Quality of Service Aware MAC Based on IEEE 802.11 for Multihop Ad-Hoc Networks

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***Abstract*—Real-time multimedia applications necessitate predictable network resources. Quality of Service (QoS) support for such applications in mobile ad hoc networks (MANETs) requires acceptable channel conditions, QoS-aware mechanisms for channel access, identification of proper forwarding (transit) nodes, as well as measures for congestion prevention and management in those nodes. This paper proposes a new QoS-aware medium access control (MAC) protocol that takes the above requirements into consideration. This novel protocol is based on the legacy IEEE 802.11, and thus can be easily integrated into existing systems without much difficulty. Simulation results confirm that our approach results in improved throughput for real-time periodic traffic, while providing deterministic delay performance.**

Keywords – Ad hoc Networks, Multiple Access Control, QoS-aware MAC, IEEE 802.11.

I. Introduction

Given that real-time applications will be used in ad hoc networks, efforts for QoS support are under way. However, in order to facilitate QoS support, a clear understanding of the difficulties and issues in provisioning QoS in MANETs is necessary. Since ad hoc networks lack fixed infrastructure, there is no dedicated agency to manage the channel resources for the network nodes. Quality of service is possible only if supported by the underlying medium access technology. In other words, the network-level QoS mechanisms cannot work in MANETs, unless the MAC ensures orderly access to the shared wireless medium, playing a crucial role in the efficient and fair sharing of the scarce wireless bandwidth [1]. The nature of the wireless channel requires that different layers, in particular the network-layer and MAC sub-layer, interact constantly in order to provide an overall QoS. Also, there must be mechanisms available to minimize or recover efficiently from packet collisions. However, most of the network-layer QoS work is tailored to the distributed coordination function (DCF) of IEEE 802.11a/b as the underlying MAC [11]. In the legacy IEEE 802.11, an ad hoc network is named Independent Basic Service Set (IBSS) [6]. An IBSS is based on the DCF that utilizes a random access method of carrier sense multiple access with collision avoidance (CSMA-CA). Since the latter is mainly meant for best-effort traffic, the present DCF-based MANET cannot support QoS at MAC-level, and subsequently overall end-to-end QoS guarantees [3][7][8][9]. The contention from multiple users to access the common medium using a random access technique often results in unavoidable packet collisions, unbounded delay, and increased jitter. The time required to resolve collisions is a function of the network load. In addition, the DCF makes extensive use of control packets as a handshaking mechanism in order to minimize hidden-node and exposed-terminal problems [2]. This approach is not desirable, especially for periodic time-sensitive traffic, as it not only increases the collision rate, but also deteriorates the overall efficiency of the channel and the system [7][8][9].

Besides the DCF, the IEEE 802.11 also incorporates an alternative access method known as the point coordination function (PCF) [4][5][6]. This access method is similar to a polling system, and uses a point coordinator (PC) to determine which station has the right to transmit. The PCF falls under demand assignment access schemes, and as such it is more suitable for an environment that requires QoS guarantees [16]. The PCF operation, however, needs a centralized node such as an access point (AP), and hence is normally used in WLAN environments. In our approach, spread spectrum techniques and collision avoidance multiple access protocols are combined to form a new MAC protocol for multimedia traffic over MANETs [2][10]. This protocol is based on a hierarchical approach consisting of two sub layers. The lower sub-layer of the protocol provides a fundamental access method using the DCF to support asynchronous data traffic, and to enable time-sensitive traffic to reserve bandwidth using a two-way handshake mechanism. The upper sub-layer is designed to support real-time periodic traffic. Our novel smart MAC, which thus consists of both random (contention-based) and regulated (contention-free) access to the medium, provides applications with enough resources in order to improve QoS.

The rest of the paper is organized as follows. Section II reviews IEEE 802.11 and related work on MAC-level QoS, and presents our motivation. The proposed MAC protocol is described in section III. Section IV presents the evaluation of the proposed scheme through simulation, and demonstrates that our MAC approach leads to improved-QoS performances. Section V presents our conclusion and future work.

II. Previous Work And Our Motivation

Given that our approach is based on IEEE 802.11, a basic description of its working mechanism is necessary here. Since the main focus of our work on the MAC sublayer is on PCF, we review the IEEE 802.11with an emphasis on the PC mode.

A. IEEE 802.11

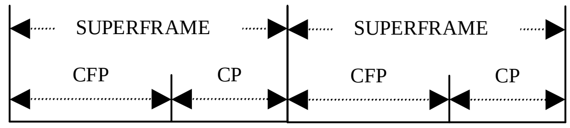

Figure 1. Timing Diagram for IEEE 802.11 MAC Operation.

The DCF mode is the fundamental access method of the 802.11 MAC [6]. The time-period during which the network operates in the DCF mode is known as the contention-period (CP). Access priority to the medium is controlled through the use of inter frame spaces (IFS). There exit four types of IFS: the Short IFS (SIFS), the Point coordination function IFS (PIFS), the Distributed coordination function IFS (DIFS), and the Extended IFS (EIFS). The SIFS is the shortest interval, and is used for transmission of acknowledgements (ACK), station responding to polls from the PC, and between fragments. As such transmissions that are required to wait only for SIFS have the highest priority over the medium. The AP uses PIFS (> SIFS) to initiate the CFP. The DIFS (> PIFS) is used by ordinary nodes during the CP. The shorter the period that a transmission has to wait for, the greater the access priority it has over the medium. The DCF mode consists of a four way exchange: request-to-send (RTS) - clear-to-send (CTS)-DATA-ACK. RTS is used for a node to acquire the medium after waiting for a minimum period of DIFS. The receiving node (destination) responds with CTS after a SIFS, indicating that it is ready to receive data. The sender then completes the packet transmission. On the other hand, in case the sender cannot access the medium after DIFS due to the medium not being idle, the transmission is deferred until the end of the current transmission. A random interval in the range of zero to Contention Window (CW) is then computed by the node to initialize its backoff timer. In addition to physical medium sensing, virtual medium sensing is achieved by using time fields in the packets, which indicate to the other nodes the duration of the current transmission.

The PCF mode provides contention-free frame transfer and the time-period in which the LAN operates in the PCF mode is known as the Contention-Free Period (CFP) [6]. The AP performs the function of the PC by gaining control of the medium in the beginning of the CFP, after sensing the medium to be idle for PIFS. During the CFP, nodes that are CF-Pollable are polled by the AP. On receiving a poll, a node transmits its data after a SIFS. In order to poll the nodes, an AP must maintain a polling-list. The CFP must alternate with the CP. The sum of the two periods is called the “super-frame” and is shown in Fig.1. The AP initiates the CFP by transmitting a Beacon frame, and ends it by transmitting a CF-End frame. The contention-free repetition interval (CFPPeriod) is the reciprocal of the rate at which the AP initiates the CFP. To support error correction, positive ACKs are used in both the DCF and PCF modes.

B. Related work on MAC-LevelQoS forMANET

It is difficult to compare different MAC protocols. Each has been developed with a different architecture and application in mind. MAC protocols can be classified based on the mode of operation into random access, guaranteed access, and hybrid access protocols [16]. Random access schemes are typically used for data traffic, and cannot support QoS. Guaranteed and hybrid access schemes normally require central nodes. Most of the works on QoS-enabled MAC have been based on guaranteed and hybrid access schemes, hence targeting infrastructure-based networks such as WLANs.

A multiple access scheme based on Time Division Duplexing (TDD) for single hop MANET is proposed in [7]. In this approach, the channel is time-slotted, and a slotted system requires network-wide time synchronization, which is relatively easy to achieve in infrastructure-based networks by using the base station as a time reference. This task becomes extremely difficult in distributed networks such as multihop MANET environments [16]. Also this work considers a network, where all the nodes are assumed to be within radio range of each other, and only a limited number (maximum 12) of multimedia sessions can be supported at a particular moment within the considered network. This is unrealistic, as MANETs tend to be multihop, and should support as many sessions as possible. This scheme further requires that a source, after having successfully reserved a time-slot, send a busy-indication packet until the end of its session. This approaches increases the number of exposed nodes. Another similar scheme, known as Soft Reservation Multiple Access with Priority Assignment (SRMA-PA), is presented in [8]. It is a Time Division Multiple Access (TDMA) frame based MAC protocol that allocates stations to different time-slots. This scheme does not take asynchronous data traffic into consideration, as all data transmissions are required to reserve slots irrespective of whether they are real-time or best-effort traffic. Also there is a possibility for higher priority traffic to starve lower priority traffic, as any higher order traffic can snap the slots already reserved by lower priority traffics. A MAC approach that combines an allocation-based (TDMA) protocol and a contention-based (CSMA-CA) protocol is proposed in [9]. In this scheme, the number of slots in each frame is dependent on the number of nodes in the network, and hence each slot belongs to a single node only. The higher the number of nodes in the network, the larger the frame size would be. This leads to unbounded delay for time-sensitive applications. Similar approach is followed in reservation CSMA-CA [3]. In this scheme, CP and CFP alternate, and the CFP is based on TDMA. Since there is no node to regulate the common medium, this scheme may lead to a “stretching” problem [4]. It also requires proper time-synchronization, and each node is supposed to maintain a “slot-table” that indicates whether each slot is “reserved” or “available”. Another MAC protocol that considers multiple channels is proposed in [10]. It combines code division multiple access (CDMA) or frequency division multiple access (FDMA), and TDMA to create a contention-free MAC, termed the sequenced neighbor double reservation (SNDR). Since it mainly considers time-slot allocation to make it contention-free, it fails to support asynchronous data traffic and requires complex slot-synchronization.

Although the IEEE 802.11 DCF is meant for best-effort traffic, there have been some efforts that investigate differentiated services at MAC-level in infrastructure-based networks [11][12]. A similar idea can also be applied to MANETs. Service-differentiation is achieved by setting different values for CW – values of minimum (CW_{min}) and maximum (CW_{max}) – for different traffic classes. Two different service classes such as high priority and best effort are considered, and the traffic packet with the smaller value of CW is more likely to be transmitted first [11]. There is, however, no explicit guarantee of the level of service differentiation. There have also been some proposals to make DCF to be "per-stream-fair", as the DCF of legacy IEEE 802.11 tends to be unfair due to the "capture-effect" [13]. With these schemes, different sessions are allowed to gain access to the shared wireless medium equally. Fairness is achieved by dynamically modifying the CW of each traffic type by the source. The fairness approach does not, however, guarantee QoS support.

Similarly each work presented above has its own drawback(s), and does not have the capability to provide MAC-level QoS for multimedia traffic in multihop MANETs. The next section describes how our approach tries to achieve improved throughput for real-time periodic traffic, while providing deterministic delay performance.

III. PROPOSED APPROACH

Having taken the common deficiencies of other approaches into consideration, our approach tries to support both asynchronous and time-sensitive multimedia traffic based on a hierarchical approach. In our scheme, both the DCF and PCF of the IEEE 802.11 are used after being modified to accommodate MAC-level service differentiation. Although the PCF does require a centralized node, we describe next how this can be introduced for the first time in multihop MANET with novelty. The motivation for this work comes from the observation that the PCF mode offers a "packet-switched connection-oriented" service which is well suited for voice as well as multimedia traffic. The "connection-oriented" aspect of the PCF mode would allow the network to provide namely throughput, delay, and jitter guarantees [4].

In order to accommodate simultaneous transmission of several data traffic, multiple parallel media (channels) are created with receiver-based spread-spectrum technology [2][10]. In this scheme, each node has its unique code, and hence its unique medium, on which it has to receive packets from others. In addition, there is a common medium, which all nodes can use to disseminate and acquire neighbor and routing related information. These codes are assumed to be orthogonal to each other, and assigned to nodes dynamically in a conflict-free manner using the common medium. In our approach, transmission by any node A to another node B has to be on the receiver's (B's) spreading code. In order to accommodate the situation in which any node can receive multiple transmissions initiated by different sources, IEEE 802.11 (both DCF and PCF) is used on top of each unique medium as depicted on Fig. 2. The common medium, however, can support only the DCF. Each node is expected to regulate and schedule its own unique medium. Also each node has to maintain constant CP and CFP on its own medium in order to minimize or completely avoid the "stretching" effect [4]. This is important in order to minimize the delay jitter experienced by applications.

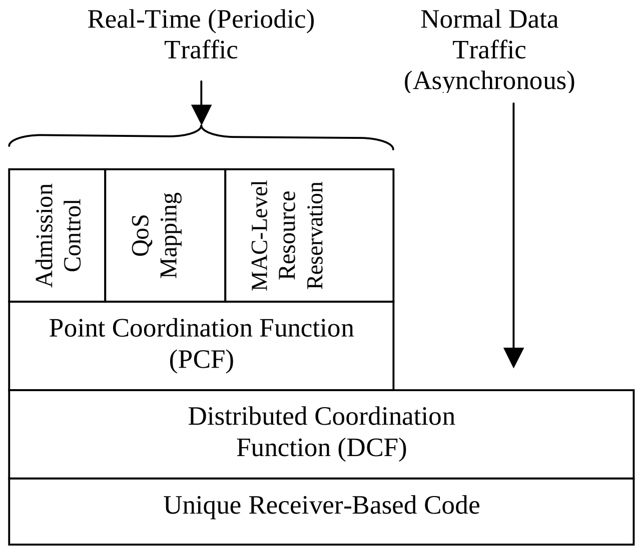

Figure 2. Structure of Our QoS-Aware MAC.

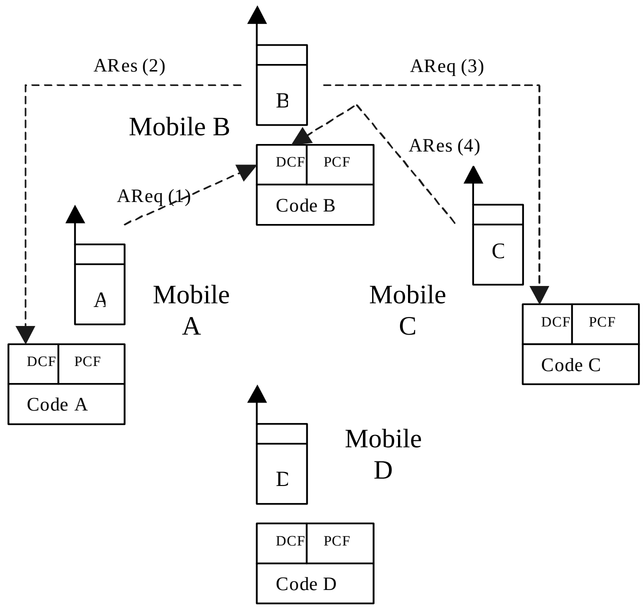

Figure 3. Working Mechanism of Our MAC.

In our work we have considered two different service classes, high-priority and best-effort. Our MAC's mode of operation on each unique medium switches between pure DCF mode and combined (DCF + PCF) mode depending on traffic types, and hence adapts. Each unique medium supports only pure DCF mode of operation as long as all traffic types are best-effort. On the other hand, whenever a high-priority traffic needs to be transmitted, the source node A has to send an "Association Request" (AReq) frame to the forwarder (transit) node B selected by the routing protocol [6]. This AReq frame is normally sent on the CP of a transit node's (B's) own unique medium (see Fig. 3). As soon as node B receives the Areq frame, it has to send Association Response (ARes) frame to the originating node A on the CP of the latter's (A's) own medium. At the same time, node B has to create a polling-list and include node A in it. At the start of CFP on B's medium, node

B has to begin polling node A. In this way, any node (B) should be able to emulate the functionality of PC, and in our approach such a node is referred to as a virtual PC (VPC). Since node B is an intermediate node, it has to forward the packet to its destination or the next forwarding node. Accordingly, it would soon send the AReq frame to node C, which is here assumed to be the destination, on C's own medium. After sending ARes frame on node B's medium, node C has to be ready to poll node B at the start of CFP on C's unique medium. If node C were to send packets back to node A, then it would follow the same process as node A has performed, but in the opposite direction. In this way, nodes along a particular path (or route) become polling-list members of each other. It is thus important that whenever a node (A) transmits to another node (B), it has to be on the latter's (B's) medium. If the traffic type is of high priority, the source (A) can transmit when the node (B) polls. This is the case even when a node transmits an ACK for the packets it receives correctly on its own medium. If, however, the routing protocol is unable to provide the next hop address (probably during the route discovery process in the case of an on-demand routing protocol), the proposed MAC will use the common channel for disseminating the packet. In all other circumstances, our MAC protocol tries to minimize flooding on the common medium, unless it is required depending on relative velocities as explained later. Because of the way in which transmissions are performed, our approach can completely eliminate the exposed-terminal problem. The hidden-terminal problem is minimized to a greater extend with a use of unique media, and with the adoption of DCF and especially PCF mode of operations. In addition, each node maintains its own polling-list dynamically in order to use it on its own medium. If a polling-node finds that it has not received any transmission from one of its polling-list members for time period greater than POLLING_TIME_OUT, then that node address will be deleted from the former's polling-list immediately. This is how a "disassociation" process is performed in our scheme [6]. This approach leads to efficient bandwidth management, and this occurs whenever nodes move out of each other's range or have finished their transmission. With this approach, a source node does not have to predict and inform others as to how long its transmission is going to last, which is often difficult in practice.

Our QoS-aware MAC protocol has three components: admission control, QoS-mapping and resource reservation as shown in Fig. 2. Provisioning of network resources uses two techniques such as resource reservation in PCF mode, and prioritization in the DCF mode of operation, as explained below. The objective of a priority-based approach is to provide service-differentiation by allowing faster access to the medium to traffic classes with higher priority [11][12]. Like in the IEEE 802.11 DCF, priority access to the wireless medium is controlled through the use of an IFS. A new IFS termed Reservation IFS (RIFS) is defined and its value is selected such that SIFS < PIFS < RIFS < DIFS. To initiate new data transmission, RIFS or DIFS is used to contend for access to the medium depending on the traffic type. A high-priority real-time (periodic) traffic uses RIFS before sending the AReq, while DIFS is used to gain access right for best-effort asynchronous traffic as in the IEEE 802.11 DCF. In our approach, the transmissions of AReq and ARes frames, and best-effort data traffic share the CP of a unique medium. Since the RIFS is shorter than the DIFS, the high-priority traffic class has priority over the best-effort traffic, which uses DIFS. ARes frame is sent by any VPC, after SIFS when operating in the DCF mode. ARes frame is sent only when admission control module has analyzed the current load as expressed by equation (2) below. Since there is a maximum limit for high-priority traffic, the probability for AReq frames of high-priority traffic to starve the best-effort traffic during CP is minimized. This achieves the "fairness" in our scheme [13]. When a collision happens in the reservation process, the back-off time is calculated using the following modified equation [12]:

$$\text{Back-off-time} = [\, p^{2+i} \times rand()] \times Slot\_time \qquad (1)$$

Where p is the priority-factor with p=2 for high-priority traffic and p=4 for best-effort traffic, i is the transmission attempt number, and rand() is a random function with a uniform distribution in [0,1]. This ensures that the high-priority traffic class still enjoys priority over best-effort traffic during the collision-resolution period [6][12]. Although this type of prioritization is an important enhancement, it is not enough to provide effective traffic protection and QoS guarantees. This is achieved with our polling-based scheme introduced in MANET in a novel way as described below. The maximum number (N_p) of high-priority traffic that can be supported in CFP, given a constant super frame size T_{SF}, is given by equation (2)[4]. In this case, the high-priority traffic is assumed to be a time-sensitive periodic interactive voice service, which is generated using a constant bit rate (CBR) source for convenience.

$$N_p = \frac{T_{SF} - T_{cp} - T_{ovhd}}{T_v} \qquad (2)$$

Where T_{cp}, T_{ovhd}, and T_v are duration of CP, overhead involved for beacon and CF_END transmissions, and time to send a voice packet generated over a T_{SF} [4]. In other word, the VPC can poll to a maximum of N_p number of times (or nodes) within a CFP on its own medium. Depending on the intensity of the high-priority traffic load, any node can request a VPC to poll it for more than once within each super frame period (T_{SF}) of VPC. The MAC-level QoS-mapping module of a particular node calculates the number of times it has to be polled by any VPC. This calculation is based on the bandwidth requested by the network-level QoS mechanism. Any node can inform any VPC as to how many times it has to be polled by that VPC during each T_{SF} of the latter through the AReq frame – the AReq frame format is modified to accommodate this in our scheme. Whenever a VPC receives an AReq frame from its neighbors, its admission control module will check whether its CFP period is fully utilized (ie. whether the N_p has already been reached). If not, the VPC is required to send the ARes frame, and allocates the required bandwidth (here allocation means how many times the requesting node has to be polled within each T_{SF} of a VPC). If the maximum number has already been reached, then the VPC should not respond to any AReq. In this case, the requesting node should look for another appropriate forwarding node, after waiting for a period of ASSO_PROC_THERESHOLD_TIME_OUT.

Since the common medium is necessary for every node to disseminate and acquire routing related information and possibly to perform dynamic code assignment, each node may receive transmission from its neighbors. On the other hand, as explained above, nodes are expected to use receiver-based unique media for data transmission. If, however, a node decides that its relative velocity with respect to its neighbors increases beyond a certain threshold within a short time-period, then it cannot rely on PCF-based operation. Only in this circumstance, the node would use the common medium for data transmission. Each node calculates its relative velocity by making power measurements from neighbors on its own medium and the common medium as explained below. Under Friis' free space propagation model, the signal power detected, say RxPr, at the receiving node is indicative of the distance between the transmitting and receiving node pairs. Since it is very difficult to calculate the exact distance between two nodes without wasting bandwidth, we try to use the MOBIC model that defines a relative mobility metric, $M_X^{rel}(Y)$, at a node X with respect to node Y [14]:

$$M_X^{rel}(Y) = 10\log_{10}\left(\frac{Rx\,\Pr_{Y\to X}^{new}}{Rx\,\Pr_{Y\to X}^{old}}\right) \qquad (3)$$

Every node X determines the above mobility metric for each neighbor Y by making subsequent power measurements, given a constant transmission power. A negative value for $M_X^{rel}(Y)$ indicates that nodes X and Y are moving away from each other, and a positive value indicates that they are moving towards each other. For a node with m number of neighbors, each node X will have m such values for M_X^{rel}. Each node X determines the aggregate local mobility value by calculating the variance (with respect to zero) of the entire set of relative mobility samples $M_X^{rel}(Y_i)$, where Y_i is a neighbor of X:

$$M_X = \mathrm{var}_0\left[M_X^{rel}(Y_i)\right]_{i=1}^{m} = E\left[(M_X^{rel})^2\right] \qquad (4)$$

Each node X computes (3) and (4) in an attempt to calculate its relative velocity with respect to its neighbors. A low value for M_x indicates that node X is relatively less mobile with respect to its neighbors, while a higher value indicates that node X is highly mobile. Whenever M_x exceeds $M_{threshold}$, node X has to rely on the common medium for data transmission. In this way, our QoS-aware MAC adapts depending on relative mobility information.

IV. Evaluation Through Simulation

TABLE I. Important Simulation Parameters

Parameter	Value
Duration of the Superframe (T_{SF})	70,000 microseconds
Value of the CFP (T_{cfp})	50,000 microseconds
The SIFS interval	10 microseconds
The PIFS interval	30 microseconds
The RIFS interval	40 microseconds
The DIFS interval	50 microseconds
A Slot time	20 microseconds

In our initial evaluation, we consider two performance metrics: throughput and MAC delay. We performed our simulations using the GloMoSim [15] simulation package, in which we implemented our MAC scheme, and compared it against the DCF mode operation of the IEEE 802.11. Nodes' movement was modeled by the random waypoint mobility model. Nodes move at a speed between 0 and 10 ms^{-1}. The pause time takes a constant value of 30 seconds. Each run is executed for 300 seconds of simulation time, and models a network of 20 nodes placed randomly in a 500m X 500m area. Each node has a transmission range of 100m, and full duplex operation is considered with two antennas per node (one for transmission and the other for reception). The propagation model is the free space model. The bandwidth is 2 Mbs^{-1}, the data packet size is 512 bytes, and packets are sent at a rate of 100 to 400 per second by each node. Other important simulation parameters are listed in Table 1.

Fig. 4 shows the total throughput as a function of offered load for both our scheme and the DCF of IEEE 802.11. The total throughput is defined here as the total number of packets actually delivered to their respective destinations within the whole network. From Fig. 4, it becomes obvious that our scheme leads to better throughput performance. The throughput of IEEE 802.11 continues to drop after a slight initial increase, due to increased collisions and the resulting binary exponential backoff (BEB) scheme. As it can be seen, the throughput in our scheme tends to increase and soon reaches a saturation point. This point is dependent on N_p of (2), which again depends on the link bandwidth and the CFP repetition interval, which here takes the value of 70 milliseconds. In our simulation, for convenience, a node determines the receiver-based code of its neighbor based on the latter's address. Fig. 5 depicts the average MAC delay incurred for a high-priority packet in both schemes. The MAC delay of a node is the time between the instant at which a packet comes to the head of the node's transmission queue and the end of the packet transmission. As load increases, there would be increased contention, and hence MAC delay tends to increase in any MAC scheme. However, in our scheme this increase is only slight compared to the original DCF, and is dependent on the link bandwidth and the CFP repetition interval. Reducing the inter-poll period or T_{SF} can further reduce the delay in our scheme [4]. On the other hand, in the DCF, the MAC delay tends to increase significantly with the number of sessions. This can be attributed to such factors as increased collision, and hence increased retransmission attempts and extended BEB delay.

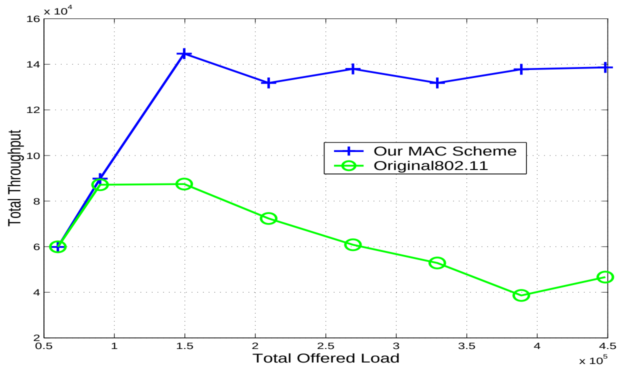

Figure 4. Total Throughput as a function of Offered Load.

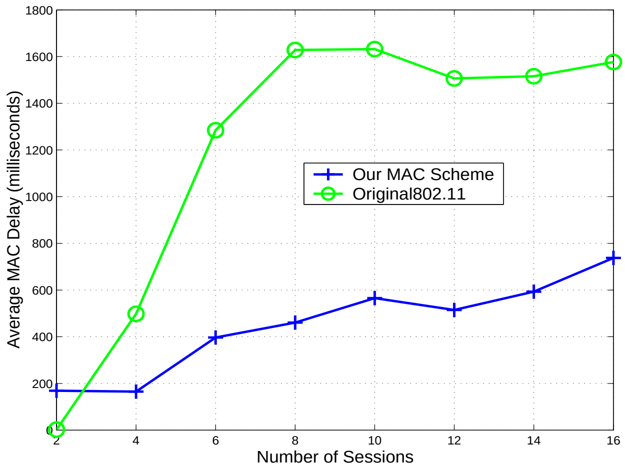

Figure 5. MAC Delay as a function of Number of Sessions.

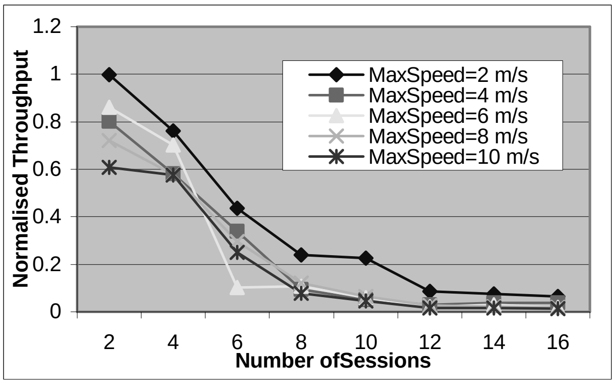

Figure 6. Normalized Throughput as a Function of Maximum Speed and Number of Sessions.

Fig. 6 shows the performance of our scheme for different mobile speeds. In this simulation, the normalized throughput performance of our scheme is observed by varying both the maximum speed of each mobile node and the offered load. The normalized throughput is defined here as the total number of packets actually delivered to their respective destinations divided by the total number of packets generated within the whole network. The minimum speed and the pause time of each node are kept at constant values of 0 ms^{-1} and 30 seconds respectively throughout this simulation run. As it can be seen, the throughput is affected by the speed. Also it can be noted that our scheme leads to better throughput and delay performance, when nodes move as groups in the same direction. This is the case in battlefields and other similar environments.

V. CONCLUSIONS AND FUTURE WORK

In this paper we presented a QoS-aware MAC protocol for multimedia traffic in MANETs and evaluated its performance through simulation. The proposed protocol introduces a packet switching concept based on the PCF in multihop MANET in a novel way. Simulation results confirm the performance (throughput, delay) improvements of our scheme. In addition, our proposed approach leads to fewer collisions and hence minimizes the need for re-transmissions. This fact will in turn conserve scarce resources such as battery power and bandwidth. As explained, the MAC functionality of a node is adaptive, depending on relative node velocities. Since this work is mainly based on the IEEE 802.11 standard, it can be relatively easily integrated into existing systems. We plan to extend this work in the future with the use of the recent IEEE 802.11e standard in order to support multiple traffic classes.

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