of collision avoidance protocol in wireless communication, the 802.11 protocol uses three link layer control packets, denoted RTS (Request-to-Send), CTS (Clear-To-Send) and ACK (Acknowledgment). RTS/CTS packets are used by sender and receiver of a unicast communication to notify all nodes around them of the duration of channel usage [12]. ACK packet is used by the receiver to confirm successful reception of data from sender.

B. AODV routing Protocol

AODV [10][9] maintains a routing table (essentially, <destination node, next hop, no. of hops to destination> tuples) on each node in the ad hoc network. When a node attempts to send a data packet to a destination for which it does not already know the route (i.e., does not have a routing table entry), it uses a "route discovery" process to dynamically determine a route. Route discovery works by flooding the network with route request (RREQ) packets. Each node receiving a RREQ, rebroadcasts it, unless it is the destination or it has a route to the destination in its routing table. Such a node replies to the RREQ with a route reply (RREP) packet that is routed back to the original source.

To reduce, network flooding of route RREQ, AODV uses expanding rings. Absence of any past information of a destination, RREQ is send with TTL (Time To Live) of 1. If a route reply is not received after timeout period of time, another RREQ is send with higher TTL and continues to increase the TTL until MAX TTL is reached. If route reply is not received, route requested are send with TTL of maximum network diameter [10].

If any link on a source route is broken, the source node is notified using a route error (RERR) packet. The source and any intermediate nodes on the way of the RERR packet remove the indicated route from their routing tables. The RERR propagation works in the following fashion. A set of predecessor nodes is maintained for each routing table entry on each node. They indicate the set of neighboring nodes that use that entry to route data packets. These nodes are notified with RERR packets when the next hop link breaks. Each predecessor node, in turn, forwards the RERR to its own set of predecessors, thus effectively erasing all routes using the broken link.

RREQ, RREP and RERR are the control packets used by AODV to discover and maintain routes. These packets are queued in priority queue with higher priority than application data.

III. Behavior of mobile ad hoc network beyond saturation

To analyze the throughput and message latencies in a mobile ad hoc network beyond the saturation, we conducted several simulations using the Glomosim simulator [1] version 2.03. We used 100 mobile nodes in a $1200 \times 1200\ m^2$ field. Node movement is specified by the random waypoint model [2] with the speed in the range of [1,19] m/s. AODV routing protocol was used to learn and maintain routes in MANET. Fifty CBR connections were used to load the network. 512-byte packets at a specified rate of r packets/s were injected by each connection. By varying r, we varied the traffic load injected into the net-

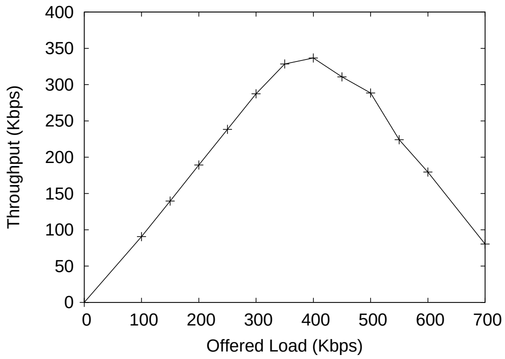

Fig. 1. Performance of a 100-node ad hoc network with AODV and 802.11 protocols.

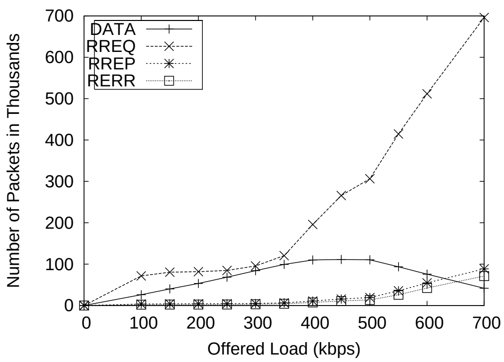

Fig. 2. Data and control packets transmitted on wireless links.

work. For each traffic load, the simulation was run for 600 seconds (first 100 seconds are use to warm-up the network and no statistics were collected) and repeated 10 times with different initial node placements. Each data point shown gives the average of the 10 simulations conducted for that traffic load.

Figure 1 shows the cumulative throughput achieved by the MANET as the load is increased from 100 Kbps to 700 Kbps. It can be seen that throughput increases nearly linearly for offered loads up to 400 kbps. For offered loads beyond 600 kbps, throughput decreases rapidly. At a traffic load of 700 Kbps, the achieved throughput is about 80 Kbps, less than 1/4th of the peak throughput. While the decrease in network throughput under extreme load may be unavoidable, it is highly desirable that it degrades gracefully under high traffic loads.

To understand the reasons for the rapid loss of throughput, we examined the packets transmitted at MAC level. AODV generates three types of control packets: RREQs, RREPs, and RERRs. RREQs and RERRs are broadcast type and each packet sent from routing layer results in a broadcast at MAC level. Data packet (denoted DATA) and RERR control packets are send using unicast address with the standard RTS/CTS exchange. Figure 2 gives the total DATA, RREQ, RREP and RERR transmitted during the simulation for each traffic load.

Since the node mobility pattern is unchanged, increase in load should not cause excessive increase in routing protocol overhead. Figure 2 indicates that the routing overhead (sum of RREQ, RREP and RERR packet transmissions) is stable up to 300-350 Kbps. Beyond, 350 Kbps, however, the routing overhead (mainly RREQs) increase rapidly. Under high traffic load, the number of instances nodes are exposed to transmissions by neighbors to other nodes is increased. This in turn causes an exposed node not to respond an RTS with CTS, which causes the sender of the RTS to falsely conclude that the route is broken. AODV responds these false route breaks by initiating route discoveries which cause a high number of RREQs to be sent.

The number of DATA packets transmitted, linearly increases up to 400 kbps and remains stable up to 500 kbps load (the reason for throughput drop off for loads 400-500 Kbps, while the number of data packets transmitted at MAC level is stable, is the chances of a packet being dropped at one of the intermediate nodes increases due to increase in false route breaks). Beyond that, there is a sharp drop in number of data packets transmitted at MAC level. To understand the reasons, we have looked at the RTS and CTS packets transmitted by MAC to precede each data packet transmission. RTS packets increase with the load, but CTS packets increase up to 400 Kbps load and then decrease for higher loads. To elicit a CTS for an RTS, the receiving node must receive the RTS (overcome the existing noise levels) and must have an idle channel (if the receiving node being exposed to other transmissions, it cannot send a CTS). In fact the rapid increase in RREQ packets indicates that wireless channels are being clogged by the control broadcasts, which increases the ambient noise level and makes the channel busy.

The IP layer typically maintains many priority queues. In our simulations, two queues are used. These queues are used by the routing layer to send data and control packets to MAC layer for transmission. AODV routing packets are queued in a high priority queue (Control Packet Priority Queue) and data (CBR) are queued in a lower priority queue. We have looked at the control queue lengths for one of the congested nodes (in one scenario) at loads before, at and after saturation. Figures 3, 4, and 5 give the control queue lengths for this node.

At and beyond saturation, the control queue size

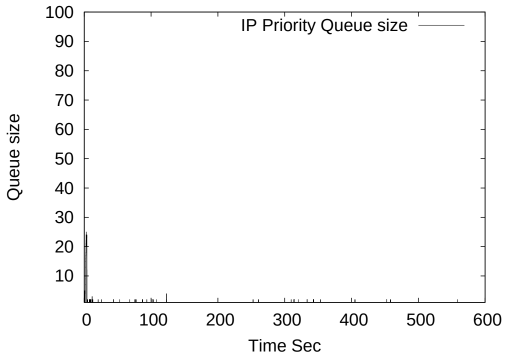

Fig. 3. Control Packet Priority queue size for node 73 when offered load is 300 Kbps

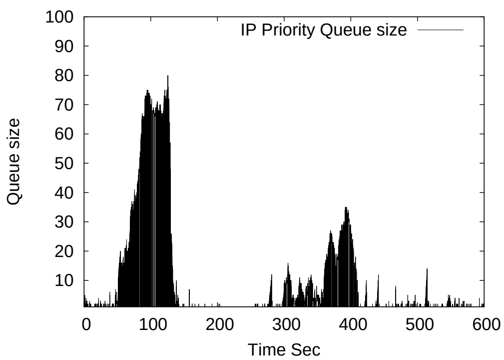

Fig. 4. Control Packet Priority queue size for node 73 when offered load is 450 Kbps

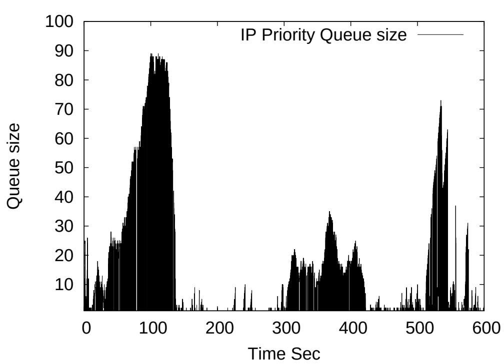

Fig. 5. Control Packet Priority queue size for node 73 when offered load is 600 Kbps

increases unpredictably. This supports the data given in Figure 2 that routing layer's control packets dominate the transmissions beyond saturation. To sustain or degrade throughput gracefully, we must limit the bandwidth used by the control packets beyond saturation.

A. *Reducing Unnecessary Transmission of Control Packets*

Further analysis of the IP layer queues revealed that multiple RREQs with the same source and destination were queued in this node. This is primarily due to the expanding rings based route discovery used. Upon a route break, the source of a the broken route connection sends a RREQ with initial TTL value based on the prior hop count of the broken route. If a RREP is not received in a preset time, which is likely in a severely congested network, it sends another RREQ for that destination with a higher TTL value. Thus a congested network causes more RREQ packets to be generated by the route discovery process. Furthermore, multiple RREQs with increase TTLs sent by a node targeted to a destination could be sitting in a congested node's IP to MAC queue. In fact, this was observed in the queues of congested nodes including node 73 indicated above.

To reduce unnecessary transmissions of RREQs by congested nodes, we propose to remove duplicate route requests from the priority queue. So, prior to placing a RREQ in the queue to MAC it is examined to see if an earlier RREQ with the same source and destination with the same or smaller TTL is present. If so, the earlier route request is replaced by the latest RREQ. Otherwise, the RREQ is queued at the end as normally done. The proposed modification increases the queue management overhead proportional to the queue length. Figure 3 shows that the queue size is rarely higher than 10 at low load, bearing no overhead for low loads. For high loads, in the worst case Figure 5 shows average queue size of 28. If the proposed modification minimizes the number of RREQ in queue, average queue size will be reduced further that would further reduce the additional queue management overhead. To evaluate the benefit of the proposed modification, we repeated the simulations and plotted the results in Figure 6. We denote the proposed modification as "reduced broadcast."

Figure 6 shows that, compared to the original AODV, the reduced broadcast method gives slightly higher peak throughput and, more importantly, degrades more gracefully under traffic overload. For a traffic load of 700 Kbps, the reduced broadcast method sustains 77% of its peak throughout, while the original 802.11 protocol can only sustain 42% of its peak throughput.

B. *Reducing False Route Breaks*

In an earlier work [5], we have shown that by modifying the behavior of CTS transmission, false route breaks can be reduced significantly at saturation. The modification applies to the MAC protocol and lets an exposed node send CTS as long as the virtual carrier sense is idle and noise level is within preset limits. (For Glomosim simulations, it is -81 dBm to -91 dBm,

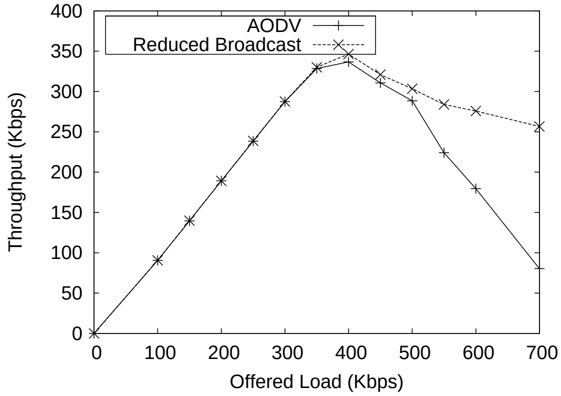

Fig. 6. Improved throughput with reduced broadcast technique.

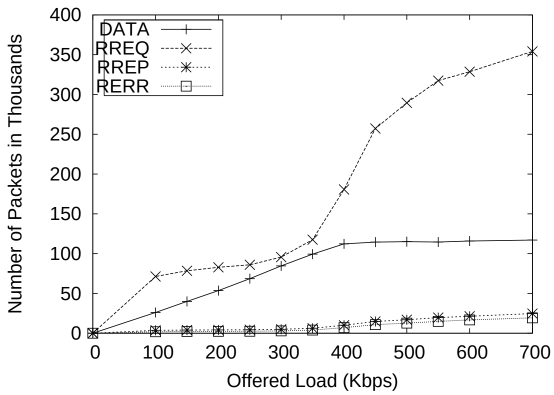

Fig. 7. Control and data packets transmitted on wireless links when reduced broadcast technique is used.

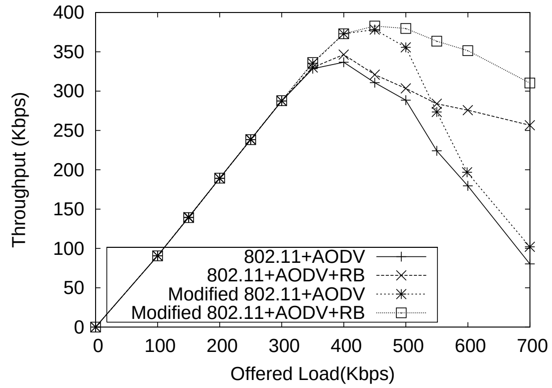

Fig. 8. Throughput improvement with modified 802.11 protocol and reduced broadcast.

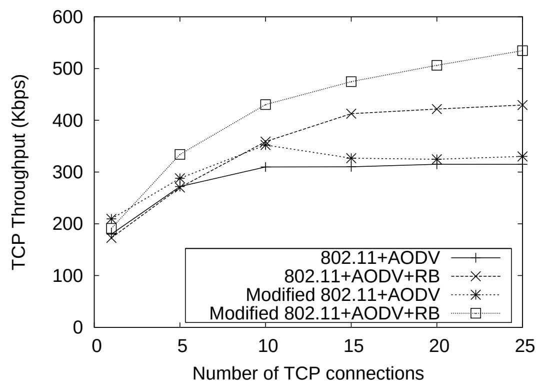

Fig. 9. TCP throughput with modified MAC protocol and reduced broadcast. A 200 Kbps CBR background traffic is used.

the range within which a signal cannot be received but is strong enough to be considered more than random noise. IEEE 802.11 standard specifies that in this range, a node may not send CTS.)

We reran the simulations with modified 802.11 and modified 802.11 with reduced broadcasts. The throughputs for the four cases, the original 802.11 with AODV, 802.11 with AODV modified to reduce broadcasts, modified 802.11 with AODV, and modified 802.11 with AODV with reduced broadcasts, are given in Figure 8.

Without the modifications to AODV to reduce broadcasts, modifying 802.11 to reduce false route breaks improves peak saturation but does not mitigate sharp drop in throughput beyond saturation. With reduced broadcasts and 802.11 modification, the throughput reduces gracefully even under heavy load. At 700 Kbps, the throughput is about 84% of its peak throughput and 250% higher than that without the modifications.

To evaluate more realistic scenario, we simulated TCP traffic on the example MANET. Twenty simulations per TCP scenario were simulated and the averages of the same are reported in the graphs presented. The new traffic load consists up to 25 TCP connections (1,5,.....,25 TCP connections) with 200 Kbps CBR background noise. Figure 9 shows the aggregate TCP throughput achieved.

Results indicate as high as 40% increase throughput from 802.11 to 802.11 with reduce broadcast for 15 or more TCP connections and 70% increase in throughput from 802.11 to 802.11 with reduced broadcast and 802.11 modification. MANET simulation archive saturation point with TCP connection, Due to the dynamic backoff nature of the TCP protocol, the MANET will operate at close to the point of saturation without performance degradation. Even in this case the reduced broadcast technique helps by reducing the control overhead and making more link bandwidth available to data packet transmissions.

IV. Conclusions

In this paper, we have examined the throughput of MANETs under heavy traffic beyond saturation.

We believe that MANETs should be designed to handle high traffic loads and exhibit graceful degradation of performance in such situations. Using AODV as the routing protocol and 802.11 as the MAC protocol, we investigated the throughput behavior of a 100-node MANET for UDP traffic ranging from 100 Kbps to 700 Kbps and TCP connection 1-25 with 200 Kbps background noise. The MANET saturates at a load of 300 Kbps when a CBR load is offered, but retains only 1/4th of its peak throughput when the load is increased to 700 Kbps. The primary reasons are (a) overactive route discovery process causes too many route control packets to fill up IP to MAC layer queues and dominate MAC level packet transmissions, and (b) exposed nodes cause RTS timeouts and false route breaks which in turn makes the route discovery process to send more control packets. This seems to cause the network go into a tail spin and throughput drops sharply.

We have proposed a simple modification to mitigate the excessive control activity by the routing algorithm. This effectively reduces number of routing control packets transmitted on the channels and also facilitates faster route repairs. We have also used a simple change to 802.11 MAC protocol to reduce the number of false route breaks. When both modifications are applied to their respective protocols, the MANET behaves gracefully under traffic overload.

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