Reliable Multicast MAC Protocol for Wireless LANs

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Abstract— **Reliable multicast in wireless applications is gaining importance with the development in technology. Applications like multicast file transfer, distributed computing, chat and whiteboard applications need reliability. However, due to mobility and wireless channel characteristics, obtaining reliability in data transfer is a difficult and challenging task. IEEE 802.11 does not support reliable multicast due to its inability to exchange RTS/CTS and ACKS with multiple recipients. However, several MAC layer protocols have been proposed that provide reliable multicast. For example, [1] have proposed the Leader-Based, Probability-Based and Delay-Based Protocols. These protocols work around the problem of multiple CTSs/ACKs colliding by providing ways to have only one of the multicast recipient nodes respond with a CTS or an ACK. These protocols perform well in low mobility wireless LANs but the performance degenerates as the mobility of nodes increases. In this paper, we discuss the inherent drawbacks of these protocols and provide an alternative approach. We present an extension to the IEEE 802.11 MAC layer protocol to provide link level reliability to both unicast as well as multicast data communications. The extension is NAK based and uses tones, instead of conventional packets, to signal a NAK. We also incorporate Dual Tones, proposed by [2], to prevent an incoming mobile node from interrupting an ongoing transmission. Simulation results suggest that our MAC performs better than those proposed by [1] in terms of both data throughput as well as reliability.**

I. INTRODUCTION

When data has to be sent to multiple recipients, multicast incurs less network cost when compared to either broadcast or unicast to individual group members. Multicasting limits the transmission of redundant data and saves bandwidth as well as energy, two resources that are scarce in a network of wireless nodes.

Most research on mobile ad hoc networks have focussed on reliable unicasting of data. Of the work that has been done in multicast, a majority of it is targeted solely at the network layer. As a result, these multicast solutions do not take adequate advantage of the broadcast nature of the wireless channel. Further, these protocols do not attempt to provide reliable transfer of multicast data. Examples of ad hoc multicast protocols include [3] [4] [5] [6] [7] [8]. It is our contention that the efficacy of multicast routing protocols in terms of reliability can be improved by providing local error recovery support in the underlying MAC layer.

In this paper we are interested in reliable multicast support at the MAC level i.e. reliable transfer of data across single-hop wireless links. Such reliability is desirable because it reduces end-to-end delays by facilitating local error recovery. MAC level reliability does not guarantee end-to-end reliability and we assume that such reliability, if required, is built into a higher layer such as the network or transport layers. In particular, we do not deal with loss of packets that result from a node moving out of the transmission range of the sender.

Several of the MAC protocols that have been proposed so far are based on the seminal MACA protocol [9] proposed by P. Karn. However, Deng et al [2] have shown that inspite of using RTS/CTS, the probability of packet collisions in a mobile network can be as high as 60%. Collisions are mainly due to nodes that stray into a transmission zone after the RTS/CTS have been exchanged and are therefore unaware of an ongoing transmission. The authors have proposed the use of Dual Busy Tones to alert incoming nodes of an ongoing transmission. Further, when applying MACA-type protocols to reliable multicast communication, we have to be careful to avoid CTS collisions from multiple nodes.

Examples of MACA-based protocols that use dual busy tones include PAMAS [10] and [11]. PAMAS [10] was developed with the objective of conserving energy and does not support reliable multicasting. Further, unlike the sine wave signals proposed by [2], the BusyTone that is used in PAMAS is simply a control packet and is prone to collisions. In [11], the authors propose a MAC protocol that uses both power control as well as dual tones to increase channel utilization. The idea behind the protocol is to transmit with power only enough to reach the receiving node and hence reduce interference. This protocol does not support reliable multicast.

IEEE 802.11 does not support reliable multicast[12]. However there are several extensions to IEEE 802.11 that have been proposed for multicasting in wireless networks. Most of them use a combination of ACKs and NAKs to attain a degree of reliability. The problem with the use of ACKs during multicasting is that only one recipient should send an ACK to avoid a collision. Different methods have been developed to handle this problem. For example Delay-Based Protocols (DBP) tackle this ACKing problem by having recipient nodes wait a random amount of time before sending an ACK. Then there is a Probability-Based Protocol(PBP) in which recipient nodes send an ACK with a given probability. In the Leader-Based Protocol (LBP) proposed by [1], a node is elected leader

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and only this leader is allowed to send an ACK. Analytical results in [1] suggest that LBP performs better than both DBP and PBP. However, LBP itself has a major drawback when applied to mobile nodes. A new leader will have to be selected each time the current one leaves the cell. As the mobility of nodes increase, this problem becomes prominent.

We propose an extension to IEEE 802.11(henceforth called 802.11MX) that supports reliable multicast. Multicast reliability is built into the protocol by the use of NAKs. As mentioned earlier, the major problem with reliable multicast is that several recipient nodes may respond to an RTS or a data packet at the same time. We avoid this problem by using a tone to signal a NAK or NCTS rather than having a NAK/NCTS packet as such. The advantage of this method is that any number of recipient nodes can signal a NAK or an NCTS at the same time and since it is only a tone, collision does not affect it. Towsley et al [13][14] have shown that for multicasting applications, a NAK based reliability scheme fares better than an ACK based scheme both in terms of complexity as well as throughput.

By incorporating dual busy tones into our protocol we attempt to reduce the probability of multcast packets being corrupted due to collision and hence we need a lesser number of retransmissions. By reducing the number of retransmissions, we can increase the throughput.

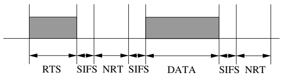
Our MAC protocol is suitable for both infrastructure-based mobile networks as well as ad-hoc mobile networks. In the case of infrastructure-based networks, our cluster would consist of a base station (that would be the source), and several mobile nodes. In the case of an ad hoc mobile network, our cluster simply consists of mobile nodes that are within range of each other.

Simulation results suggest that our protocol performs better than LBP both in terms of data throughput as well as reliability. While only 0.1% of data packets go undelivered in our protocol, LBP losses up to twice as many data packets. Further, unlike in LBP, the throughput of our protocol does not degenerate with increasing node mobility. We have validated our simulation results for throughput by comparing it against a mathematical analysis of the throughput for our MAC.

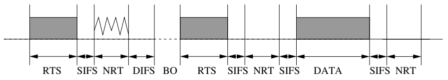
II. SYSTEM MODEL

Our system consists of a $cluster$ of nodes that are within communications range of a *cluster-leader*. In an infrastructure-based network, a *cluster-leader* would correspond to a base station or an access point. In an ad hoc network, the *cluster-leader* is any node that is the $source$ of multicast information or is forwarding multicast information. In the context of ad hoc networks, a $cluster$ is the set of all nodes that are within transmission range of this node. All nodes in the $cluster$ will receive multicast data at the same time.

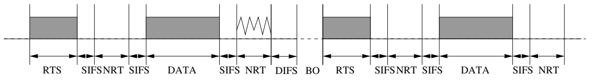
We assume that an antenna is capable of picking up both data bits as well as busy tones. Each node will have two antennas. One antenna is required for transmitting and receiving the busy tones while the other antenna is for transmitting and receiving data packets and NAK tones. The antennas are not capable of sensing the channel and transmitting at the same time.



Case I : Ideal Case



Case II : Some receiver not yet ready to receive. Transmits NAK tone in signalling channel.



Case III : Data received in error. Receiver transmits NAK tone in signalling channel

BO − Backoff Time
NRT − Not−ready Response Time

Fig. 1. **Slot diagrams of the protocol**

Packet transmissions are prone to collisions with other packet transmissions. We also assume a channel bit error rate of 10^{-5}. In our study of reliability, we do not account for packet losses due to a node moving out of range of the sender. Recovery from such packet losses should be done at the transport layer and is not a MAC layer function.

III. PROTOCOL DESCRIPTION

A. Definitions

Inter-Frame Spacings: The *Short Inter-frame Spacing* (SIFS) and the *Distributed Inter-Frame Spacing* (DIFS) are the same as defined in the IEEE 802.11 specifications.

Not-ready Response Time (NRT): NRT is the time within which a node can send a tone to indicate that it is not yet ready to receive data or that the last packet it received was in error.

Tone: A tone is a narrow-bandwidth sinusoidal wave signal. A tone is transmitted on a frequency that is outside of the channel that is used for packet transmission.

Busy Tone: A busy tone is transmitted by nodes to indicate that they are currently busy with some communication. A node wanting to transmit data will do so only if it does not sense the presence of a busy tone.

NCTS Tone: This tone is transmitted in response to an RTS and indicates that the node is not yet ready to receive data or that the RTS packet was received in error.

NAK Tone: This tone is transmitted by nodes that received the data packet in error.

B. Description of Algorithm

We have designed our protocol around the IEEE 802.11 MAC. When a node wants to transmit any data (state S1 of fig. 2), it senses the channel. If the channel is free for DIFS

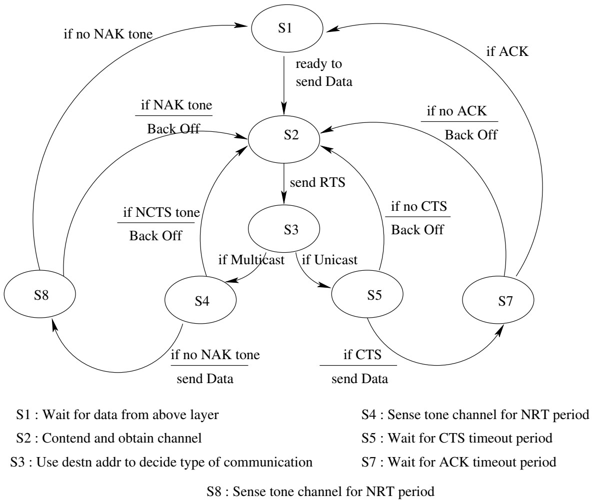


Fig. 2. **State diagram of the sender (base station).**

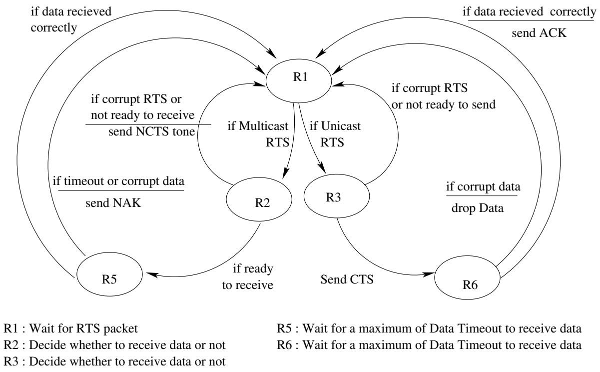


Fig. 3. **State diagram of the multicast receiver.**

period, the node resumes its backoff timer. If the channel is still free when the backoff timer expires, the node can start transmission. In unicast transmission, the node sends an RTS and expects to receive a CTS (states $S2 \rightarrow S3 \rightarrow S5$). If a CTS is received, the node transmits the data packet and waits for an ACK (states $S5 \rightarrow S7$). If the ACK is received, the data transmission was successful (return to state $S1$). Otherwise, the node goes through the channel access process all over again. For unicast data, we simply use the IEEE 802.11 specification.

When multicast data is to be sent, channel access is done just like in unicast. But when the RTS is sent (states $S2 \rightarrow S3 \rightarrow S4$), the sender node does not expect to receive a CTS packet. Instead, it listens on the signalling channel to see if any node is transmitting an NCTS tone. If no such tone is sensed, the sender begins transmission of the multicast data packet (states $S4 \rightarrow S8$). At the end of the packet transmission, the node senses the signalling channel again to see if any node is transmitting a NAK tone. If there is no NAK tone, the sender assumes that the data transmission was successful (states $S8 \rightarrow S1$).

On the receiver side, when a node receives an RTS it checks to see if the RTS is addressed to it or if the address is that of a multicast group to which it belongs. If the RTS is specifically addressed to it, then this is a unicast transmission and the receiver node is expected to send a CTS if it is ready to receive (states $R1 \rightarrow R3 \rightarrow R4$ of fig. 3). If the RTS is addressed to a multicast group to which this node belongs, then this node will have to prepare to receive a multicast data packet (state $R1 \rightarrow R2 \rightarrow R5$). If it is not ready to receive a packet, it sends an NCTS tone in the signalling channel and terminates the packet exchange (state $R1 \rightarrow R2 \rightarrow R1$). If the node is ready to receive, it starts a timer. If the data packet is not received before the timer expires, it probably means that some other recipient node has sent an NCTS and terminated the packet exchange. The node will send a NAK and go back to its idle state. If a data packet is received before the timeout, the recipient nodes check to see if the packet was received without error. If the packet was received without error or with Forward Error Correction (FEC) correctable errors, the packet is accepted and sent to the higher layers ($R5 \rightarrow R1$). If the packet is received with uncorrectable errors, the packet is dropped and a NAK tone is transmitted in the signalling channel (states $R5 \rightarrow R1$). As the response is only a tone, it does not matter if the NAKs from multiple recipients collide. In case of a NAK, the $source$ will have to re-aquire the channel again by sending an RTS. Fig 1 shows the working of the protocol.

Nodes that receive the RTS packet but are not interested in the transmission will simply update their Network Allocation Vectors for virtual carrier sensing. The slot diagram for the protocol is shown in fig. 1.

C. *Incorporation of Dual Busy Tones*

In a network of mobile nodes, an RTS-CTS exchange does not guarantee that the channel is available solely to one transmission at a time. For instance, a node that was originally out of communication range of a pair of nodes may not have heard the RTS-CTS exchange. Such a node may stray into the range of the communicating nodes and may sense the channel during the long silence between an RTS and data packet transmission (for multicast data). This silence could be mistaken for the channel being free and the straying node may start transmitting, thereby possibly causing a collision. The receiving nodes will detect such packet corruption and send a NAK causing a retransmission of the data. Hence the algorithm described so far is resilient enough to handle such straying nodes. However, we note that retransmission has an adverse effect on channel throughput. We can prevent such collisions by using the Dual Busy Tones, a mechanism proposed by [2].

After sending the RTS, if the $source$ does not detect a tone in the signalling channel during the NRT period, it will assume that the channel is available. After the NRT period, both the $source$ and the receivers will transmit a busy tone in the corresponding busy-tone channel to indicate that a data transmission is in progress in the data channel. Any node that wants to transmit will sense this tone to find that the channel is busy. The busy tones are disabled at the end of transmission. In case the transmission is cut short due to an NCTS, the transmitting node will disable its tone on sensing the NCTS tone. The other nodes will disable their tones when their timers expire without any data being received.

IV. SIMULATION RESULTS

We used network simulator *ns-2* [15] to simulate both our protocol as well as the Leader-Based Protocol. In order to study the throughput as well as the reliability of the protocols, we have run the simulations for two kinds of scenarios. For both the scenarios, we ran simulations for mobility ranging from 0 to 35 m/s in steps of 5 m/s. We used the Random Waypoint Model for node mobility. For each speed, we took the average of five simulation runs. For throughput study, each run was 500 seconds and for the reliability study, each run was the time taken for the multicast source to send 50,000 data packets.

A. Data Throughput

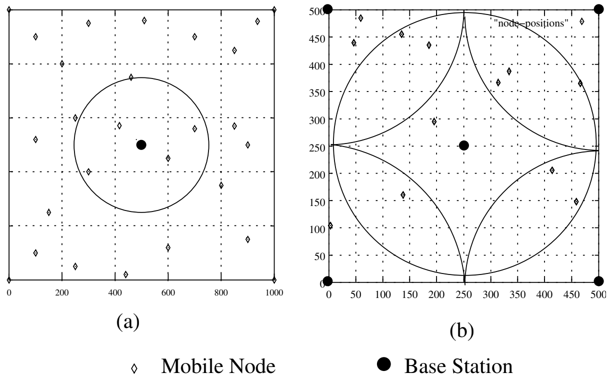
Fig. 4(a) shows the scenario we used for testing the data throughput of the protocols as a function of node mobility. Though we used a 2Mbps channel, the actual throughput is much lower for both the protocols because of overhead in terms of control packets, interframe spacings, random backoffs and packet retransmissions. In this scenario, we have only one transmiting node. There is no contention for the channel. Packet errors can only occur due to channel error. We have assumed a constant Bit Error Rate of 10^{-5}. Care was taken to ensure that there was atleast one node in the base station's transmission region. This was done so that the Leader-Based Protocol's throughput is not adversely affected due to the lack of a leader node.

In order to validate our simulations, we did a mathematical analysis of the throughput of 802.11MX. Due to space constraints we provide only the final equations of the analysis. Equation 1 gives the channel holding time of 802.11MX.

$$\begin{aligned} T_1 &= T_{DIFS} + T_{bo} + T_{RTS} + T_{SIFS} + T_{NCTS} \\ T_2 &= T_{SIFS} + T_{DATA} + T_{SIFS} + T_{NAK} \\ T_{CH-MX} &= \frac{T_1 + T_2(1 - L_{RTS}P_{err})}{(1 - L_{RTS}P_{err})(1 - L_{DATA}P_{err})} \qquad (1) \end{aligned}$$

where L_x is the length of packet x, T_{bo} is the backoff time, and P_{err} is the probability that a bit is in error, the inverse of bit error rate.

Fig. 5 shows the relative throughputs of 802.11MX and LBP. In order to give the reader a reference point to compare with, we have also plotted the throughput of IEEE 802.11 unicast. It is seen that the throughput for 802.11MX obtained through simulation agrees very well with the throughput obtained through mathematical analysis. It is also seen that LBP's throughput gradually decreases with increasing node mobility. This can be attributed to the fact that with increasing mobility, the probability of a leader moving out of the base station's transmission region increases. This increases the frequency of selection of a new leader. The time taken for the base station to detect that the leader is missing added with the time it takes to select a new leader has an adverse effect on the channel throughput. From the figure, it also appears that our multicast protocol has better throughput performance than IEEE 802.11 unicast. This is partly attributed to the fact that the NAK tone is transmitted out-of-band of the data channel and hence the data channel becomes free at the end of the data packet transmission. On the other hand, in IEEE 802.11 and LBP the data channel becomes free only at the end of the ACK packet transmission. Further the NCTS/NAK tones do not carry any information and their transmission duration only needs to be as long as it takes for the receiver to sense the presence or absence of a tone. In IEEE 802.11 and LBP, on the other hand, control packets with much information are transmitted for the same purpose and are several 10's of bytes long. Finally, control packets such as ACK are themselves prone to channel error and may result in unneccassary retransmissions. The cumulative effect of these factors contribute to a significant difference in the data throughputs of IEEE 802.11 and LBP when compared with our protocol.



(a)

(b)

Fig. 4. **Scenario for studying (a) throughput (b) reliability of the MAC protocols.** The position of the base station is fixed. Position of mobile nodes are only sample positions.

B. Reliability

Fig. 4(b) shows the system configuration used for testing the reliability of the protocols as a function of node mobilitiy. There are five base-stations with overlapping transmission regions. The base stations themselves cannot communicate directly but it is possible that a node can receive from multiple base stations at the same time. Further, we also introduce random broadcast and unicast communications between some mobile nodes. We study a set of 10 mobile nodes that are always within the range of the central base station. The packets recieved by these nodes are prone to collision with packets from other base stations and with packets from the unicast and broadcast transmissions. Further, packets can also be corrupted due to channel error. Here we have taken Bit Error Rates of

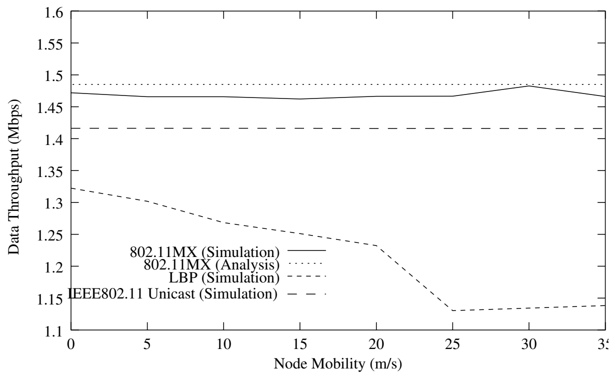


Fig. 5. **The throughput of LBP drops with increasing node mobility due to the frequent reselection of leader node.**

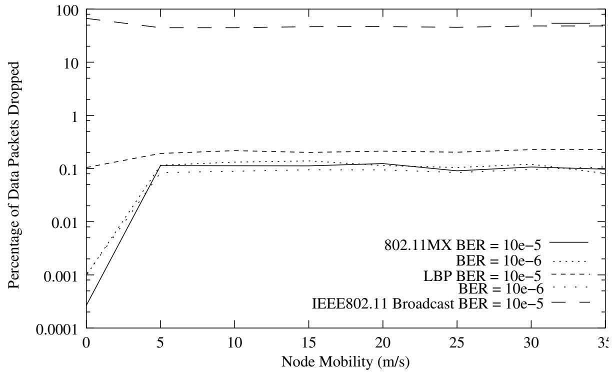


Fig. 6. **The reliability of both LBP as well as 802.11MX are not significantly affected by mobility.**

10^{-5} and 10^{-6}.

To guage the relative reliability of the protocols, we had the central base station of fig 4(b) transmit 50,000 multicast data packets. We then measured the average number of data packets that each of the 10 designated nodes should have received but did not. It is possible that for some packets, some nodes received them while others did not. This metric gives us an idea of the efficacy of the local error-recovery capability of the various protocols. Packets that are missed (dropped) by this local error-recovery mechanism will have to be recovered by the higher layers in the protocol stack of the individual nodes.

Fig. 6 shows the percentage of packets dropped by each of the protocols as a function of node mobility. None of the protocols studied provide 100% reliability. However, it is seen from the graph that on an average our protocol drops only half as many packets as LBP. Our protocol drops 0.1% of the packets while LBP drops 0.2%. The IEEE 802.11 broadcast drops as much as 40% of the data packets under similar traffic conditions.

V. ADDITIONAL HARDWARE REQUIREMENT

The higher data throughput and reliability of 802.11MX comes at the cost of an additional transceiver. One tranceiver is required to handle the dual busy tones while another is required for the data/NCTS/NAK. Further, the tranceiver that handles the data/NAK/NCTS should be capable of handling both modulated data signals as well as narrowband sinusoidal wave signals.

VI. CONCLUSIONS

In this paper, we proposed an extension to the IEEE 802.11 MAC to improve link-level reliability for multicast data. A novel feature of this extension is that it uses tones rather than packets to signal a NAK and hence is not prone to NAK packet collisions. Further, dual busy tones have been incorporated to reduce packet collisions due to node mobility. The reduction of these two types of collisions results in a significant increase in data throughput and reliability. Simulation results suggest that our protocol extension performs better than LBP in terms of both actual data throughput as well as reliability.

ACKNOWLEDGMENT

We thank A. Natarajan for her help with the LBP simulations. This work is supported by NSF grant ANI-0196156.

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