IMPLEMENTING MESSAGE PRIORITY POLICIES
OVER AN 802.11 BASED MOBILE AD HOC NETWORK

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ABSTRACT

In a mobile ad hoc network (MANET) for military or emergency applications, it is required to give priority to certain messages or message sources. In this paper, mechanisms are considered for implementing priority treatment of packets in a MANET using the DSR ad hoc network multihop routing protocol based on modifying an IEEE 802.11 MAC layer operating in the distributed mode. The mechanisms include queuing in order of priority and several methods for giving higher priority messages an advantage in contending for channel access. Simulation results are given for OPNET models of these schemes.

INTRODUCTION[1]

A mobile ad hoc network (MANET) [1, 2] is a collection of autonomous mobile users (nodes) that communicate over links with relatively low bandwidth because of the limited frequencies allocated and because of the impairments typically present on the mobile wireless propagation channel. Due to nodal mobility, the network topology may change rapidly and unpredictably over time. The network is decentralized in that network organization and routing of messages must be executed by the nodes themselves. Nodes may also contend with multiple access interference, multipath fading, and shadowing. A MANET may operate alone or be connected to a larger network.

Ad Hoc Network Protocols

MANETs need efficient distributed algorithms to determine network organization in terms of connectivity, link scheduling, and routing. An efficient approach is to use routing algorithms in which connectivity is determined in the process of establishing routes. While the shortest path based on some cost function is usually the optimal route in a static network, this idea must be extended to include factors such as power expended, variable link quality, propagation loss, multiuser interference, and topological changes are relevant issues in the selection of a path. In addition, in a military environment, preservation of security, latency, reliability, intentional jamming, and recovery from failure are significant concerns.

Several protocols have been proposed in the Internet

Engineering Task Force (IETF) for performance of routing functions in a MANET [3]. For the studies described in this paper, the protocol used was the Dynamic Source Routing (DSR) protocol [4, 5], implemented as an OPNET simulation model by NIST [6]. Its main feature is that every data packet follows the source route stored in its header. When a node needs to send a data packet, it checks first its route cache for a source route to the destination. If no route is found, it attempts to find one using a route discovery mechanism. A mechanism called route maintenance is used in each operation along a route to monitor the validity of each route used.

Our studies were specifically designed to evaluate the effectiveness of a MANET in delivering priority messaging service using a standard routing algorithm such as DSR but altering the protocols used at the medium access (MAC) and physical (PHY) layers according to the IEEE 802.11 specification [7].

Background on IEEE 802.11

The 802.11 standard defines two operating modes: *infrastructure mode* and *ad hoc mode*. In the infrastructure mode, called a Basic Service Set (BSS), the wireless network consists of at least one access point connected to the wired network infrastructure and a set of wireless end stations. Since most corporate wireless LANs require access to the wired LAN for services (file servers, printers, Internet links) they will operate in infrastructure mode. The ad hoc mode (called an Independent Basic Service Set, or IBSS) is a set of 802.11 wireless stations that communicate directly with one another without using an access point or any connection to a wired network. While designed for fully connected network (LAN) configurations, the ad hoc mode can be adapted to multihop use.

The 802.11 MAC layer is designed to support multiple users contending for access to a shared medium by having the sender sense the medium before accessing it at a random "backoff" time following a "distributed interframe space" (DIFS), as illustrated in Figure 1. If there is a collision due to two users transmitting simultaneously, the users must re-enter contention. After a collision, the size of the contention window is increased, repeatedly if necessary, to make a collision-free transmission by one of the terminals more likely. Figure 2 shows the increase in contention window size (number of slots) as a function of

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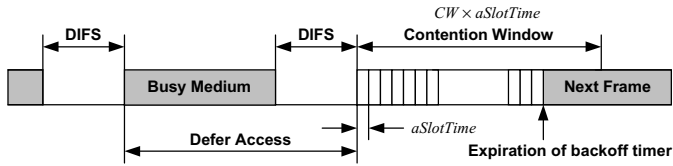
Fig. 1. Carrier-Sense Multiple Access (CSMA)

Fig. 3. CSMA with collision avoidance

the number of retries that are necessitated by collisions. Indirect detection of collisions is implemented by acknowledgement (ACK) of correct reception from a receiver. If an ACK is not returned, it is assumed that a collision of two transmissions at the receiver has destroyed the information in both messages. The "defer access" interval shown in Figure 1 is implemented in the ad hoc mode as the "virtual carrier sense mechanism" [7] of a distributed coordination function (DCF) that provides information at the beginning of data messages about their duration; listening nodes defer their contention for the next transmission opportunity until after the projected end of the current transmission (including the ACK), plus a DIFS interval. In effect, the channel is "reserved" for the duration of the message by the transmitter that successfully competed for the transmission opportunity.

Although a wireless LAN generally is a network in which all the nodes can hear each other (*i.e.*, a fully connected network), in the ad hoc mode (and MANET applications) it is possible for some nodes in the wireless LAN's coverage area to be unable to hear each another. To solve this "hidden node" problem, 802.11 specifies a "collision avoidance" feature that is implemented using a Request to Send/Clear to Send (RTS/CTS) protocol at the MAC layer, as illustrated in Figure 3. To save on overhead, there is an option to omit the RTS/CTS exchange when the message length is shorter than a threshold, thereby trading off the risk of repeating a short message with the certainty of using up air time with more signaling traffic than data traffic.

Time-bounded data applications such as voice and video are supported in the 802.11 MAC specification
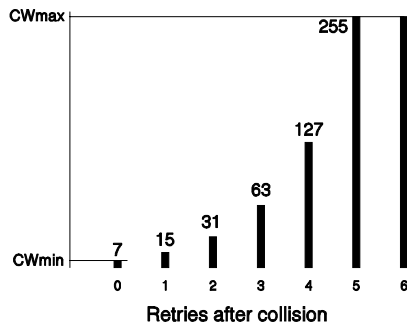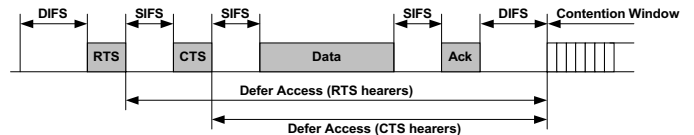

Fig. 2. Backoff timer adjustment.

through a point coordination function (PCF). If an IBSS is set up with PCF enabled, the available transmission opportunities are divided between the PCF mode the DCF mode. During the former, the access point will sequentially poll each station for data. No station can transmit unless it is polled, and stations receive data from the access point only when they are polled. A mobile station with high priority or with a high priority message to or from it can be polled more frequently, thereby providing a higher proportion of the channel bandwidth. In this paper we consider modifications to the IEEE 802.11 MAC layer procedures to implement priority in the DCF mode.

PRIORITY IN MANETS

MANETs have characteristics similar to those of the packet radio networks that were studied extensively in the 1970s and 1980s (*e.g.*, [8, 9]). Many analytical and experimental studies were conducted to determine the best methods for providing multiple access to packet users in terms of maximizing network throughput while maintaining acceptable delay, that is, maximizing the statistical multiplexing efficiency of the network. In recent years, there has been a renewed interest in packet networks that are configured as LANs or as mobile versions of the Internet, and instead of throughput *per se*, the performance of the network in terms of quality of service (QoS) issues has been stressed. This reflects the fact that packet radio networks and MANETs are being tasked to carry different classes of traffic, some of which (such as digital voice) require timely delivery of its packets, while other types of packets on the same network are more tolerant of delays. Since the limited bandwidth of the mobile radio channel prevents giving every class of traffic the same QoS except when the network is very lightly loaded, some means for providing each class a different QoS must be implemented to assigning priority to one class over another in terms of allocating network resources. Thus the linkage between QoS and "priority" is a common one in the literature, and the two terms are almost synonymous. A general model for MANET QoS is proposed in [10].

For a static situation, in which the traffic flows originating at the network nodes are known and are fixed, it is possible using various algorithms to calculate a "schedule" of transmissions that maximizes network throughput while providing the desired QoS to the various traffic classes. As long as the total traffic does not exceed

the capacity of the channel(s) allocated, the schedule guarantees performance in a non-contention access mode. Extension to a mobile network requires periodic or adaptive recalculation of the schedules. A survey of distributed scheduling algorithms is included in [11].

Decentralization by means of distributed network management functions does not necessarily imply that the channel access is based on contention, nor that all signaling is done on the common channel, but most algorithms developed for MANETs are based on these assumptions. Our interest is primarily in those schemes that are distributed and do not require a central station or a separate signaling channel. Most distributed schemes for implementing priority in packet radio networks utilize various "mechanisms" that give an advantage to priority users, thereby providing them a better grade of service.

A fundamental method for implementing priority messaging is static priority scheduling (SPS). Under SPS, each priority class of traffic has its own first-in first-out (FIFO) queue, and the queues are served in order of delay priority, first in first out, as suggested in Figure 4. In connection with General Packet Radio Service (GPRS), [12] contains a list of scheduling methods. The paper considers FIFO, SPS, and EDF (earliest deadline first) for the case of three delay-service classes. Numerical studies include different traffic models. In [13] three access priority schemes are proposed: random chip delay (RCD), random backoff based (RBB), and variable logical channel based (VLC) access priority schemes.

Proposed Mechanisms for Implementing Priority at the 802.11 MAC layer

Taking the approach of modifying the MAC layer procedures of IEEE 802.11 to create mechanisms that prioritize traffic in a MANET, we propose new procedures and corresponding mechanisms, and study the performance of MANETs with and without such mechanisms.

The first mechanism is the SPS approach illustrated in Figure 4. For the purpose of this study, we implemented only two priority levels, sufficient to indicate the effectiveness of the concept. We replace the single 802.11 packet buffer with two queues: one containing the "standard" packets (⇔ queue priority level 2) and the other the packets with "priority" (⇔ queue priority level 1).
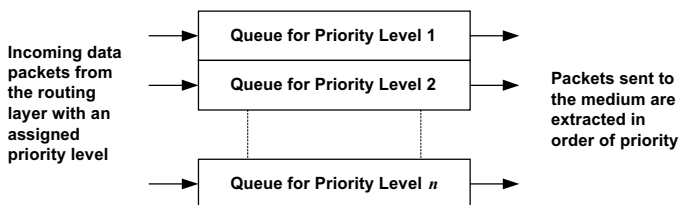

Fig. 4. Priority queuing approach

The second mechanism permits a node wanting to send the highest priority packet to be the first to transmit on the channel. As illustrated in Figure 5, this objective can be achieved by defining different DIFS times (each one separated by at least one small slot time to follow the 802.11 specification). To implement this "prioritized waiting time" mechanism in our simulation, we assign the shortest waiting time (DIFS) to packets with "priority" and for the "standard" packet we add one more slot time to it.

A third priority mechanism calculates the random backoff time depending on the priority level of the packet. We use different distributions to calculate this random backoff time as illustrated conceptually in Figure 6, in which the standard backoff time calculation is represented by the "Standard" or uniform probability distribution in the upper part of the figure. The concept behind this distribution is that each node contending for the channel randomly selects a transmit time from a set of equally likely, discrete values, with the spacing between the values providing sufficient time to allow the carrier-sense mechanisms in later-scheduled nodes to keep them from transmitting when another node has randomly selected an earlier transmit time slot. Also in Figure 6, a "prioritized backoff time" calculation is represented by a "High Priority" probability distribution, representing the concept that a high-priority user has the same set of potential transmission times, but the earlier times are more probable, making the high-priority user more likely to "win" contention for the channel during the backoff period.
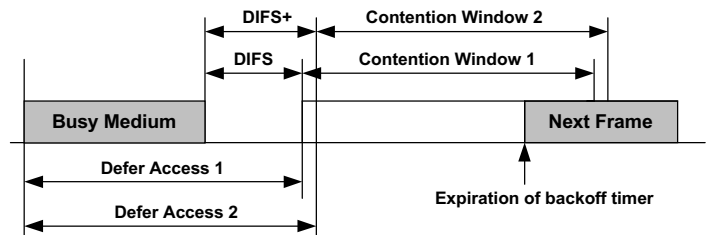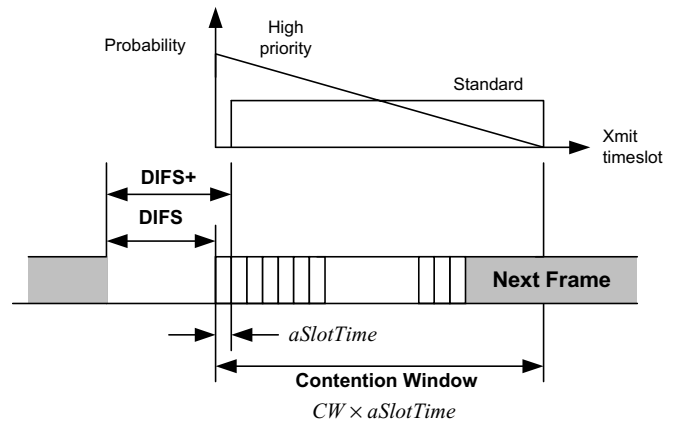

Fig. 5. Prioritized waiting time mechanism

Fig. 6. Prioritized backoff time distribution mechanism.

The concept of a prioritized backoff time distribution can be implemented in combination with the concept of prioritized waiting times. The distribution of backoff time for a standard packet is uniform and delayed relative to the contention window for a prioritized packet, whose backoff time distribution favors selecting an early transmission.

Our implementation of the prioritized backoff time distribution concept is based on the OPNET exponential distribution model, for which the mean is $1/\lambda$. The standard 802.11 interval for choosing the backoff number of slots is variable from [0, *CW_min_size*] to [0, *CW_max_size*], depending on the number of medium access attempts as illustrated previously in Figure 2. We implemented a similar mechanism for the priority backoff distribution by using a variable mean $1/\lambda$, where

$$\lambda = 0.1 + \left(\frac{CW\_\max\_size - CW\_current\_size}{CW\_\max\_size - CW\_\min\_size} \right) \times 0.3$$

and "*CW*" denotes Contention Window. When the contention access has been collision-free and the window size is minimal, the distribution with $\lambda = 0.4$ is used, and when collisions have forced the window size to its maximum value, the distribution with $\lambda = 0.1$ is used.

SIMULATION OF THE PRIORITY SCHEMES

An OPNET model was developed for simulating a wireless network node incorporating the proposed priority mechanisms when the network layer model implements the DSR routing protocol [6]. The link and physical layers contain modules for IEEE 802.11 that are part of OPNET 7.0, but were modified by NIST for multihop MANET simulations as described in [6]. Details of the model are given in [11]. We concentrated on a few scenarios that show how the proposed priority mechanisms work, including diagnostic scenarios designed to examine the operation of the mechanisms in detail.

For example, the network topology used to test delay and throughput is depicted in Figure 7, in which the outer nodes must communicate through the central node; to analyze the priority mechanisms as the volume of traffic increases, the level of traffic is increased until a saturation point is reached on the central node. Simulations of the scenario depicted in Figure 7 were run for different values of the packet traffic generated at each node, with the packet link (one-hop) delay vs. packet rate results shown in Figure 8 for a data rate of 1 Mb/s. Equal amounts of standard and priority data packets were generated, each with 512 bits of data, 184 bits of DSR routing header, and 224 bits of 802.11 header, totaling 920 bits per data packet. The DSR routing request, reply, and error packets had 168, 161, and 168 bits of data, respectively. Because
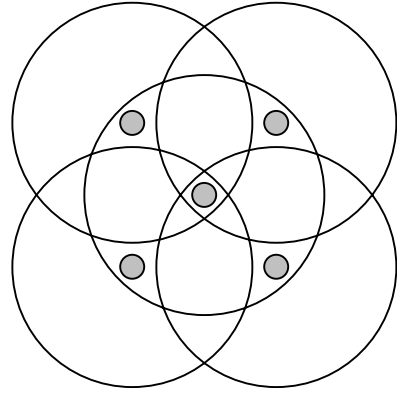

Fig. 7. Scenario for delay and throughput analysis
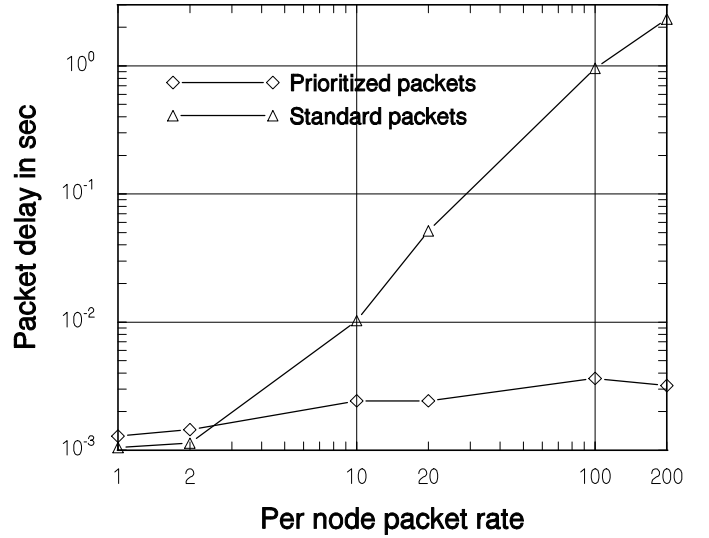

Fig. 8. Packet link delay vs. packet rate, scenario of Fig. 7

of the small size of the packets, the RTS/CTS mechanism of 802.11 was turned off for this particular result, and thus the minimum one-hop packet delay equals DIFS + packet transmission delay + SIFS + 96-bit ACK transmission delay, where for a slot time of $T_{slot} = 50 \, \mu s$,

$$\text{SIFS} = 28 \, \mu s$$

$$\text{DIFS} = \begin{cases} \text{SIFS} + 2 T_{slot} = 128 \, \mu s, & \text{priority packet} \\ \text{SIFS} + 3 T_{slot} = 178 \, \mu s, & \text{standard packet} \end{cases}$$

ACK transmission delay $= 96 \, \mu s$

Data packet transmission delay $= 920 \, \mu s$

Routing packet transmission delay $\approx 390 \, \mu s$

The total of these delays is 1.172 ms for a priority data packet and 1.222 ms for a standard data packet; the minimum routing packet delays were about 658 µs and 708 µs, respectively. The results in Figure 8 are averages of simulated 5-minute periods, and the values of delay at very low packet generation rates are consistent with the

respective minimum delays. The priority packet delays increase only slightly for the range of packet rates shown, while the standard packet delays increase approximately with the square of the packet rate for rates greater than about 2 packets per second. This trend is reasonable because the transmission time available for standard packets is decreasing in proportion to the packet generation rate at the same time that the packet rate is increasing.

Example plots of throughput vs. time are shown in Figure 9 for the central node and for all nodes, with throughput calculated as the cumulative number of bits offered to the MAC layer divided by the time. After an initial period in which there is route-finding activity, the throughput decreases until, at $t = 13s$ the priority traffic begins to gain an advantage over the standard traffic. The timing of this event is confirmed in Figure 10, where it is
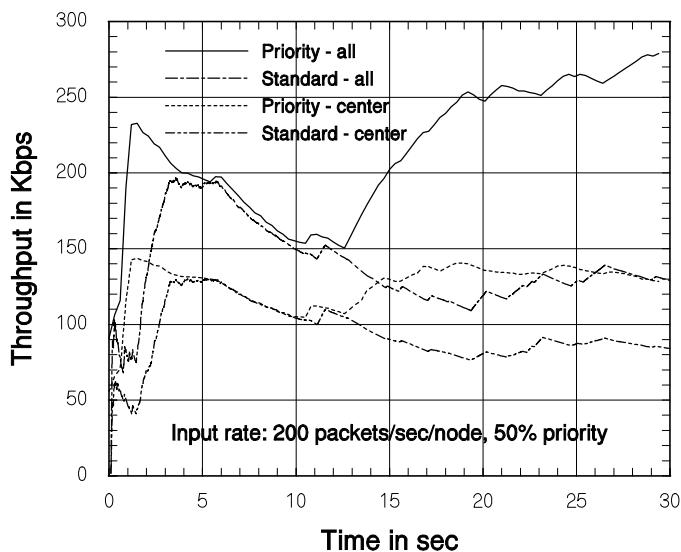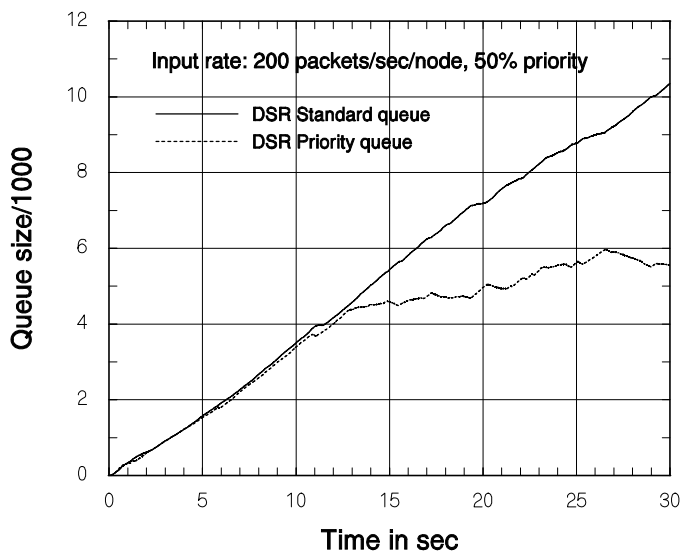
shown that the routing layer queue for standard packets continues to back up, while the slope of the queue size for priority packets decreases significantly. This behavior represents a type of "capture" of the network resources by the priority traffic.

Further parametric simulations and analyses are ongoing to gain an understanding of the capture effect observed in Figures 9 and 10, and to develop mechanisms for controlling or limiting it in order to provide some "fair" or perhaps minimal allocation of resources to the standard traffic.

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Fig. 9. Throughputs for scenario of Fig. 7.

Fig. 10. Average queue sizes for scenario of Fig. 7.