On the Impact of Noise Sensitivity on Performance in 802.11 Based Ad Hoc Networks

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Abstract— **The IEEE 802.11 Medium Access Control (MAC) layer plays a crucial role on the overall throughput obtained in a mobile ad hoc network. We show that the virtual carrier sense mechanism as designed and used in 802.11 could have crippling effect on distant but competing transmissions. We propose a modification to mitigate this situation and show using simulations that the proposed modification provides as much as 50% higher User Datagram Protocol (UDP) throughput for static wireless networks and 10-25% higher throughput for mobile ad hoc networks.**

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 teh aid of an established infrastructure. So the communication protocols for MANETs are designed to work in peer-to-peer networking mode. To extend the reachability of a node, the other nodes in the network act as routers. Thus, the communication may be via multiple intermediate nodes from source to destination. Since mobility of the nodes may break communication links frequently, designing ad hoc networks to provide sustained performance is a challenging problem.

There are a couple of technical challenges that must be addressed to make such networks usable in practice. First, to handle continually changing topology in an ad hoc network, a dynamic routing protocol must be employed to maintain routes between a pair of source-destination nodes. Second, the access to the shared wireless medium by the competing nodes must be efficient and fair. Our focus is primarily on the design of 802.11 and its impact on the overall throughput seen by applications running on the mobile nodes.

The nature of the wireless medium makes the medium-access control (MAC) problem nontrivial. For example, the received power and the SNR (signal-to-noise ratio) falls rapidly with increase in the distance between receiving and the transmitting nodes. Thus, it is difficult for a transmitting node to sense the carrier or detect packet collision at the receiver. The IEEE 802.11 standard [5] defines the commonly used wireless MAC protocol. To minimize transmission collisions, short control packets, denoted RTS (Request-To-Send) and CTS (Clear-To-Send) , are used to reserve the channel by the sender and receiver of a transmission.

Recently, several researchers investigated the effectiveness of 802.11 MAC protocol and its impact on overall MANET performance [15],[14],[16], [9]. Simulation studies of ad hoc networks have shown evidence of unfairness (unfair distribution of channel access) at MAC layer, which causes short and long term unfairness (bandwidth distribution) in application layer. Hu and Saadawi [9] demonstrate that TCP connection with strongest signal (relative to the noise level) can capture the cannel and exacerbate the unfairness problem. In another study of the MAC layer[13], the authors shows that RTS/CTS handshaking protocol can not prevent all interference.

In this work, we investigate the interference in 802.11 protocol and its impact on transport layer performance. Using simple network configurations, we show that 802.11 performs poorly when the noise level around the intended receiver of a transmission is higher than a threshold value, because the protocol prevents it from responding to its sender's transmission. This increase in noise could be due to distance wireless transmission or some random source. We propose a simple modification to mitigate this and analyze the performance improvement in static and mobile ad hoc networks.

II. Background

A. Routing protocols

Routing protocols can be divided into proactive and reactive protocols. Proactive protocols constantly maintain all possible routes from source to the destination. Reactive protocols, generates routes on demand or when needed. In general, proactive protocols are low latency and do not scale well, whereas reactive protocols are high latency and scales better than the proactive routing protocol. There are several different dynamic routing protocols in both proactive and reactive protocol categories [12], [10], [3], [11]. The advantages and disadvantages of proactive and reactive protocols have its advantages and disadvantages are studied in detail in [4], [2], [7] In this paper, we will use two commonly studied protocols, Ad hoc On demand Distance Vector route protocols (AODV) [12] and Dynamic Source Routing (DSR) [10], for mobile ad hoc networks.

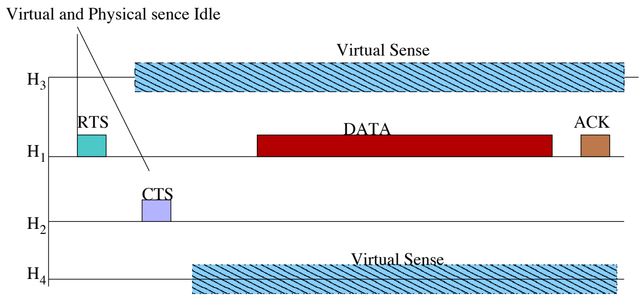

Fig. 1. 802.11 MAC protocol DATA transfer with RTS, CTS, and ACK control packets.

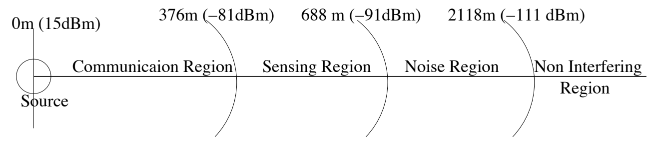

Fig. 2. Different regions in the propagation of a transmission signal. Free space 2-ray model is used to determine signal strengths at various distances.

B. 802.11 MAC protocol

IEEE 802.11 protocol provides peer-to-peer networking using distributed coordinate function (DCF) based on a carrier sense multiple access with collision avoidance (CSMA/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 noise level is higher than a preset limit. To maintain virtual carrier sense, each transmission at MAC level includes 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 unreliability inherent in wireless communications, the 802.11 protocol uses three link layer level control packets, denoted RTS(Request-To-Send), CTS (Clear-To-Send) and ACK (ACKnowledgement). 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 [5]. The ACK packet is used by the receiver to confirm successful reception of data from sender.

Figure 1 illustrates the data transfer from node H_1 to H_2. Assume H_3 is a node in H_1s communication range and out of H_2s communication range, similarly H_4 is in H_2s communication range but out of H_1s communication range. To initiate a unicast data transfer, sender (H_1) must send an RTS if both virtual and physical carrier senses indicate that the channel is idle. Nodes receiving the RTS (H_2 and H_3 in our example) packet update their Network Allocation Vector (NAV) to the transmission duration (virtual sense) indicated in the RTS frame. H_2, the intended receiver of the RTS, sends a CTS frame if the NAV (prior to the reception of RTS) at the receiver indicates that channel is idle and the physical sense indicate the channel is idle. All nodes receiving the CTS (H_4), updates the NAV table to transmission time specified by the CTS packet. H_1 then sends the data (DATA) packet. Upon correctly receiving the DATA, H_2 sends an ACK to H_1.

Interference to transmissions affects the performance of wireless networks significantly. There are two types of interferences in wireless networks. The first type of noise is caused by external signal interference: devices such as cordless phones and Microwave ovens, which may use same frequency band as 802.11 devices. The second type of noise is caused by transmission of distant nodes in the ad hoc network. In this paper, we consider only the latter type of interference, which is caused by a communicating node to nodes that are within and out of the communicating node's communication range. It is shown that this type of interference causes unfairness and capture effect in MANETs [15], [14].

C. Communication and interference regions

To explain the propagation characteristics of the radio channel used for 802.11 based networks, we use the implementation of 802.11 MAC model in the commonly used Glomosim simulator [1] version 2.03 as an example. Several other studies used the currently available hardware and came up with similar parameter values [6], [8].

With respect to a transmission, nodes can be in one of four regions depending on their distance from the sender. They are Communication, Sensing, Noise and Non-interfering regions. Nodes in the communication region will have both physical sense and virtual sense indicating a busy channel. In the sensing region, nodes detect physical carrier sense but not the virtual carrier sense. The virtual carrier sense is not available, since the node is beyond the communication distance. Physical carrier sense is detected because nodes transmission signal propagates beyond the communication distance and increases the noise level beyond a preset threshold. When a node receives an RTS from its potential sender while in this region, it does not respond with a CTS because of the higher noise level. This causes the sender to retransmit RTS several times until it receives a CTS or reaches the retransmission limit. Nodes in the two regions beyond the sensing region will detect idle virtual and physical carrier sense. In these regions, nodes can freely communicate with other nodes without any interference. A node in the noise region detects increased noise, but the noise is not high enough to detect a busy carrier. In the non-interfering region, there is no noise due to the example transmission. Figure 2 depicts these four regions and distances and the signal strengths at the boundaries of these regions. In the Glomosim implementation, the sensing region is from 377 m to 688 m when a constant ambient noise of -100.97 dBm is used.

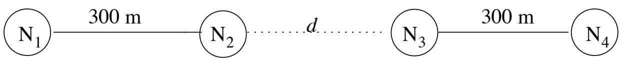

Fig. 3. 4-node simulation setup. There are two communications: $C_{1,2}$ between nodes 1 and 2 and $C_{3,4}$ between nodes 3 and 4. The distance d between nodes 2 and 3 is varied to see the impact of competing transmissions.

TABLE I

ACHIEVED CBR THROUGHPUTS FOR THE 4-NODE NETWORK WITH $d = 689$ AND 688 METERS.

Topology			Achieved Throughput (Kbit/s)			
	Direction		$d = 689$ m		$d = 688$ m	
	$C_{1,2}$	$C_{3,4}$	Noise region		Sensing region	
T_1	$\Longrightarrow$	$\Longrightarrow$	1579	1579	**455**	1528
T_2	$\Longrightarrow$	$\Longleftarrow$	1579	1579	1564	1564
T_3	$\Longleftarrow$	$\Longrightarrow$	1584	1579	**1150**	**1149**
T_4	$\Longleftarrow$	$\Longleftarrow$	Similar to T_1; $C_{3,4}$ underperforms			

III. IMPACT OF COMPETING TRANSMISSIONS

Using a simple 4-node network, we show the impact of a competing transmission on the throughput achieved for a communication of interest. The network, shown in Figure 3 has 4 static nodes. Nodes N_1 through N_4 are arranged in a straight line. The distance between N_2 and N_3 is d. The other two distances are fixed at 300m each. There are two constant bit rate (CBR) transmissions, $C_{1,2}$, which denotes the communication between N_1 and N_2, and $C_{3,4}$ the communication between N_3 and N_4. At each source, the maximum sustainable load of 1.62 Mb/s is offered. (Though the nominal channel BW is 2 Mb/s, owing to overheads of various protocols the actual throughput achieved is 1.62 Mb/s.) We varied d and the directions of $C_{1,2}$ and $C_{3,4}$. For each combination of d and connection directions, the achieved bandwidth for each connection is measured. The routes between nodes are established using AODV routing protocol at the start of the simulation and preserved for the rest of the simulation to avoid any impact of AODV's behavior in these simulations.

Depending on the directions of the data transmissions, 4 different simulation topologies are possible (see Table I). Since T_1 and T_4 topologies are symmetrical, T_4 topology is not considered any further. Results of these simulations are shown in Table I.

In the first set of simulations, the distance d is set at 689 m. So N_2 and N_3 are outside the sensing range of each others transmissions. As expected, both connections achieve about 1580 Kbps, nearly the maximum possible throughput, for all possible directions of transmissions.

In the second set of simulations, the distance d is reduced by 1 m to 688m. Now, N_2's transmission can cause N_3 to go into the sensing state, and vice versa. As discussed earlier, nodes in the sensing state will detect a busy medium and will not initiate a new transmission.

Consider topology T_1: $C_{1,2}$ achieves only 29% of the bandwidth it achieved when $d = 689$m, but $C_{3,4}$ is nearly unaffected. The reason for the divergence in behavior is as follows. N_2 is the receiver of the data in $C_{1,2}$, and N_3 is source of data in $C_{3,4}$. Since N_2 and N_3 are within each other sensing range, when N_3 is transmitting, N_2 will be in the sensing state and is prevented from sending RTS or CTS. In response to RTS from node N_1, N_2 can transmit CTS only when N_3 is in the idle state, or N_3 is receiving a frame (ACK or CTS from node N_4). Since, N_3 is transmitting data to N_4, N_3 spends a significant portion of time in the transmitting mode and very small amount of time in the receiving mode. Furthermore, a CTS that can not be sent immediately upon receiving an RTS is dropped, not queued for later transmission. The protocol is designed so that the source will time out, backoff and retransmit RTS. As consequence, there is significant loss of bandwidth for $C_{1,2}$ connection. On the other hand, if $C_{1,2}$ is transmitting, N_2 spends only a small portion of the time transmitting (CTS,ACK) and most of the time receiving data. So, N_3 will spend only small portion of its time in the sensing state due to the transmission of N_2. Therefore, it is very unlikely $C_{1,2}$'s transmissions could adversely affect those of $C_{3,4}$.

In the T_2 topology, node N_2 and N_3 are both receivers. So they interfere with each other only when sending ACK or CTS frames. Time spent in transmitting CTS or ACK is significantly small compared to transmitting data frame. Therefore, N_2 and N_3 spent very little time in sensing mode. Since, N_2 and N_3 are able transmit CTSs and ACKs without interference, both communications are able to achieve the full bandwidth.

In the T_3 topology, nodes N_2 and N_3 are the source of data and RTS. N_2 and N_3 spend most of their time transmitting data frames. Therefore, N_2 and N_3 will put each other in sensing state while the other node is transmitting. Both N_2 and N_3 must initiate transmission of RTS while the other node is not transmitting frames. Since both are competing for the channel to send data and RTS, they both have equal probability of using the shared channel. Therefore, equal bandwidth is expected and is confirmed by the simulations. The loss of throughput, approximately 25% of that achieved at $d = 689$m, accounted by the occasional collisions and searching for each others transmission gaps.

IV. MODIFICATION TO 802.11 PROTOCOL

The throughputs drop-off in T_1 as d is reduced from 689 m to 688 m is because N_2 is close enough to be put in the sensing mode by the transmissions of N_3 to N_4. Since a node can transmit an RTS or CTS only when it is not in a sensing state (as specified in the IEEE 802.11 standard [5]), N_2 is prevented from sending CTS to N_1's RTS transmission. We have checked the simulation data and verified that N_2 receives RTS transmissions from N_1 reliably, but is unable to send CTSs most of the time due to the increased noise level by the competing transmission from N_3.

Our observation is that, if the node can receive RTS, it is able to receive the data from the same source. Furthermore, if the overall noise level is low, ≤ -81 dBm in Glomosim implementation, then sending a CTS is not likely to disturb any other transmissions. Not responding to RTSs in such instances reduce the network bandwidth without any notable benefit.

To eliminate this unnecessary loss of throughput, we modified the MAC protocol such that when a node receives an RTS, it will respond with CTS packet transmission if the virtual sense is idle and noise level is within the sensing range (-91 dBm to -81 dBm in Glomosim).

V. Performance Analysis

We evaluated the performance of the proposed modification using Glomosim simulator and AODV as the routing protocol.

A. 4-node network

First, we reran the 4-node (Figure 3) simulations with $d = 688$m. Instead of the standard 802.11, we have used the modified response for determining when to send CTS packets by a node that received RTS packets. All the other aspects of the standard are unchanged. Now both connections achieve about 1575 Kbit/s throughput for the T_1 topology. It is to be expected, however, since the modification is designed to work well for the situations indicated by T_1.

B. Static grid

Next we considered a 10×10 grid of nodes with 300 m between adjacent nodes. Nodes are stationary and each node has a connection to send data to the node on the right along the row, if it exists. So there are a total of 90 connections and 90 nodes act as senders and receivers, while the nodes in the left column are senders only and the nodes in the right column receivers only. Once again we used AODV to set up the routes initially and turned it off to minimize its impact on the performance. Since the network is static, there is no need for the routing algorithm after the routes are obtained. The proposed modification improves the throughput by 50% at the load of 250 Kbps per connection (see Figure 4). More importantly, the proposed modification sustains the throughput as the network is overloaded, while the original 802.11 protocol degrades the performance significantly.

C. Mobile ad hoc network

Next we conducted simulations of MANETs. The original version of 802.11 protocol is compared with the modified version. One hundred nodes in a 1200×1200 m^2 terrain was simulated. Nodes movement was patterned by the random waypoint model [2] with speeds in the range [1,19] m/s. Fifty CBR connections with a packet size of 512 bytes were used to offer varying network loads. Each simulation was run for 600 seconds (the first 100 seconds are used to warm-up the network and no statistics were collected) and repeated 10 times with different random seeds. Figure 5 and 8 show the average network throughput of these ten runs for different network loads with AODV and DSR as routing protocols. We will discuss the results of AODV first.

The proposed modification increased the peak throughput by 11%, and gave performance gains of 25% at high network loads. The proposed modification increases the reliability of wireless links by reducing the false route breaks–next hop is within the communication rage but failed to respond. This reduces the need for routing protocol to flood the network with broadcast control packets to find an alternate route, which reduces the overall broadcasts in the network. We found that the number of such broadcasts were reduced by much as 30% for AODV at high loads with the proposed modification (see Figure 6).

We further analyzed to see if the modified MAC protocol would increase the total collisions in the network. Based on Glomosim data, radio signal collisions were reduced by 23% with the proposed modification (see Figure 7). The reduction in collisions is due to the reduction in number of broadcasts transmitted. We added additional counters to count only the collisions that cased loss of transmissions intended received at each node. This count indicates that the modification increases the number of collisions by 5%.

We have repeated the above simulation by replacing AODV with DSR as the routing protocol. Figure 8 indicates that the modified MAC improves the peak throughout by 7%, and by 16% at high loads. The number of false route breaks are reduced by as much as 33% at high loads (see Figure 9.

VI. Conclusions

We have investigated the 802.11 MAC protocol behavior in the presence of competing but distant communications on one another. We have shown using a simple 4-node static network that a connection could be dominated by another even though neither can interfere with the other's ability to receive radio signals successfully. The problem is due to the over cautious use of noise level, in the absence of virtual carrier sense, to infer the transmission activity by others. We have shown that by relaxing the constraint slightly, we can improve the performance significantly. Our proposed modification lets a node respond in more instances with a CTS when it receives an RTS from a potential sender. This improves the performance significantly in the pathological situations where the sender of a communication causes the receiver of another transmission into sensing range without a virtual carrier sense. While these situations are temporary in a mobile ad hoc network, they do occur frequently. For an example MANET with 100 nodes and 50 connections and AODV with routing protocol, we have shown using simulations that the proposed modification improves throughput by 11% and reduce routing packets by 30%. In future, we plan to evaluate the proposed modification using FTP and HTTP traffic.

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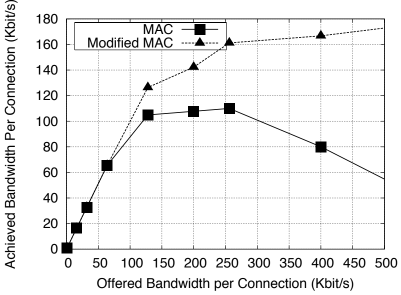

Fig. 4. Throughput achived for grid topology.

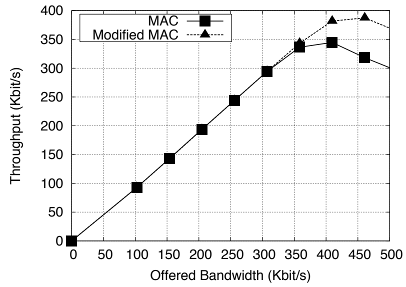

Fig. 5. Throughput achieved in a MANET with the 802.11 and modified MAC protocol using AODV.

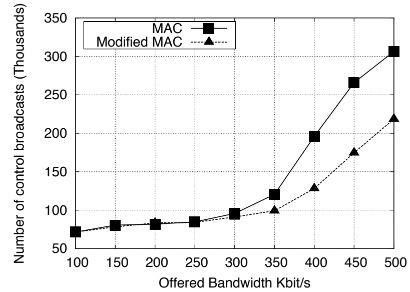

Fig. 6. Radio signal collisions.

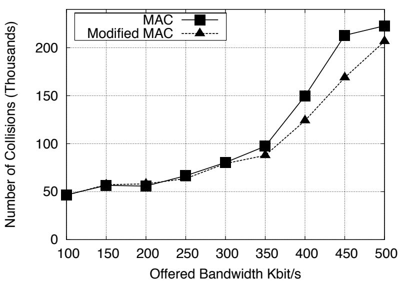

Fig. 7. Total collision reported by Glomosim in MANET.

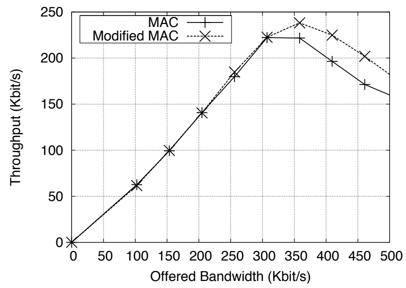

Fig. 8. Throughput achieved in a MANET with the 802.11 and modified MAC protocols using DSR.

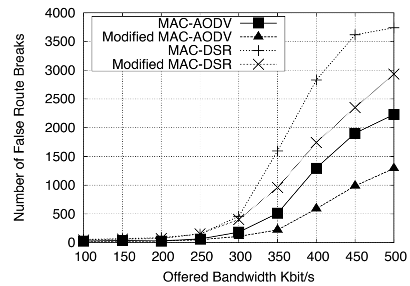

Fig. 9. False Route Breaks in a MANET.

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