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Medium Access Control in a Network of Ad Hoc Mobile Nodes with Heterogeneous Power Capabilities

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ABSTRACT: *MAC layer protocols for wireless ad hoc networks typically as- sume that the network is homogeneous with respect to the transmit power capability of individual nodes in the network. The IEEE 802.11 MAC pro- tocol has been popular for use in ad hoc networks. We investigate the per- formance of this protocol when it is used in a network with nodes that trans- mit at various power levels. We show that overall throughput is lower than the throughput of a network in which all nodes transmit at identical power leveh. In addition, low power nodes have a disadvantage in accessing the medium due to higher levels of interference from the high power nodes. We consider propagating the control messages generated by a node wishing to initiate communication to distant nodes so that they may forbear transmis- sions for some time, thereby allowing clear access to the initiating node. We find that the overhead incurred due to the additional message transmissions outweighs the potential gain achieved by propagating these masages. This indicates that the signalling mechanism used in the IEEE 802.11 standard or the variants thereof are not sufficient to alleviate the loss in throughput and the lack of fairness engendered by networks that are heterogeneous with regard to the transmit power capabilities of individual nodes.*

I. I NTRODUCT ION

A Mobile Ad Hoc Network (MANET) is defined as "an au- tonomous system of mobile routers (and associated hosts) con- nected by wireless links the union of which form an arbitrary graph"[l]. Mobile ad hoc networks are primarily deployed in the military and in disaster relief operations. These networks need to be rapidly deployable, easily reconligurable and are de- void of any centralized support infrastructure. This usually ne- cessitates protocols that are distributed in nature for functions such as routing and medium access eontr‹›l. The mobility of nodes further complicates the design of such protocols in many ways.

The Medium Access Control (MAC) protocol is critical to achieving a statistically equitable distribution of the available capacity between contending users. This is also important for ensuring that the QoS requirements of different users are satis- fied. The design of a good wireless MAC pr‹›tocol has to address challenges raised by (i) mobiliy of the nodes and (ii) an unreli- able, time-varying channel. Mobility affects the MAC protocol because the set of tlsers competing for capacity on the medium keeps changing. This makes it difficult to allocate bandwidth in[1] This rork was done when the author was at HRL Laboratories, LLC." an equitat›le fashion. Time-varying effects such as fading and interfereii‹:e also make it difficult to administer medium access control on the channel.

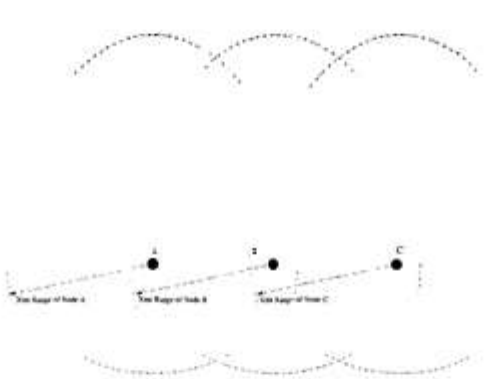

Fig. 1. An Example to illustrate the Hidden and Exposed Terminal Problems

The simplest medium access control mechanism would per- mit users to transmit any time they desire. The ALOHA pro- tocol [2] ‹)perates based on this principle. While this method works well for light loads, at heavier loads it results in a high incidence of collisions among simultaneous transmissions. The “Carrier S‹znse Multiple Access” (CSMA) protocols [3] attempt t‹› address this problem. When CSMA is deployed, nodes listen on the channel to sense the carrier due to another node’s trans- mission. Inf a carrier is detected, the sensing node refrains from transmittirig. CSMA protocols do not, however, deal adequately with the hidden terminal problem [4] or the exposed terminal problem. 'The hidden terminal and exposed terminal problems are briefly explained by means of an example in the rest of this paragraph. In the scenario depicted in Fig. 1, say node A is transmittir g to node B. Just sensing the channel will not make node C aware of the aansmission because it is beyond the range of node A. It may therefore attempt to transmit at the same time, thus causing a collision at node B. This is the hidden terminal problem. 14ow if node B is transmitting to node A, node C will sense the ti ansmission and defer its transmission even though its range is not large enough to cause a collision at node A. Thus the channel utilization effieiency suffers in this case. This is known as the exposed teminal problem. Note that the collisions occur at the receiver and not at the transmitter.

Phil Karn proposed the “Multiple Access with Collision Avoidance” (MACA) protocol [5] in 1990, based on the Ap- ple LocalTalk protocol. MACA does away with carrier sensing. Instead the initiator and intended receiver of a data transmission exchange control messages to gain access to the channel before commencing the transmission. The initiator sends a Request-to- Send (RTS) message to the intended receiver. The receiver re- sponds with a Clear-to-Send (CTS) message. The initiator starts data transmission upon receipt of the CTS message. The initia- tor includes in the RTS message, the amount of data it intends to ransmit. This information is also included in the CTS from the receiver. Nodes that overhear the RTS will defer their trans- missions long enough for the CTS to be successfully received at the initiator. (Note that there is an assumption of symmetry here. If a node, say node X, can hear a second node Y, then node Y can also hear node X). Likewise, nodes that overhear a CTS message will defer their transmissions for a period long enough to ensure that the ensuing DATA packet is successfully received by the receiver.

MACA does not have link-level acknowledgements of data transmissions. If a data transmission fails, retransmission has to be initiated by the Yansport layer. This can cause significanl delays in the transmission of data. MACAW [6] extends the RTS-CTS-DATA exchange by introducing a link level acknowl- edgement (ACK) from the receiver after the successful reception of data. The use of an ACK complicates the exposed terminal scenario. An exposed terminal can benefit from an opportunity to transmit only if it can hear the ensuing reply (a CTS or an ACK). For example, going back to Fig. 1, say node B is trans- mitting to node A. If node C elects to transmit an RTS to an- other node at the same time, it may not successfully receive the CTS from its intended receiver due to a collision with the trans- mission from node B. Also the transmission from node C may itself cause a collision in node B’s reception of an ACK from node A, thus rendering node B’s data transmission futile. To ad- dress this issue, MACAW utilizes a Data Sending (DS) message from the initiator before the actual DATA transmission. The DS message announces to the neighbours of the initiator that there was a successful RTS/CTS dialog and a DATA transmission is about to follow. Nodes that hear this message will then defer their transmissions long enough for the initiator to transmit the DATA packet and successfully receive the ACK message from its intended receiver.

The IEEE 802.11 MAC protocol [7], [8J is derived from MACA. It uses both a physical and a virtual carrier sense mechanism to determine when the medium is busy. It uses an RTS-CTS-DATA-ACK dialogue to accomplish data transmis- sion. Each message in the dialogue contain duration information for the remainder of the dialogue. The virtual carrier sense is implemented in the fom of a neMork n/Jocnrion vector (NAV) maintained by each node. The NAV at each node maintains a value which represents a time instant that indicates the duration upto which the medium is going to be busy due to transmissions from other nodes. The NAV is updated based on the duration information advertised in messages overheard by the node.

Note that all the above protocols assume the presence of sym- metric links. This is valid for a network in which all nodes transmit at the same power level. The rapid spread of multi- farious “wireless network enabled” devices jeopardizes the as- sumption of homogeneous power capability. An ad hoc network may comprise low power transducers, PDAs, handheld comput- ers and larger file servers. These devices will have different transmit power capabilities. Some of them may be “tethered” to a power supply at all times and others may be dependent on battery power for long durations of time. In any event, it will be critical to ensure that the MAC protocol in use does not un- duly favour devices that can transmit at higher power levels. In the next section, we describe some of the issues associated with using the IEEE 802.11 MAC protocol in a network in which dif- ferent nodes may transmit at different power levels. In Section III, we consider some modifications to the IEEE 802.11 MAC protocol in order to address these problems. In Section IV we provide the performance results of simulations of these modifi- cations, interpret them and compare them to the performance of the standard protocol. In Section V we summarize our work and present our conclusions.

II. PROBLEM DESCRIPTION AND S IM ELATION OVERVIEW

In this paper, we will concentrate on the IEEE 802.11 MAC protocol. We investigate a network with heterogeneous power capabilities and the inequities and ineffieiencies in the use of the medium in such a network. In our study, each individual device is assumed to have a constant transmit power, but this transmit power may be different for different devices in the network. The term porer capability will refer to the power level that a node is capable of using for transmissions. The terms homogeneous net- work and heterogeneous neMork will refer to networks in which all nodes have, respectively, identical or non-identical power ca- pabilities. Simulations are performed using the NS network simulator.

$$\eta = \frac{\text{total time spent in successfully transmitting data}}{\text{total simulation time}}$$

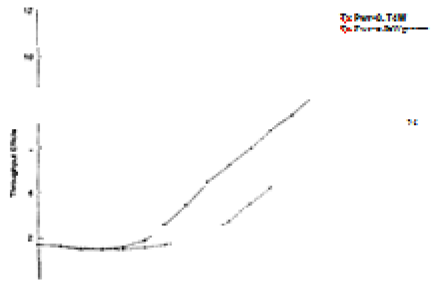

Fig. 2. MAC layer throughput for a homogeneous network

Typically MAC layer throughput is affected by routing and transport layer artifacts. For instance, TCP retransmissions and acknowledgements make it difficult to model the input load to the MAC layer accurately. Also, the use of stale routing in- formation may manifest inappropriately as transmission failures at the MAC layer. In order to deeouple these effects from our study of the MAC protocol, we extended the NS simulator to introduce a traffic generation agent immediately above the MAC layer. This agent has perfect information about the node's neigh- bours at every instant. Every time a data packet is generated, it 2 Specifieally, we study the IEEE 802.11 MAC protocol in the framework of the Disributed Coordination Function (DCF)[7]" will be randomly destined for one of the nodes that are neigh- bours at that instant. The data packets are fixed-size packets of 1000 bytes each. The traf£c model at each node has expo- nentially distributed packet inter-arrival ti›nes with the average rate h being varied to vary system load. The mobility model is a random waypoint model with constant speed of 6mph be- tween points and pause time 0.1 seconds. In other words, each node chooses a random direction in which it moves at a con- stant speed of 6mph for a random time. After this time, the node paused for 0.1 seconds, then chooses a new direction at random 12 , and repeats the process.[3] The simulation network is assumed to be deployed in a square region whose area may be varied so as to vary the geographical density of nodes in the network. The medium is assumed to be free of noise and :tny errors due to fad- ilsl' or interference other than the interference from other users in the network. The channel bandwidth is set at 2Mbps. The radio specifications are based on the AT&T WaveLAN with only the transmit power being varied. The same frequency band is used by all users in the network. Two or more simultaneous transmis- sions received by a node either result in a collision or capture. A transmission captures the medium when the the received power due to that transmission exceeds ten times the received power due to any other simultaneous transmission. In order to quantify channel usage, we define throughput efficieny at each node as follows:
total time spent in successfully transmitting data total simulation time is true for the network operating at higher transmit ~~power level. However as the grid area incr~~eases, we notice that the network in which rodes transmit with the lower transmit power does much better than the other network. This is because the lower transmit power increases network capacity by increasing spatial reuse of the spectrum. This is in marked contrasi to what happens in the operation of a heterogeneous network with nodes operating at two trarismit power levels. Fig. 3 depicts a network of 40 nodes with half of the nodes transmitting at 0.14W and the other half transmitting at 0.56W. We note that the low power nodes suffer a 5Cl% degradation in throughput efficiency in compari- son with their performance in a homogeneous network in which there are no high power nodes. A similar trend was discerned at lighter ti•affic loads of 100, 50 and 10 packets per second per node. Cle«irly the low power

nodes are being overwhelmed by the higher power nodes in accessing and using the channel suc- cessfully.

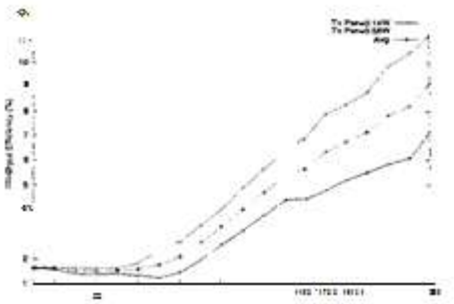

Fig. 3. MAC layer throughput for a heterogeneous network

’‘The IEEE802.11 MAC protocc›l uses a reservation scheme based on the exchange of Requesi to Send (RTS) and Cle r to Send (CTS) messages between a source and destination as ex- plained in Section I. For a homogeneous network, on average this mechanism works satisfactorily in ensuring a fair allocation oi the char nel. But in a heterogeneous network, when a low- p‹)wer nodi: attempts to reseme the channel for a subsequent

In Fig. 2, we show the throughput of two homogeneous net- works at power levels of 0. l4W and 0.56W and an average of- fered load (h) of 1000 packets/second at each node. The to- tal number of nodes in the network is fixed at 40 and the node density is varied by varying the area of the sql2are grid used in the simulations. The parameter along the X axis indicates the length of the square grid. We note that at very high densities (grid length <t 500m), both networks perform virtually identi- cally. This is because the nominal ransmit range at the smallest power level (0. l4W) is about 205m, which implies that all the nodes are sharing a single channel almost all the time. The same

3 Note that this raffic model hu been chosen for simplicity and cy generic traffic model may be expected to result in similar performance” data Yansm ission, it may not be heard b high-power nodes that are potentiiilly close enough to disrupt $_{lts}$ data exchange. instance in Fig. 4, node A is a high-power node, node B is a lor-power node and node C is another high-power node. Node C may potentially interfere with the reception of data at node B in spite of the RTS/CTS exchange between nodes A and B since it is unable to hear the CTS message from node B.

As the use of ad hoc wireless networks becomes more ubiqui- tous, the assumption of uniform transmit power capability will be less and less valid. NeMork-enabled devices with disparate power eapalailities will be pressed into service and some of them may not be able to operate satisfactorily in the network due to unfairness in the MAC protocol. Therefore MAC protocols will need to be designed to be more sensitive to the different aansmit power capalailities of devices.

Fig. 4. Failure of RTS/CTS in heterogeneous power environment

III. MODIFYING THE RTS/CTS RESERVATION SCHEME

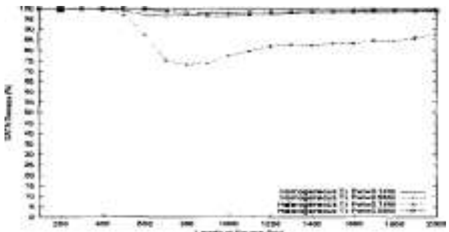

Fig. S. Success rate for DATA transmissions

As shown in Fig. 4, a successful RTS/CTS exchange will not guarantee successful transmission of data in a heterogeneous network. This is borne out by the graph in Fig. 5 which shows the percentage of successful DATA transmissions after a suc- cessful RTS/CTS exchange for homogeneous networks operat- ing at different power levels as well as for a heterogeneous net- work comprising two types of nodes. We see that in the hetero- geneous network, the degradation in DATA transmission suc- cess rate for the low power nodes can be as high as 309c. As the network density goes down, there are fewer neighbours that can interfere with the DATA transmission. Hence the success rate of DATA transmissions from low power nodes improves, but it is still far below the success rate for high power nodes.

Fig. 6. Using BWWES mesmge to propagate CTS

A possible solution to prevent this degradation is to extend the reach of the RTS/CTS reservation so that all high power nodes that could potentially interfere with the DATA transmission are made aware of the reservation. One way to extend the reach of the RTS/CTS reservation mechanism without boosting transmit power is for nodes that hear the CTS message to propagate it again. For instance, let us revisit the earlier scenario in Fig. 6, now with an additional node D in the picture. Say node D broad- casts the CTS it hears from node B. The CTS from node B could not reach node C, but the broadcast message from node D will reach node C and node C will then defer its own transmissions during the ensuing DATA/ACK sequence between nodes A and

B. Note that in most cases a single broadcast of the CTS will not suffice. At the same time, we obviously do not want to keep broadcasting the CTS ad infinitum. We need to propagate the CTS a reasonable number of times to ensure adequate reach for the reservation without causing too much overhead. Adequate reach means covering a radius equal to the transmission radius of the highest power node in the network. Assuming that the network is not partitioned, and transmit ranges are normalized such that the lowest power node in the network has range 1 unit and the highest power node in the network has range A' units, we have the following result:

Lemma 1. With the nodes distributed along a straight line such that the distance between any two neighbours is less than one unit (no partitioning, in some sense) and each transmission having a range of one unit, and assuming that among the nodes that hear a transmission, the node that is furthest from the trans- mitting node will retransmit the message, we have:

A message needs to be propagated 2N - 1 times to ensure that it is heard at a distance N from the originator of the message.

Proof: Let transmission refer to both, the original transmis- sion of a message or subsequent retransmissions by nodes that hear the message. Say the originator of the message is at the origin and transmissions occur along the positive X axis. The first transmission covers one unit. Say rn transmissions of the message are needed to ensure a reach of k units, specifically a distance £ + d. If there is a node in \k, k d], its transmission of the message will cover distance k + 1. In this case we need rri + 1 transmissions to cover k -t- 1 units. Suppose now that there is no node in [h, L + dj. Then 3 a node rtt in (k + 6, k + 1] (else there will be two neighbours with the distance between them being greater than 1 unit) and a corresponding node in (k - l + 6, k such that d(n ,na) < 1. Then one transmission from »2 followed by one transmission from nt will be required to cover distance k + 1 units. In this case we require m + 2 trans- missions to ensure that the message covers a distance of k + 1 units, Thus the original transmission covers one unit and for each additional unit of coverage, two additional transmissions are required. Therefore, the minimum number of transmissions required to ensure coverage of N units is 2N - 1.

An illustration of the lemma for N = 3 is provided in Fig. 7. We extend the RTS/CTS mechanism by adding another mes- sage called BWWES which is essentially a broadcast propa- gation of the CTS message. The BWMS message format is shown in Fig. 8. It is similar to the RTS message format ex-

Fig. 7. An example of five transmissions required when N — 3

I-.g.8.' “The BWWES‘frame

cept that the fr ame comer o1 field has an additional attribute called s eqno. This is a sequence number intended for the de- tection of duplicate BW.RES messagcs that may be reccived when a standard flooding algorithm is used to propagate these messages. A similars eqno attribute is ‹idded lo the I rame cont rod field of the CTS frame. For our simulations, the To DS, From D8 and More Fr ag bits of the frame contr ol field (see [7]) were overloaded in the CTS and BW.RES mes- sages to indicate a ’Time to Live’ (or cC1) for the message. The Lc l is initially set to 2N - 1 when the CTS is sent out and then decremented appropriately by each nodc that rctrans- mits the message (in the form of a BW-RES), depending on the transmit power level of the node. Each node that hears the CTS and determines that it needs to send a BW.RES, waits a random number (between 0 and 6) of sho rt interframe space (SIFS) [7] units before transmitting the BW.RES messap•e. This is to min- imize collisions due to multiple simultaneous BW.RES trans- missions frnm neip•hbours that hear the same CTS message. The complete RTS-based data transfer sequence with the extended scheme is depicted in Fig. 9.

IV. EFFECTS OF THE MODI FIICAT I ONS

We performed simulations with the modified RTS/CTS mech- anism for a two-level hcterogcneous network of 40 nodes with half the nodes operating at a transmit power level of 0.14W

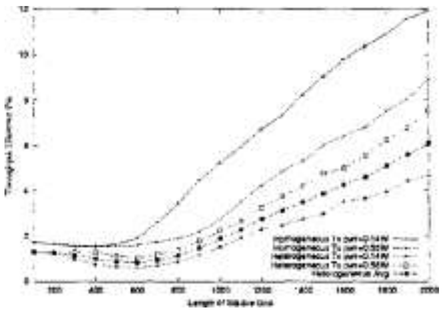

Fig. 10. Throughput for niotlifieil reservatitin scheme

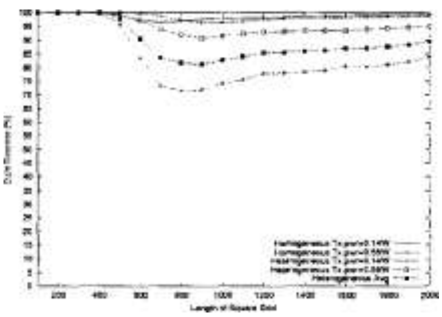

Fig. 11. DATA transmission success ratio for extended reservation scheme

and the other hall at 0.56W. Results were obtained at differ- ent netw‹ k densities and for dii’ferent offered loads. Owing to space constraints, graphical results for all offered loads that were tested are not presented here. Initially, the system was configured such that the CTS messages would be rebroadcast 2 times (sin‹:e N < 2). The results for an average offered load of 1000 p‹ickets per second per node are shown in Fig. 10 and Fig. 11. Fig. 10 shows the throughput of the heterogeneous sys- tem along with that of the homogeneous networks operating at each power level. We see that overall system performance has actually degraded significantly. Though the extended RTS/CTS mechanism brings about fairness in the sense that the difference in through put between the high power and low power nodes is not as high, thc additional message overhead probably exceeds the benefit accrued in propagating the CTS mcssages. We also note from psig. 11 that while there is no significant change in the DATA transmission success rate for low-power nodes, the rate for high-pt›wcr nodes goes down by about 5 to 10 percent.

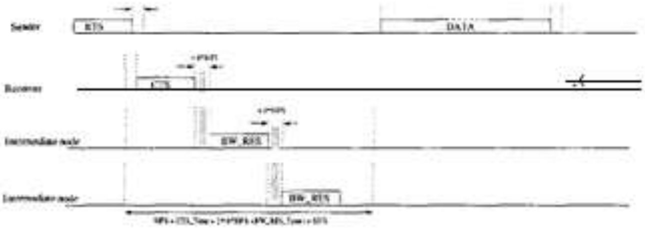

Fig. 9. The modified reservation scheme

In order‘ to reduce the overhead involved in sending the BW-RES messages, we considered a location information sys-_-‹tern like CAPS to optimize the transmission of BWMS mes-sages. We made changes to the simulation software so that the MAC layer at each node was aware ot the node’s position. This position information was then incorporated into the CTS and **BW.RES** messages. Three optimizations were performed based on the loc‹ition information now contained in each message in conjunction with the node’s awareness of its own location:

- Among nodes that overhear a CTS message, nodes that arc

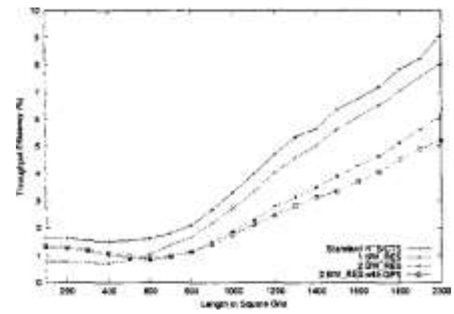

Fig. 12. Heterogeneous network throughput comparisons for different reserva- tion schemes (A — 1000a

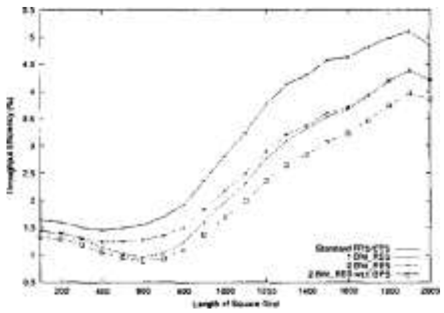

Fig. 13. Performance ot modified RTS/CTS mechanism at low load (A = 20)

If a node that receives a **BW.RES** determines that the mes- sap•e is being propagated back toward the sender ot the CTS (i.e. if the receiver of the **BW.RES** is closer to the sender of the CTS than the sender of the **BW.RES), it** will not propagate the BW.RES message further evcn if the mcssagc has a non-zcro time-to-live.

Surprisingly, we found that these modifications only give marginal benefit at high densities and actually degrade perfor- mance further at low densities. We surmise that one reason for the degradation is that addinp• location information to the CTS and BW RES messages increases the respective packet sizes by almost fifty percent. We also considered a scenario in which a CTS message orig- inating at a low-power node is propagated only once by nodes that hear it. Fig. 12 provides a comparison of results for the var- ious modifications at saturation load. Fig. 13 provides a similar comparison at a lighter off'ered load. We note that for saturation load, throughput for the heterogeneous network keeps worsen- ing as the overhead in the form of BW.RES messages increases. However at relatively lighter loading, throughput for a heteroge- neous network in which a CTS message is propagated twice (i.e. 2 **BW-RES)** is sometimes better than and never worse than that further from the sender of the CTS are more likely to transmit a BW RES first.» If a node that receives a BW.RES message is already as tarfrom the sender of the CTS as the range of the strongest node in for a heterogeneous network in which a CTS message is propa- gated only once. However ior every modification, the through- put is still worse than the throughput for the standard protocol.

Thus the modifications to the **IEEE** 802.11 protocol to ex- tend the reachability of the CTS messages by means of flood- ing actually degrade the performance ot the protocol. We are considering intelligent dissemination mechanisms whereby the gain achieved in avoiding collisions actually outweighs the loss incurred in tcrms of ovcrhead.

V. C ONCL USIONS

We have shown, in the context of the **IEEE** 802.11 protocol, that heterogeneous networks suffer significant degradation in performance in comparison with homogeneous networks. This degradation is primarily caused by poor medium access for the low-power nodes in the network. It is clear that the MAC proto- col has to be changed to make medium access more efficient in a heterogeneous network. We have investigated the feasibility of one such mechanism. This involves extending the RTS/CTS mechanism by adding another message type, to ensure that the reservation information is propagated a greater distance than be- fore. We have found that the overhead due to the additional mes- sages outweighs the potential benefits of the greater reach of the reservation mechanism. Hence other mechanisms, possibly in- volving a different kind of reservation scheme, will need to be investigated.

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