Exploiting Multi-User Detection (MUD) Radio Capabilities to Improve Stability of CSMA/CA for MANETs

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***Abstract*—CSMA/CA MACs for mobile ad hoc networks (e.g. the 802.11 suite) exhibit an unstable behavior (i.e., their throughput goes to zero under high load) in the presence of *hidden nodes*. In this paper, we show that even the simplest Multi-User Detection (MUD)-enabled radio can mitigate the MAC's *loss-of-state*, which is the culprit of the MAC instability. Thus, a MUD-enabled CSMA MAC – with just a few modifications – can significantly reduce the instability associated with CSMA/CA MAC and achieve high throughput even under very high traffic load. High fidelity simulation results, with a radio model that includes important technological constraints, are presented for both a simple idealized topology as well as for a very realistic scenario. In both cases, it is shown that the combined CSMA/CA MAC and MUD radio system is able to achieve high throughput with much improved stability.**

***Keywords*-Medium access control, multi-user detection, multipacket reception, carrier sense multiple access.**

I. Introduction

Coordinating access to the physical medium in mobile ad hoc networks (MANETs) has proven to be quite challenging. Traditional Time Division Multiple Access (TDMA) techniques, while known to have the potential to maximize the achieved throughput, have difficulty coping with high levels of mobility. Indeed, small local changes may render a TDMA schedule ineffective and trigger network-wide reconfigurations and relatively long convergence times. On the other hand, Carrier Sense Medium Access (CSMA) techniques can quickly deal with immediate changes in the network topology and traffic patterns. For this reason, as well as their simplicity and widespread availability, most work on MANETs have centered around CSMA with collision avoidance techniques (CSMA/CA), in particular the widely popular IEEE 802.11 suite of protocols[1].

However, when a CSMA/CA MAC is employed in large multi hop MANETs (e.g., sensor, disaster recovery, vehicular networks) and as traffic grows, hidden nodes can cause significant throughput degradation[2], [3]. As traffic load increases, flows with source and destination more than a few hops apart experience an ALOHA[4]-like behavior, where throughput approaches zero as load increases.

Our studies has shown that the culprit of this instability is the loss-of-state (i.e NAV information) on nodes within transmission range of a *targeted* communication. At high loads, these nodes cannot benefit from the NAV information, and are left only with carrier sensing (CS) as the only means to prevent collisions. But, if the transmitters are outside these nodes' CS range (i.e., hidden nodes) the communication cannot be detected, and some nodes will start a RTS transmission resulting in a collision. As more and more collisions occur, more nodes loose NAV state information, rendering the entire RTS/CTS mechanism ineffective.

In this work we study the use of the simplest Multi-User Detection (MUD) radios, capable of just decoding two packets simultaneously (level 2), to protect the RTS/CTS packets, prevent loss-of-state, and avoid destructive collisions. Our main contribution is to quantify the impact of level 2 MUD on the end-to-end (e2e) throughput of a MANET running a CSMA/CA MAC algorithm. It is found that, for topologies an traffic patterns of interest, level 2 MUD capability is able to increase e2e throughput by 70% while significantly increasing stability. This is a somewhat surprising result, given the relatively small capacity gain that a MUD level 2 radio provides at the physical layer. However, the actual e2e throughput achieved by a practical (and imperfect) CSMA/CA-based system is greatly improved. That is, while a MUD level 2 capability does not increase the network's theoretical e2e capacity by much, it makes much easier for the higher layers (MAC and above) to realize a e2e throughput closer to this capacity.

This paper is organized as follows: Section II discusses related work. Section III explains the rationale behind the instability (throughput degradation) exhibited by CSMA/CA MACs running over conventional Single User Detection (SUD) radios. Section IV presents the model for the level 2 MUD radio used in our study. Section V presents OPNET simulation results, showing that MUD capabilities result on 70% higher throughput without the high instability presented in the SUD case; and Section VI presents our conclusions.

II. Related Work

There are several radio techniques to provide multiple packet reception: (i) multi-channel radios [5], [6], (ii) Multiple-Input Multiple-Output (MIMO) radios [7], [8], [9], (iii) busy tones [10], etc. All these techniques require extra

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transceivers. Some (MIMO and Busy tones) also require additional antennas. Our work, on the other hand, focuses on single-antenna single-transceiver radios where the MUD-capability is provided by powerful digital signal processing algorithms. We believe that current trends in chip manufacturing, and as processing power becomes cheaper and cheaper, will result on these solutions being more cost-effective than solutions that require additional RF hardware.

There have been several studies on the impact of MUD capabilities for wireless networks ([11]-[16]), with diverse results based on the scenario assumptions. For instance, when close to optimal rate adaption is possible, [11] shows that MUD provides little gain. In [12] the authors show that when MUD is employed in combination with carrier sensing, moderate gains can be obtained. On the other hand, the works in [13]-[16] show good performance gains under more realistic (and less efficient) protocols. A common thread among all these approaches is that some aspects of the interference behavior is known in advance. For example, ZigZag[14] exploits the quasi-immediate retransmission at random backoff times of packets colliding at an access point (AP) to let the AP the correlate both transmissions with independent collision-free segments to decode both packets via a variant of successive cancellation at the link layer. These works focus on single-hop WLANs are not applicable to the e2e throughput of a *multihop* MANET.

MUD performance issues for multihop MANETs have been studied in [17]-[20]. The work in [17] focuses exclusively on the physical layer, studying different receiver architectures for interference cancellation, and therefore provide no insight into e2e throughput. The e2e throughput capacity of a MUD-enabled MANET is studied in [18]. This work, however, assumed infinite MUD-detection capability (i.e., an arbitrary large number of packets may be simultaneously decoded) and therefore is of little practical applicability. Our work focuses on a MUD level of 2. The works in [19], [20] limit their protocols and the analysis to a Manhattan network. In [19] it is assumed that the transmitter scheduling and feedback is perfectly transmitted on a separate channel while in [20] it assumed that all users have the same traffic and delay requirement. Therefore both works cannot be used in a real MANET.

To the best of our knowledge, this is the first work that quantifies the e2e throughput gains obtained by level 2 MUD radios on realistic multi-hop MANETs running CSMA/CA.

III. Loss of state, bridge links, and Instability of Single-User Detection (SUD) systems

While virtual carrier sensing (VCS) helps to mitigate collisions due to hidden terminals in multi hop MANETs, it cannot fully eliminate them [2], [3]. Under certain neighborhood topologies and intense traffic load, VCS is unable to prevent collisions. For example, Figure 1 shows a configuration where under a high bidirectional traffic load, node C cannot keep his NAV table up-to-date, and his "loss of state" leads to a collision. In this example, nodes A, B, C, D, and E are arranged in a line topology. A dotted arrow indicates the direction of a targeted communication, and a solid circumference indicates the interference range (or footprint) of a transmission. For clarity, the network links are not shown but it is understood that node A has only one neighbor (node B), node B has two neighbors (nodes A and C), and so forth. In this example, nodes can only carrier-sense their one hop neighbors. Let's consider two flows traversing the network in opposite directions.

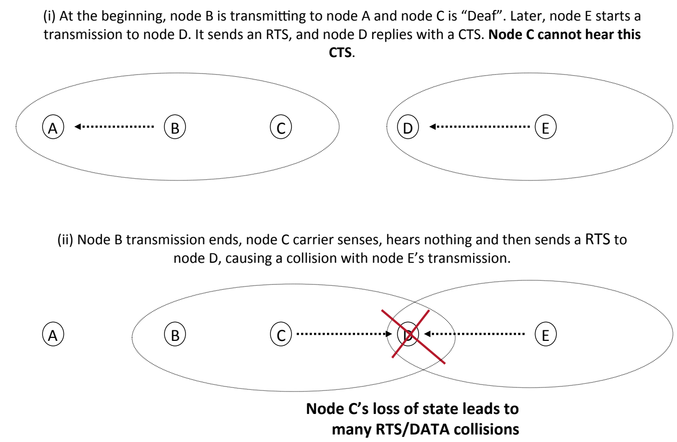
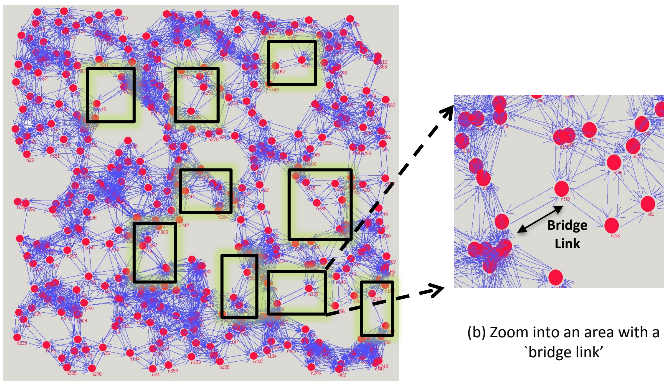


Figure 1. In the presence of 'bridge' links (e.g. link C – D) 802.11b behaves as unstable ALOHA, even if using RTS/CTS.

At the beginning (Figure 1(i)), node B is transmitting a DATA packet to node A. Node C is within this transmission footprint, and therefore it is *captured* by this communication and will not be able to decode any other packet until this communication ends. While the $B \rightarrow A$ communication is still taking place, node E decides to start a transmission towards node D, and sends it a RTS packet. Since node D cannot carrier sense node B's transmission, it decides to accept node E's communication request. It sends a CTS packet, which not only instruct node E to start transmitting, but it is also supposed to inform node C of the upcoming transmission so that it can update its NAV table and refrain from transmitting until the $E \rightarrow D$ communication is completed. Unfortunately, since node C is under the interference of node B's transmission, it cannot receive node D's CTS, and therefore it is unaware that node D is about to receive a packet ("loss-of-state").

After node B's transmission ends (see Figure 1(ii)), node C has a packet to transmit in the opposite direction (i.e. towards node E) and decides to start a communication with node D. It then sends a RTS request while node D is in the middle of a DATA packet reception. A collision ensues. Collisions will continue until the offered load along the link C – D is significantly reduced (e.g. backoff interval increases to maximum level, flows' TCP congestion window



(b) Zoom into an area with a 'bridge link'

(a) Large network presents several "bridge links" (bottlenecks)

Figure 2. Bridge links appear naturally in large Ad Hoc Networks. Long source-destination paths are highly likely to include at least one bridge link.

is decreased) Thus, MAC throughput is severely degraded, at least in the area around the middle link (C – D), which we will refer to as *bridge* link.

To understand the impact of these *bridge* links in the overall e2e throughput, let's consider the 400-node network shown in Figure 2. The nodes are uniformly distributed in a square area. It can be seen that the network is comprised of a combination of densely connected and sparsely connected regions, joined by a few *bridge* links at their boundaries. These links appear naturally under a uniform distribution, and even though they may be small in number, they have a significant impact on performance. When the traffic distribution is uniform, or at least not fully localized, and the typical communication path is several hops long, it is *highly likely* that the each e2e path includes one or more of these *bridge* links. Thus, the *bridge* links are the throughput bottlenecks (traffic jams) that determine e2e throughput in a large MANET.

IV. Successive-Cancellation Multi-User Detection Model

Our goal is to evaluate the impact of the simplest MUD capability (the ability to simultaneous decode two packets) on a CSMA MAC performance. We do not want our results to be dependent or tied up to a particular coding scheme or receiver implementation. Instead, we want a model that is general enough to capture the universe of possibilities, while still capturing some important medium-term technological constraints.

To this end, we extend the simple unidimensional ($SNIR > \gamma$) packet acceptance rule to the case where two packets are decoded simultaneously. The resulting *acceptance region* characterizes the set of received power vectors (P_1, P_2) that results in a successful joint-decoding of both packets. We developed the *Successive Cancellation-based* acceptance region, based on the performance and limitations of a practical and popular receiver architecture[21], and as such, it is more realistic incorporating some technological limitations that – although not fundamental – seem likely to remain in effect for the foreseeable future.

The Successive Cancellation model assumes a decoder that operates on a received signal composed of the sum of a first user signal, a second user signal, and background noise as follows:

- Attempts to decode the stronger signal first, considering the weaker signal as noise.
- Once the stronger signal has been successfully decoded, it is removed from the original received signal. Perfect removal is not possible, so a *residual noise* is left in the remaining signal.
- The remaining signal is decoded.

Let P_i, R_i, and g_i represent the receive power (in Watts), bitrate (in bps), and processing gain (in dB) for the i-th signal respectively. That is, $R_i = R\,10^{\frac{-g_i}{10}}$, where R is the highest bit-rate allowed under the modulation scheme (i.e., "full rate" achieved when the processing gain is zero). Also, without loss of generality assume that $P_1\,10^{\frac{g_1}{10}} > P_2\,10^{\frac{g_2}{10}}$. Then, the packets will be successfully decoded if:

$$SNIR_1 + g_1 \geq \gamma \quad \text{and} \quad SNIR_2 + g_2 \geq \gamma$$

Where

$$\begin{aligned} SNIR_1 &= 10\log_{10}\left(\frac{P_1}{P_2 + WN_0}\right) \\ SNIR_2 &= 10\log_{10}\left(\frac{P_2}{P_1 10^{-\frac{\Phi}{10}} + WN_0}\right) \end{aligned}$$

where Φ is a parameter capturing quantization errors as well as limits in the Automatic Gain Control (AGC) of the receiver (i.e. if one signal is much stronger than the other it will inevitably overshadow it). In our experiments we used a value of $\Phi = 30dB$, which is in line with today's receivers.

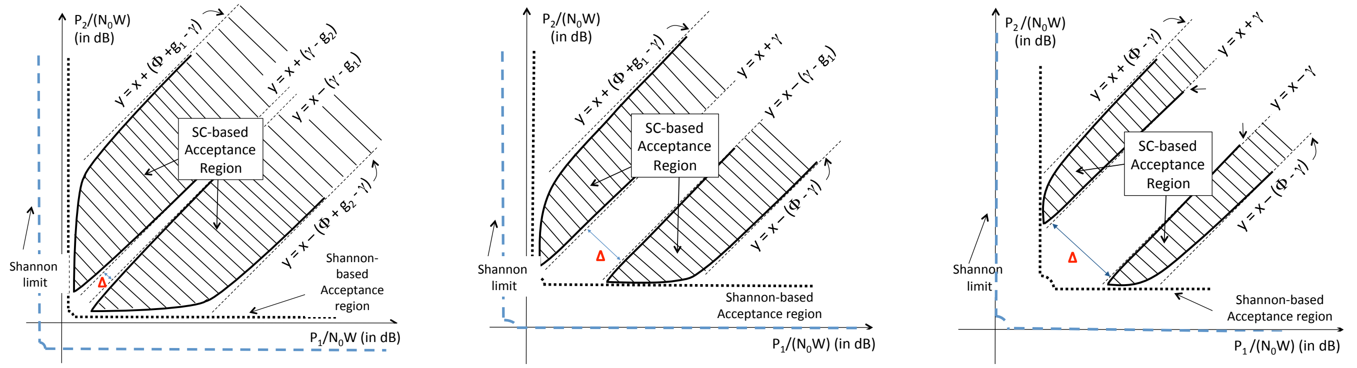
Figure 3 shows the acceptance region (in logarithmic scale) for three different cases: (a) when both packets are low rate, (b) one packet is low rate and the other is high rate, and (c) when both packets are high rate.

When both signals have roughly the same power, we can see that there is a "gap" in the acceptance region. When the signals' receive power fall inside the "gap region", there is destructive interference and no signal is successfully decoded. The width of the gap region (Δ, in dBs) is:

$$\Delta = \max\{0, \gamma - g_1\} + \max\{0, \gamma - g_2\}$$

where g_1 and g_2 are the processing gains (in dB) of signals 1 and 2, respectively. It can be seen in Figure 3(a) that the smallest gap occurs when both signals are low rate. In that case, if the processing gain is greater than the reception margin γ, then the gap actually disappears. Figure 3(c) shows that the widest gap (2γ dB wide) occurs when both signals are high rate and their processing gain is 0 dB.

When one signal is much stronger than the other, it can be seen in Figure 3 that there is a limit to the receiver's



(a) Both signals are low rate (b) 1st signal low rate, 2nd signal high rate (c) Both signals are high rate.

Figure 3. Acceptance region for Successive-Cancellation model (logarithmic scale).

capability to recover the weaker signal (Near-far problem). Indeed, if signal 1's receive power is $(\Phi + g_2 - \gamma)$ or more dBs above the receive power of signal 2, then signal 2 cannot be decoded. In that case, only signal 1 will be successfully decoded.

V. Simulation results

We conducted OPNET simulations analyzing CSMA/CA behavior in two scenarios. The first scenario is the simple 30-node network shown in Figure 4(a), which exhibit a *bridge link* in the middle. This topology (termed "simple topology") is easy to understand and model the behavior around *bridge* links, which – as discussed in Section III – dominate the end-to-end (e2e) throughput in large, uniformly distributed MANETs. We then validated our observation in the smaller but more realistic scenario shown in Figure 4(b) (namely, the "Lakehurst topology").

We conducted experiments with an off-the-shelf OPNET implementation of 802.11b (ad hoc mode) as well as our own GPMAC (omnidirectional version of the MAC presented in [22]). We choose 802.11b since it is widely popular and as such it is of utmost interest. We also included our GPMAC in the analysis for two reasons: (i) to show that the observed behavior was not an artifact of the particular 802.11b specification but common to all CSMA/CA MACs, and (ii) to be able to easily modify the MAC as needed to accommodate a MUD-enabled radio. Since GPMAC was designed to tolerate a multiple-antenna system, its state machine was friendlier to "unexpected" packet delivery (e.g. an RTS arriving in the middle of a DATA packet reception). Indeed, updating GPMAC to work with a MUD-enabled radio required changing just a few lines of code.

Once equivalence between 802.11b and GPMAC for the simple 30-node topology was established (see Figure 5), we focused on GPMAC and in extending it to operate over a MUD-enabled radio. It should be noted that the same could have been done with the 802.11b MAC, but that would have required substantially more effort to modify the state machine of the available off-the-shelf OPNET implementation, without adding much value to our study.

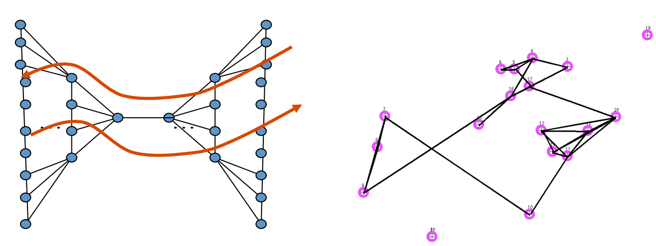
The physical layer parameters are the same for both scenarios. The receiving margin γ is set to $12dB$, to match 802.11b modulation and coding for a packet size of 8000 bit. Control packets are sent at 1Mbps (processing gain of $10 \log_{10} 11 = 10.4dB$) and data packets are sent at 11Mbps (processing gain of $0dB$).

For the MUD case, we replaced the OPNET single-user-detection based physical layer pipeline stages with our implementation of the SC-based model described in the previous section, with $\Phi = 30dB$. Thus, multiple packet reception was possible and receiver no longer suffered from the *capture effect*[23].

To avoid higher layer effects, we modified the forwarding queue policy at the nodes to give higher priority to packets that have traversed the farthest. This provides a form of flow-based access (as opposed to packet-based access). Otherwise, under very high load, e2e throughput would decrease to zero due to the lack of a network-wide fairness enforcing mechanism.

A. Simple topology

Figure 5 shows the resulting e2e throughput for the 30-node network shown in Figure 4a. Due to space constraints,



(a) 30-node "simple" topology (b) 20-node "Lakehurst" topology

Figure 4. Scenarios under study. (a) Simple scenario capturing the behavior of the *bridge* links that appear in large MANETs, and (b) high-fidelity 20-node Lakehurst scenario.

only the e2e throughput is shown, but it should be noted that this e2e throughput closely matches the MAC-level throughput of the "bridge link".

The nodes in the network are arranged in 6 columns. The outmost columns have 10 nodes each. The medium columns have 4 nodes each, and the innermost columns have exactly one node each, joined together by a *bridge link*. Nodes in a column are one-hop neighbors of all nodes in their own and neighboring columns. Nodes can only carrier sense their one hop neighbors (i.e. nodes two hops apart are *hidden nodes* with respect to each other).

The traffic is composed of 10 unidirectional CBR flows, 5 in each direction. Each flow traverses the network from one extreme to another. For example, a flow whose source is a node in the leftmost column will have as its destination a node in the rightmost column. Each node in one of the outmost columns will either be a source or a destination of one CBR flow. We increased the UDP flows' packet generation rate and measured the achieved e2e throughout.

It can be seen that the network behavior of both 802.11b and GPMAC under a SUD radio is similar to that of an unstable ALOHA system. The throughput is extremely sensitive to the offered load, meaning that even a small deviation of the optimum operating point results in a drastic loss in performance. Such sensitivity presents a significant challenge to higher-level flow/congestion control mechanisms. Thus, even in the presence of sophisticated flow control mechanisms, the application level performance of a CSMA/CA-based ad hoc network is quite low.

On the other hand, the use of a MUD radio resulted not only on a 70% increase in e2e throughput, but also on a very robust e2e throughput-vs-load curve. Some degradation under high loads is still observed, but this is due to the lack of a network-wide fairness criteria. [1]

Furthermore, the low sensitivity of the e2e throughput in Figure 5 to small changes (say a 50% increase in offered load) means that even existing congestion control techniques such as TCP/IP – while not fair or able to guarantee individual flow rates – can be effective in controlling the transmission rates of source nodes and achieve close to the highest possible e2e throughput (i.e. preventing source nodes in the first column from starving the forwarding node in the second column).

Seeing that both 802.11b and GPMAC exhibit very similar behavior, for the second scenario ("Lakehurst topology") we focused on GPMAC only.

[1] At the MAC layer, all senders are treated the same, and as such the set of transmitters at the first column (5 sources) get a bigger share of the channel than the forwarding node at the second column (1 node, since the same node is chosen by the min-hop routing algorithm to forward packets for all 5 reverse-direction flows), even though that forwarding node is carrying traffic on behalf of the 5 sources at the sixth column. Thus, as the traffic load increase, the nodes at the first column get 5 times the bandwidth share of the forwarding node. Thus, the e2e throughput does not go to zero (as in the SUD case) but converges to a positive value (1/6 of the maximum).

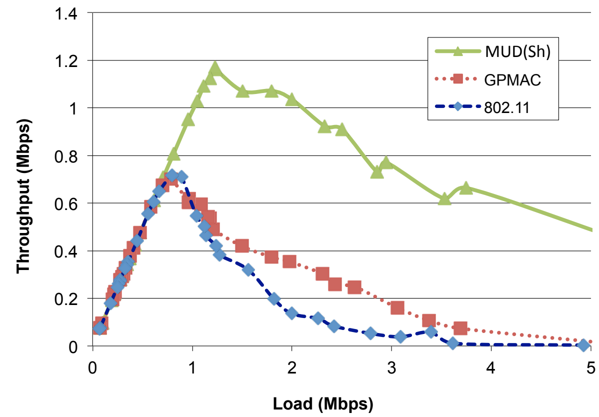


Figure 5. End-to-end throughput comparison for SUD and MUD for the simple 30-node network.

B. Lakehurst topology

Figure 6 shows our e2e throughput results for the very realistic (obstructions, mobility patterns, etc.) 20-node network topology used in the field demonstration described in [22], named "lakehurst topology". This model is used to validate the observations/conclusions obtained from the previous simple network model. The model corresponds to two sets of vehicles (i.e the nodes) moving in two concentric rings. It includes a very high fidelity model of the terrain, the obstacles present, and other relevant propagation characteristics. The pathloss values predicted by this model were then compared against *in situ* real-life measurements, and a very good matching was found, as explained in [22]. As nodes move, their relative distances change over time. We chose 6 node pairs that were mostly far away during the span of our simulation lifetime as the source/destination of 6 flows.

As before, for a CSMA/CA MAC over a SUD radio, the network behavior for source/destination pairs *relatively far away* is similar to that of an unstable ALOHA system. It should be noted that – although not shown – the e2e throughput of source/destination pairs close to each other (1 or 2 hops away) was high and stable with respect to traffic load. Further analysis of the data revealed that the culprit of the excessive number of collisions is the nodes' loss of state information (i.e. NAV tables become out-of-date).

It can also be seen that a level 2 MUD system achieves an e2e throughput close to 70% higher than the SUD system. Furthermore, the level 2 MUD system shows a much more stable behavior with respect to increase in the network load. This was due that under the SC-model (and control packets being sent at a lower rate) most control packet vs data packet "collisions" were recoverable. This is somehow surprising taking into consideration the reduced acceptance region showing susceptibility to the near-far problems as well as a "gap interval".

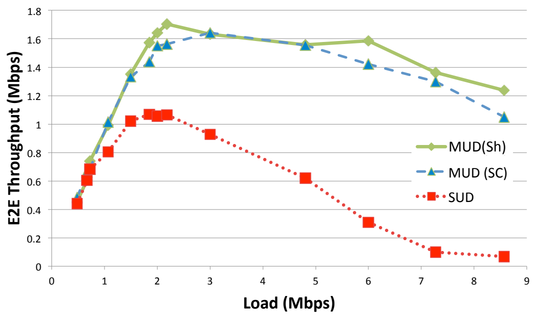


Figure 6. End-to-end throughput comparison for SUD and MUD for the Lakehurst topology.

One possible explanation for this good behavior is a combination of factors: (i) most nodes transmit at similar power levels, (ii) collisions occurs over *bridge* links, that are long and tend to have close to the highest acceptable pathloss, resulting in receive powers that are within 30dB of each other (minimizing the near-far problem), and (iii) still, the pathloss process between different nodes is random and seldom results on two signals experiencing the same pathloss/receive power level (avoiding the gap).

While one can easily draw scenarios under which loss of state is unavoidable – e.g., a star topology with a specific packet arrival sequence, – the above results suggest that such situations are rare/temporary in practical scenarios. While far from conclusive, our results show that *the use of simple level-2 MUD has great potential to alleviate the problems of CSMA/CA MACs in MANETs and deserve further study*.

VI. Summary and Conclusions

In MANETs, CSMA/CA-based MACs suffer of instability under a high load. Virtual carrier sensing is ineffective to prevent collisions due to loss-of-state at critical times.

By using the minimum MUD-capability – i.e. being able to simultaneously decode 2 data packets – to embed low-rate control information without disrupting high-rate DATA transfers, in our simulations nodes were able to regain state information and prevent collisions, significantly improving the system stability.

Thus, even in situations where the physical layer capacity gains achievable by MUD systems is small, the resulting gain in application layer throughput may be quite significant.

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