Infrastructure-Based MAC in Wireless Mobile Ad-hoc Networks[1]

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Abstract - *The IEEE 802.11 standard is the most popular Medium Access Control (MAC) protocol for wireless local area networks. However, in an ad-hoc environment, the Point Coordination Function (PCF), defined in the standard, cannot be readily used. This is due to the fact that there is no central authority to act as a Point Coordinator (PC). Peer-to-peer ad-hoc mode in the IEEE 802.11 standard only implements the Distributed Coordination Function (DCF). In this paper, an efficient and on-the-fly infrastructure is created using our proposed Mobile Point Coordinator (MPC) protocol. Based on this protocol, we also develop an efficient MAC protocol, namely MPC-MAC. Our MAC protocol extends the IEEE 802.11 standard for use in multihop wireless ad-hoc networks implementing both the DCF and PCF modes of operation. The goal, and also the challenge, is to achieve QoS delivery and priority access for real-time traffic in ad-hoc wireless environments while maintaining backward compatibility with the IEEE 802.11 standard. The performance of MPC-MAC is compared to the IEEE 802.11 DCF-based MAC without MPC. Simulation experiments show that in all cases the use of PCF benefits real-time packets by decreasing the average delay and the discard ratio. However, this may come at the expense of increasing the average delay for non-real-time data. On the other hand, the discard ratio for both real-time and non-real-time packets improves with the use of PCF. Therefore, our MPC-MAC outperforms the standard DCF IEEE 802.11 MAC protocol in multi-hop ad-hoc environments.*

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Keywords *– Wireless Ad hoc Networks, Medium Access Control, Clustering, QoS, Simulation.*

1. INTRODUCTION

In the ad-hoc [1] type of wireless network portable devices are brought together to form a network *on the fly*. In such an environment, there is no infrastructure to coordinate access to the network. Usually every node is able to communicate with every other node when all nodes are spread around a relatively small geographic range. However, nodes may spread over a larger geographic range than the communication signal can reach. In this case nodes may have to communicate over multiple hops. There is only one medium that is shared by all the nodes that are in the same radio communication range, and the radio frequency bandwidth is limited. As well, packet collisions are unavoidable due to the fact that traffic arrivals are random and there is non-zero propagation time between transmitters and receivers. Therefore, Medium Access Control (MAC) schemes are used to coordinate access to the single channel in the network.

Since there is no centralized authority to assign specific radio frequencies, time slots or codes to different mobile nodes that are totally distributed. Mobile terminals have to contend for the medium access by themselves. Carrier Sense Medium Access (CSMA) [2] is the main mechanism to implement medium access. Consequently, transmissions of packets from distinct mobile terminals are more prone to overlap, resulting in packet losses. Retransmissions are required and a noticeable delay appears. To make the existing infrastructure-based wireless protocol usable in the ad-hoc environment and also to make the ad-hoc wireless networks more manageable for routing and MAC, developing an

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infrastructure for the infrastructure-less wireless mobile ad-hoc networks is of utmost importance. A number of clustering techniques have been proposed for wireless ad-hoc networks [3-12]. The criteria for choosing the cluster-head include (i) Highest-Degree heuristic [3-5] (ii) Lowest-ID heuristic [3,6-8] and (iii) Node-Weight heuristic [9-12].

Recently, a lot of research has been done on local wireless MAC protocols. For wireless LANs, the IEEE 802.11 [13-17] is the most popular MAC protocol. It consists of a Distributed Coordination Function (DCF) and a Point Coordination Function (PCF). The DCF is based on the CSMA/CA mechanism and thus works efficiently even without an access point controller. However, the proper operation of PCF needs a Point Coordinator (PC) to administer the data transmission among a group of MTs. In the IEEE 802.11 wireless local networks, the access point naturally is chosen to act as the PC. However, in the ad-hoc environment, there is no infrastructure and nodal mobility may be high. The lack of a point coordinator renders the PCF protocol of the IEEE 802.11 ineffective. So, transmission of all packets (non-real-time and real-time) is through the DCF. Real-time packets cannot then achieve their QoS requirement.

Other MAC protocols designed for the ad-hoc network are based on the principle that the ad-hoc network is totally distributed. So, the direction of design to improve the QoS for the real-time packets is by optimizing the CSMA/CA, trying to give the real-time packets higher priority when they compete for the medium. However, all such proposals do not conform to the IEEE 802.11 protocol, and hence pose compatibility and economic issues.

We have noted that there are great economic benefits in reusing all the existing functions defined in the IEEE 802.11 standard, and that central control can achieve the most effective management in the wireless network, not just in MAC but also in routing and many other functions. We, therefore, propose a Mobile Point Coordinator (MPC) selection protocol that will select some MTs as MPCs to function as access point coordinators in ad-hoc environments. Based on this MPC system, an efficient MAC protocol that is compatible with IEEE 802.11 has also been proposed.

This paper is organized as follows. The next section discusses MPC creation protocol in wireless mobile ad hoc networks. In Section 3, MPC MAC protocol is described in detail. Performance evaluation of the protocol is provided in Section 4. Conclusion and future research can be found in Section 5.

2. THE MOBILE POINT COORDINATOR (MPC) PROTOCOL

In this section we propose a *Mobile Point Coordinator* (MPC) selection protocol that selects some MTs to act as access point coordinators in ad-hoc networks. In our scheme, The MT can be in one of three modes of operation: (1) free MT (with no registered MTs), (2) zone-MT (registered to an MPC other than itself) or (3) MPC. Consider Figure 1, and assume that node "A" is an MPC, and nodes "b" and "c" are zone-MTs that are registered to node "A". Every MT, regardless of its current operating mode, lies in the center of two imaginary circles. In Figure 1, the area within the solid circle around node "A" is the Communication Range (resembling the so-called "cell" in cellular networks) of node "A". All other nodes in this range, such as "b" at time b1 and "c" at time c1 can communicate with node "A" directly. The dashed circle, whose radius is half that of the communication circle defines the MPC range of node "A". Ideally, all the MTs that are registered to MPC "A" are within its MPC range. Every node declares its existence by sending a "hello" message, and the receiver of the "hello" message decides in which area the sender is located, depending on the strength of the received radio signal. If the receiver can hear the signal, then the sender must be in its *communication range*; and if the received signal is stronger than the value of the so-called MPC candidate threshold, then the sender is within the receiver's *MPC range*.

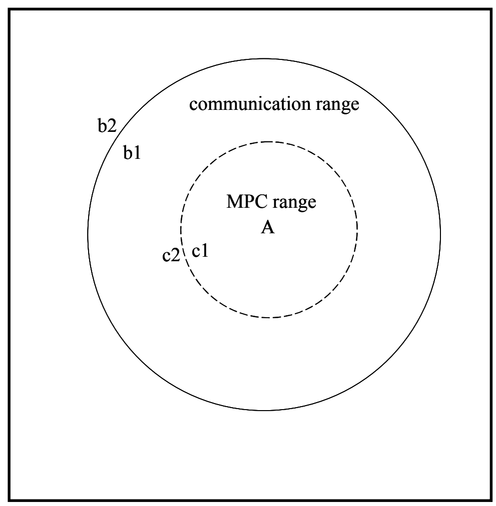

Figure 1 Communication range and MPC

When an MT is turned on, it broadcasts its so-called "hello" message periodically. The "hello" message contains the node's local information and information about the wireless ad-hoc network. Explanations of the fields contained in the hello message are listed below:

- **(a)** **My_ID** – this is the MAC ID of the MT and is unique to every MT.
- **(b)** **My_MPC** – this parameter indicates the ID of the MT's MPC. If the MT is a zone-MT, its My_MPC variable will set to the ID of the MPC to which it is registered. If the MT is an MPC it will be set to "0". If the MT is a free MT, its My_MPC variable will be also set to "0".

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(c) My_sequence_num – any connectivity change will result in an increase of the sender's My_sequence_num. It is initialed to "0" when the MT is turned on.

(d) My_reg_MT_num – this variable stores the number of the zone-MTs that are currently registered to an MPC. Both the zone-MTs and the free MTs will have their My_reg_MT_num set to "0".

(e) My_neighboring_MPC_num – this variable parameter counts the number of the MPCs or free MTs that are in this MT's communication range.

(f) Probing_MT_list – this parameter contains the IDs of all the zone-MTs that are registered to a particular MPC. Both the zone-MTs and free-MTs will set this parameter value to null.

Other parameters that need to maintained by all MTs include:

(g) inner_outer_threshold (MPC candidate threshold) – A constant radio signal strength value. If the receiving radio signal is stronger than this value, the sender will be considered currently in my MPC range, and thus suits being an MPC candidate.

(h) need_MT_list_search_for_MPC – A flag used to indicate where to find the best MPC. When the MT turns on or the zone-MT disjoin from an MPC, this value is set to "true".

(i) MT list – A table maintained in every MT's MIB to store information of the neighboring MTs, which are currently in its communication range. Each entry will contain the following: (1) My_ID (2) My_MPC (3) My_reg_MT_num (4) My_sequence_num (5) My_neighboring_MPC_num (6) Last_received_time (7) received_signal_strength. The first five parameters are exchanged by the "hello" message. The Last_received_time records the time of the last message received from a neighboring MT. The received_signal_strength records the signal strength of last message received from this MT.

(j) "Data sending" queue – A queue maintained by every MT's MAC layer to store the non-real-time, real-time, and management data packet, prior to transmission.

(k) "Control frame" stack – Another buffer in the MAC layer used to buffer the control frames that cannot suffer delay such as ACK, and CTS. The "control frame" stack has higher priority than the "data sending" queue in data sending.

Figure 2 shows the process of MPC selection. All the MTs will periodically broadcast "hello" messages. All the MTs in the sender's communication range can receive the "hello" messages if there is no collision. The receiver will record or update the sender's local information contained within the "hello" message, including the receiving time and signal strength. If the MT does not receive any signal from a certain MT that is listed in its "MT list" within a timeout period, it will regard the target MT as out of its communication range and will delete it from its "MT list". Another time that a MT can realize a neighboring MT has shut down or has moved out of its communication range is when it sends packet to this destination MT without receiving an ACK for several times continuously.

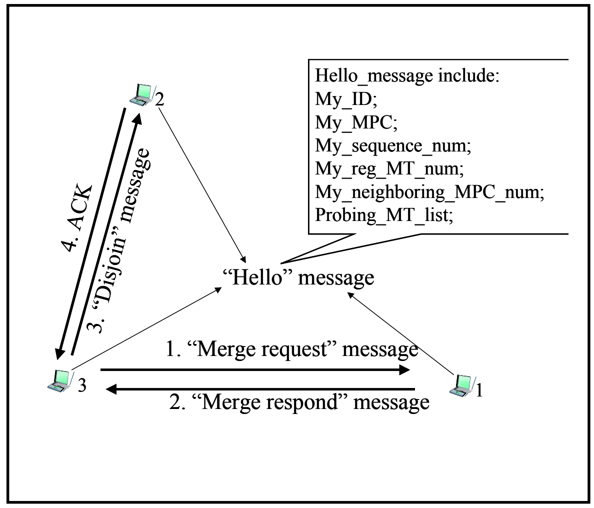

Figure 2 MPC Selection Mechanism

After having been turned on for a period of time exceeding the "observing period", as an MT needs enough time to collect the neighboring MTs' information to avoid selecting an MPC depending on partial information, the MT selects an MPC from its list of possible candidates. The criteria upon which an MPC is chosen are as follows:

I. An MT whose My_MPC value is "0" will join an MPC whose signal strength is at or above the inner_outer_threshold.

II. MPCs with largest My_reg_MT_num are given preference. This MPC selection criterion tends to discourage multiple cluster-heads within MPC range of each other. According to this criterion, if two MPCs move within MPC range of each other, the smaller group will finally merge into the larger group.

III. MPCs that can communicate with a large number of other MPCs are given preference. This is because the MPC with a higher My_neighbor_MPC_num has more MPCs or free MTs to coordinate with directly.

IV. If the all the above three criteria are the same for two or more candidate MPCs, then the MT will select the MPC with the lowest ID.

After choosing the candidate MPC, if the candidate is not an MPC itself, the MT will send a "merge request" message to the candidate MPC during the DCF period. The candidate MPC will either send back a "merge response" message with "merge accept" or "merge reject" information. The latter occurs only when there is a limitation on the number of zone MTs (access control mechanism) or if the receiver has moved out of the MPC range of the sender. If the sender of the "merge request" message does not receive the "merge response" message on time, it will retry until it receives the response message. If the merge request is accepted, then the MT will change my_MPC to reflect its new MPC and increase the My_sequence_num by 1. The MT will send a "disjoin" message to its old MPC, if it had one. The old MPC will respond with an ACK to announce the receipt of the message and update the topology parameters. The previous MPC's My_sequence_num will be incremented by one, and its My_reg_MT_num will also change to reflect the revised number of group members.

3. MPC-MAC PROTOCOL

In this section, we describe an IEEE 802.11 compatible MAC protocol for wireless ad-hoc networks. Our protocol is based on the MPC infrastructure-creation scheme described in the previous section. Section 3.1 gives an overview of the protocol. Section 3.2 describes the MPC-MAC system parameters. Section 3.3 provides a description of the protocol.

3.1. Protocol overview

When an MT turns on, it is initialized as a free MT. All MTs run the MPC creation protocol, and some are elected to act as MPCs. The MAC protocol consists of DCF and PCF components. There is no synchronization between different MTs.

In the DCF active period, every MT, regardless of its mode of operation, can compete to acquire the medium for data packet transmission. In DCF mode, non-real-time data packets, management data packets, and control packets can be sent, as well as real-time data packets. However, during the PCF active period, all the MTs, except for MPCs and free MTs, are prevented from competing for the medium until being polled by their MPC. When an MT is polled by its MPC, it will search for real-time data packets to send. If the polled MT has no real-time packet to send, it will answer with an empty data packet. Therefore, when the DCF and PCF act in turn, the real-time data packets have a better QoS level because they can be sent at any time of the super-frame period. On the other hand, non-real-time packets can only be sent during the DCF active period. If the PCF controller is an MPC, it will send its buffered real-time data packet and poll message to poll the MTs, which are registered to it in a round robin manner. A free MT just sends its buffered real-time data packets during the PCF period. If the nodal density becomes high in a single communication region, to increase the efficiency of PCF, the MPC may poll part of zone-MTs in its polling list. Here, a call admission control mechanism would play a very important role in separating the zone-MTs that have been given admission, from all the zone-MTs in the polling list.

As described in Section 2, in the MAC layer, the data packet buffer consists of a "data sending" queue and a "control frame" stack. If the buffer is not empty, it will trigger the DCF to work. The DCF will try to send all the data packets in the "control frame" stack first, then the packets in the "data sending" queue one by one when the value of its NAV is equal to 0. Before sending any data packets in the "data sending" queue, it should make sure that the "control frame" stack is empty.

As in the IEEE 802.11 MAC standard, each MT is in PCF mode is polled once per super-frame time period. An MPC will suspend the DCF (by setting its NAV to a non-zero value), and will initiate the PCF period. After controlling the medium, the MPC sends its buffer's real-time data packets, if any, and polls the MTs registered to it one by one. A Free MT will check the "data sending" queue first for real-time data. If it does not find any real-time packets in the queue, it does not initiate a PCF period. However, if it finds real-time data packets in its buffer, it will suspend its DCF period, and go into the PCF active period. Therefore, the PCF active period for a free MT is only for sending its own real-time packets.

Within the MPC-based MAC framework, several MPCs and free MTs can simultaneously have PCF initiation rights, and may co-exist in the same communication range. As shown in Figure 3, MPCs "A", "B" and free MT "c" is in the communication range of one another. They compete for the medium using the PIFS, which is shorter than the DIFS. So, they always beat their neighboring nodes that run the DCF. However, collisions may happen among the PCF initiators if they simultaneously contend for the medium using the PIFS only. To solve this problem, we propose to use the random *Slot Defer Number* (SDN), as is done in the IEEE 802.11 DCF, to extend the PIFS to several time slots to avoid collision among the MPCs and free MTs. (Details of the operation of the IEEE 802.11 [13-17] are in the Appendix.)

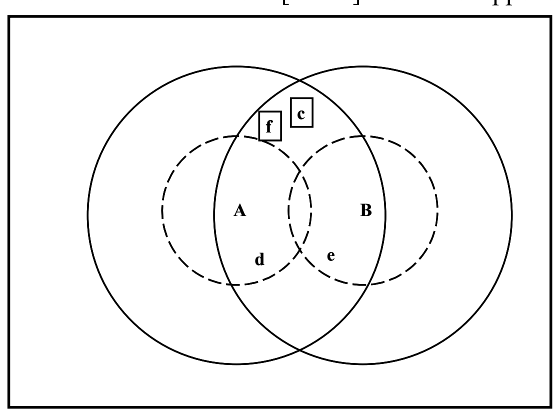

Figure 3 Three roles of MT

Using SDN may still not prevent collisions. However, unlike the DCF, in which the data transmission is unpredictable, the beginning of a PCF period is predictable, because the time interval between the PCF initial time points is about the length of the super-frame time interval. We can use this characteristic to avoid PCF initiation collisions. When it is time for an MPC or a free

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MT to initiate the PCF, it will first check the recent PCF records of its neighboring MPCs and free MTs, estimate its possible competitors for the medium, and create a competitor list. The position of a competitor in the list will match its last PCF initial order sequence. The SDN will be the same as the position number in the list. Normally, if the real-time traffic is light, PCF periods of co-existing MPCs and free MTs will spread sparsely in one super-frame time period. As Figure 4 shows, in the first super-frame period (time t_0 to t_3), real-time traffic is light, each initiator's PCF duration is short, and they all fit in the predicted time frame established by history (for example, node "A" finishes PCF at time t_1 before the predicted PCF initial time of node "B" which is at time t_2). In this period, any PCF initiator when trying to initiate the PCF will find that there are no candidates to compete with for medium access. The PCF initiators will use the PIFS with an SDN value of 0 to compete for the medium. If the real-time traffic is light, the PCF initiators will always have higher priority over users of DCF and no collision will take place between the PCF initiators.

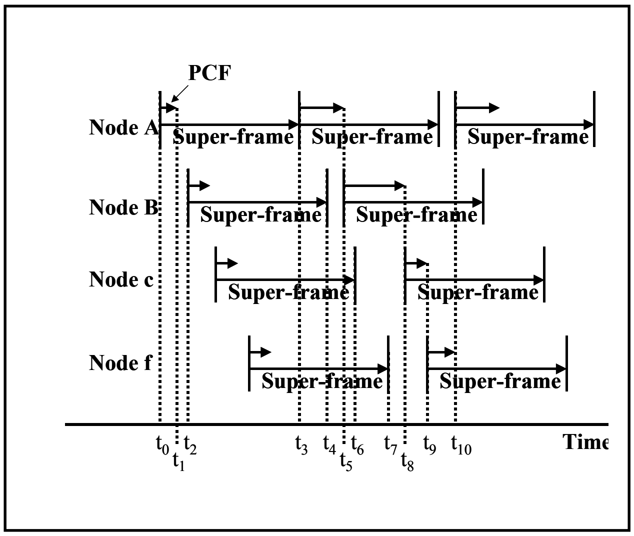


Figure 4 The enhanced PCF mechanisms

4.1.3. TRAFFIC MODEL. If the real-time traffic becomes heavy, some PCF durations will become longer. An initiator's PCF period may extend over the predicted start time of the next initiator's PCF. As shown in Figure 4, in the second round, the real-time traffic becomes heavy, the PCF period of node "A" lasts up to time t_5 (beyond the second predicted PCF start time, t_4). When "B" initiates the PCF in the second round, it still gets no other candidate to compete with it, thus it waits only for PIFS and then gains control over the medium. When node "B" finishes its PCF at time t_8, it is beyond its predicted time, and there are two nodes, "c" and "f", to compete for the medium. Node "c" finds that it is the first candidate in the predicted sequence, thus it gets an SDN of "0", whereas node "f" gets an SDN of "1". Node "c" gains access to the medium. If node "c" is shut down or just quits the PCF, node "f" has the chance to acquire the medium. If all nodes suffer postponement of their predicted PCF initiation time, this causes wasted bandwidth. Such an unpredictable situation cannot even be controlled in cellular-like wireless LANs, and is beyond the scope of this paper.

In our protocol, the MPC will inform all its group members of the list and the order by which the MTs will be polled using the "hello" message. When the MPC announces the start of the PCF, all the group members will keep track of which MT will be polled next. When the PCF starts, every member MT will copy the polling MT list into volatile memory. With the process of polling, deleting the member that responds back with an empty data frame will modify the temporary polling list. With this method, every member can calculate the time it will be polled. If the MT does not hear the polling signal, it assumes its MPC must have been shut down, or might be out of range. In this case, another group member can take over as an MPC. Since all zone MTs maintain the polling order, the new MPC can continue the current PCF period.

3.2 MPC-MAC system parameters

The following system parameters are used by our MPC-based MAC protocol:

- **(a) my_next_PCF_poll** – A variable that will be initialized when the zone MT receives the beacon from its MPC. It will be modified when it receives the information from the MPC and count down with the time going. When it reaches "0", the MT will doubt its MPC has shut down. During the PCF period, it always has a positive value, but during the DCF period, its value will be set to "-1".
- **(b) polling_list** – A table maintained by every MT to keep track of its group members that have the same MPC as itself. The MPC will update it and broadcast it in the "hello" message.
- **(c) unfinished_polling_list** – For a specific PCF period, this list is used to track which MT in the group has sent all its real-time data, and hence will not be polled again.
- **(d) RTSThreshold –** If the data packet size is larger than the value of this constant, the virtual sense mechanism will be triggered.
- **(e) my_MPC_is_in_PCF** – A boolean variable used to indicate whether the group the MT belongs to is currently in PCF mode or not.

3.3 Description of The MPC-MAC Protocol

When a packet is generated at a node, it will trigger the DCF, which will send the control frame packet in the "control frame" stack using SIFS to compete for the medium. The transmission of a packet in the "control frame" stack is not limited by the NAV and state mode. Even if the NAV is not "0" or the MT is in PCF mode, the transmission of control data like ACK, CTS is not deferred. So, in our MPC-MAC protocol, after the polled MT sends a real-time packet, before the MPC polls the next MT, a gap (about SIFS+ time to send an ACK) should be reserved to let the destination MT confirm with ACK. Using DCF to send the packet in the "data sending" queue will be limited in the DCF mode, and the NAV is set to "0". If the condition is not satisfied, the routine will suspend itself till the NAV reaches "0" or the MT goes into DCF mode. When competing for the medium for the packet in the "data sending" queue, the routine will use DIFS + randomly created SDN. After winning the medium, it will send the packet directly (for a small size packet) or send "RTS" first (for a large size packet). In the latter case, all the MTs around it will set a value in NAV. If the receiver is the destination of the RTS, it will send the CTS packet. Similarly, the receiver of the CTS will set the NAV.

In the MPC system, there can be several PCF initiators co-existing together, which need to share a super-frame time period. Therefore, in an MPC system, in a super-frame, there may be several PCF periods and DCF periods fragmented and interleaved together. The MT uses "my_MPC_is_in_PCF" to coordinate the DCF and PCF in the super-frame. This variable is set to "true" in only one PCF period fragment that is initiated by its native MPC, and is set to "false" at other times. When the MT receives a beacon signal (no matter whether the sender is its MPC or not), in its NAV, a value equal to the length of PCF duration will be set. The same thing happens, when it receives the "CF_end signal", in its NAV, the corresponding value will be reset to "0". If the sender of the "CF_end signal" is the MT's MPC, then the variable "my_MPC_is_in_PCF" will be set to "false".

In the MPC, the PCF will be activated periodically. It uses PIFS and a calculated SDN to compete for the medium. The method to create SDN is different from that in DCF, which is created randomly. In PCF, the MPC could check the neighboring MPCs' beacon record for "SDN's value equal to the number of MPC around me which should have sent a beacon but still have not till now". After this MPC wins the medium, it will send the beacon signal to initiate a PCF period. All the MTs around it will reserve the medium by setting NAV and initiating my_next_PCF_poll, estimating the time to being polled that may trigger an MT to replace its MPC if the MT is not polled for a certain period of time. When the MT replaces the MPC in the PCF period, it will finish the current PCF. After it initiates the PCF, the MPC will poll and send real-time packets within the MPC group. All the group members, including the MPC, will maintain their unfinished_polling_list, and the MPC will follow the sequence in the list to poll the MTs, one by one, by sending poll tokens to the MT. All the group members will update the time to be polled. If the MT is the destination of the poll token, it will send a real-time packet from its buffer or send an empty frame if it has no real-time packets to send. The MPC and all other group members will delete the empty frame sending MT from the unfinished_polling_list. After all the real-time packets have been sent or the PCF reserved time has expired, the MPC will send the "CF_end signal" to finish the PCF period. The MTs around the MPC will set the NAV to "0" and unlock the data-type packet's sending with the DCF.

4. PERFORMANCE EVALUATION

In this section, we study the performance of our MPC wireless MAC protocol. The performance of the IEEE 802.11 in an ad-hoc wireless environment, where only DCF can operate, was examined and tested, and compared to the performance of our proposed MAC protocol. In our protocol, the DCF and the PCF (as defined in the IEEE 802.11) can co-exist. A packet-level simulator was developed using the Java programming language in order to monitor, observe and measure the performance of our protocol, using different input parameters.

4.1. Simulation model

4.1.1.Experimental setting. In our simulation experiments, the channel capacity is set to 2 Mbps. All the MTs are assumed to be within a 400 × 400 unit grid. The three IFS periods, SIFS, PIFS, DIFS and the slot defer time have been set to an effective length of 2, 3, 14 and 1 octet, respectively. There is a gap between the PIFS and the DIFS, which enables several neighboring MPCs to compete for the medium without interference with the DCF nodes. To avoid collision between MPCs, several neighboring MPCs may wait for the PIFS plus a calculated number of defer slots provided that the total does not exceed 14 octet periods (equal to DIFS). (Note: Here, to improve the performance of PCF, we have slightly modified the IEEE 802.11, which defines the difference between PIFS and DIFS as one time slot.) The size of the Collision Window (CW) is between 8 and 128. When the MT suffers repeated collisions, the CW may reach 128. When an MT is successful for 4 consecutive times, the CW will be halved till it reaches 8. In our simulations, when packet transmission is attempted 3 times without receiving an ACK, the packet will be discarded. If the MT discards 3 packets in a row for the same destination, the destination MT is removed from the "MT list". The PCF period is periodic with the super-frame being equal to 1 second. "Hello" messages are exchanged every 0.2 seconds. If the MT does not hear from its neighboring MT for 2 seconds, it will remove it from its "MT list".

Each experiment tests the behavior of the system for a given number of nodes, N, for 60 seconds. Our simulations consist of two stages: the network initiation stage, and the testing stage. During the network initiation stage, the MTs are created one at a time. When a MT is generated, it tries to establish neighborhood and MPC associations with the existing MTs. After all specified MTs have been created for 5 seconds, the simulation then goes into the testing stage where data is collected for an additional 60 seconds.

4.1.2. Mobility Model. In the simulation, every MT is in one of two mobility states: moving or pausing. When in the moving state, the MT moves towards its target location determined in the last pause period, with a specific speed (randomly generated with a mean equal to Move Speed (S)). When the MT reaches its target location, it will reach its pausing state. The length of the pausing period is also randomly generated with a mean equal to a user defined input parameter, Pause Time (P). During the pause period, it will determine the next target location and its moving speed. Hence, the MT's lifetime will consist of moving periods (each with its own speed and direction), and pausing periods (of different time intervals) in turn. Another variable parameter related to the mobility model is the transmission range, R, which is discussed later (Section 4.2.2). The MPC range is always set to half of the transmission range.

4.1.3.Traffic model. There are a number of packet types: MAC control packets (ACK, RTS, CTS, etc.), application/data packets (real-time and non-real-time), and MPC-related packets (hello, merge request, merge response and disjoin). The length of the control packets and MPC-related packets is set to 20 and 80 octets, respectively. The length of the data packets is determined by the parameter Packet Length, L. The mean packet arrival rate is determined by the parameter λ.

When an MT receives a data packet addressed to it, it creates and sends an ACK to confirm receiving the packet. When the MT plans to send a data packet whose length is over RTSThreshold, it will create and send an RTS packet first to reserve the medium and trigger the destination MT to respond back with a CTS packet. In our simulation experiments, RTSThreshold is set to a value such that the RTS-CTS exchange is used at all times.

4.1.4.Performance metrics. The following are the performance metrics of interest in this paper: (1) the transmission delay, which is measured from the time when the packet is created until the time the MT receives an ACK from the destination MT of this sent packet. We calculate the *Average Delay (AD)* of all the successfully received packets. (2) The *Discard Ratio (DR),* which is the ratio of the number of discarded packets to the total number of packets sent. There are several reasons for an MT to discard a packet. For example, before sending the packet, the MT checks the packet's destination to see whether it is reachable, if the packet's destination is not in the MT's reachable neighborhood MT list, the MT discards the packet without trying to send it. This kind of discarding does not occupy any medium resources. The packet may also be discarded because sending failed 3 consecutive times. When we calculate DR, we count the packets that are sent but failed and are finally discarded relative to the total number of packets that are sent (both those that are successful and those that fail). (3) The *Compensation Rate (CR),* which is a measure of the performance loss of non-real data to the performance gain of real time data. With the help of the PCF, the average delay of real-time packets always decreases, but at the same time, the average delay of non-real-time packets often increases. CR is expressed using the equation below. A large value for CR means that the PCF brings in a greater negative effect on non-real-time packet's AD than the positive effect on AD of real-time packets. Ideally, CR should be less than 1. CR can be used to represent the benefit of PCF; a smaller CR leads to a better PCF performance.

$$CR = \frac{AD\ of\ non\ real\ time\ with\ PCF - AD\ of\ non\ real\ time\ without\ PCF}{AD\ of\ real\ time\ without\ PCF - AD\ of\ real\ time\ with\ PCF}$$

4.2. Discussion of the results

A number of simulation experiments were conducted in order to study the effects of Packet Arrival Rate (λ), Radio Transmission Range (R), MT Mobility (including Moving Speed – S, and Pause Time – P), Number of Nodes (N), and Data Packet's Length (L). The results are shown in Figures 5-10. In the Figure pairs, Figures on the left show the Average Delay of real-time packets and non-real-time packets with and without the PCF, and Figures on the right show the Discard Ratio of real-time and non-real-time packets with and without the PCF.

The results of the experiments, which show the effect of changing the packet arrival rate (λ), are shown in Figure 5. In all experiments, an increase of λ results in an increase in the Average Delay (AD) and the Discard Ratio (DR). Comparing the AD of the experiments with the PCF to the AD without the PCF, we found that using the PCF benefits the MAC performance by decreasing the AD and DR of real-time packets in all cases. In Figure 5(A), with the PCF, the AD of real-time packets decreased by 11% but that of non-real-time packets increased by 10% when λ is 1 packet/sec (CR=0.93). When λ increases, the PCF gives more benefit to real-time packets than the negative effect on non-real-time packets. When λ is 3.5 packet/sec, the AD of real-time packets decreased by 20%, while the AD of non-real-time packets only increased by 14% (CR= 0.66). From Figure 5(B), we see the advantage of the PCF, which decreases the DR of both real-time packets and non-real-time packets. When λ is 1.5 packets/sec, the DR of real-time packets decreased by 43% and at the same time, the DR of non-real-time packets also decreased by about 5%. The reason is as follows: when we lower the DR of real-time packets this implies that collisions of real-time packets decrease, and this would ease the traffic load on the medium. Then during the DCF period, less MTs take part in the competition for the medium, and that leads to lower collision of non-real-time packets, and thus the DR of non-real-time packets may also decrease.

Figure 6 shows the effect of changing the radio transmission range (R) on the performance. The use of the PCF benefited real-time packets by reducing AD and DR.

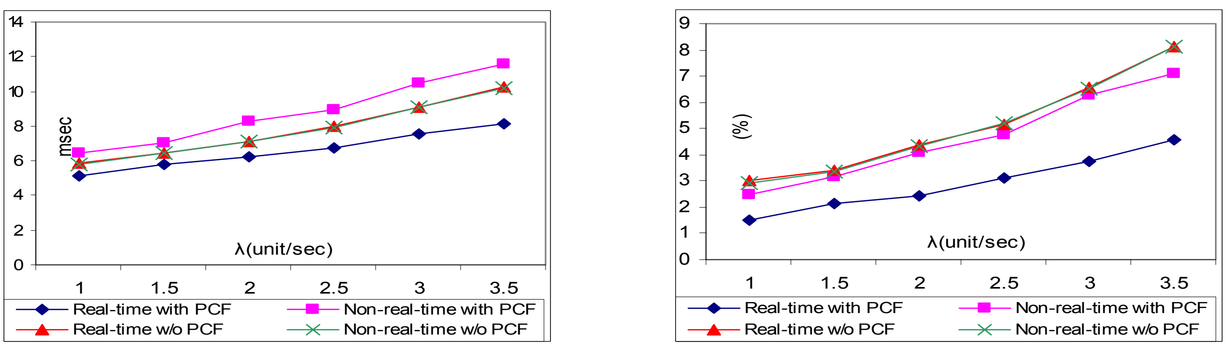
In Figure 6(A), we found that with the decrease of R, AD also decreases. If the traffic load is low enough, the MT will send the packet immediately, and the packet delay will be very small. When R is large, the PCF decreased both AD and DR for real-time packets. When R was 200 units, using the PCF, AD for real-time packets decreased by 24%, and DR decreased by 69%. In Figure 6(B), DR for real-time traffic using the PCF stayed very low, and with the decrease of R, there was almost no change in the value.

The experiments in Figure 7 show the effects of changing the speed (S) of MTs on the performance. In Figure 7(A), it shows that the effect of mobility on the average delay is limited. However, the MT's speed had a greater effect on DR. For example, in Figure 7(B), when S grew from 1 to 51 units/sec, DR for real-time packets with the PCF increased by 879%. The experiments in Figure 8 show the effects of changing the pause time (P) on performance. The results in Figure 8 show that both AD and DR are generally improved with increasing the pause time for the MTs. This is because with a higher pause time, packets can be usually delivered in fewer attempts.

The experiments in Figure 9 show the effects of changing the number of MTs (N) in the simulation on the performance. Both AD and DR increase as the number of nodes increases. In Figure 9(A), we see that with the increase in N, the performance advantage of the PCF for real-time packets is more apparent. When N was 40, with the PCF, AD for real-time packets decreased by 11.5%, as opposed to 23% for N=140. In Figure 9(B), the use of the PCF decreased DR for real-time packets by at least 41%. DR for non-real-time packets also decreased.

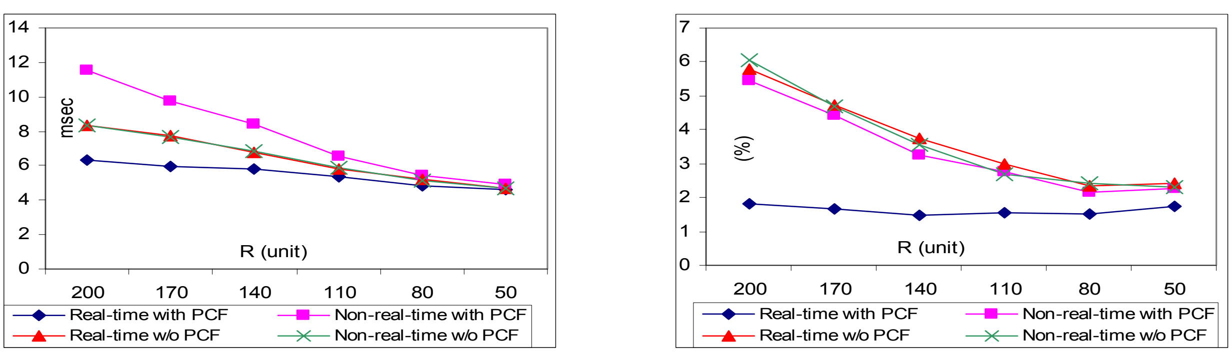
The experiments in Figure 10 show the effects of changing the packet size (L) on the performance. The results shown in Figure indicate that both AD and DR increase as the packet size increases. However, the value of CR tends to decrease. For example, in Figure 10(A) (with N=40, λ =1), when L=600, the CR was 2.00, but when the L=1600, the CR decreased to 0.62. This confirms the fact that the performance gain is more apparent for larger packet sizes.

Simulation experiments show that in all cases the use of PCF benefits real-time packets by decreasing the Average Delay (AD) and the Discard Ratio (DR). However, this may come at the expense of increasing the Average Delay for non-real-time data. The Discard Ratio for both real-time and non-real-time packets improves with the use of PCF. Therefore, our MPC-MAC outperforms the standard DCF IEEE 802.11 MAC protocol in multi-hop ad-hoc environments.



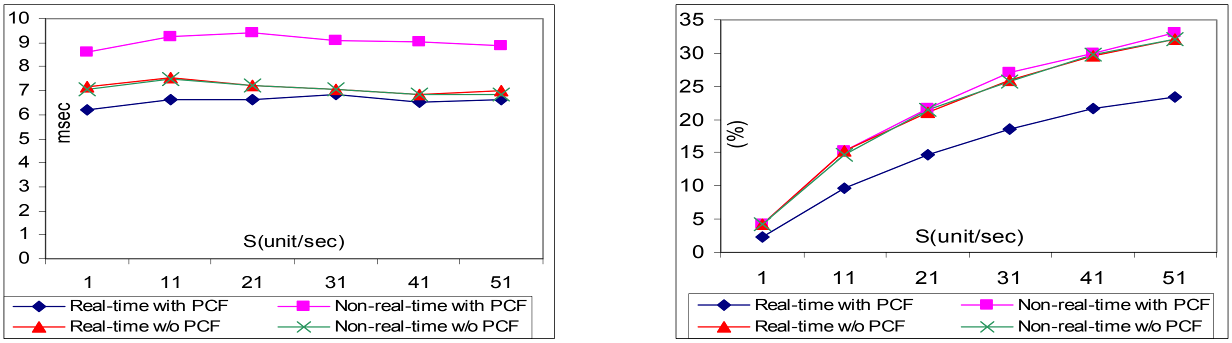
(A) Average Delay **(B) Discard Ratio**

Figure 5 Effect of arrival rate (R=100, S=1, P=4, N=40, L=1000)



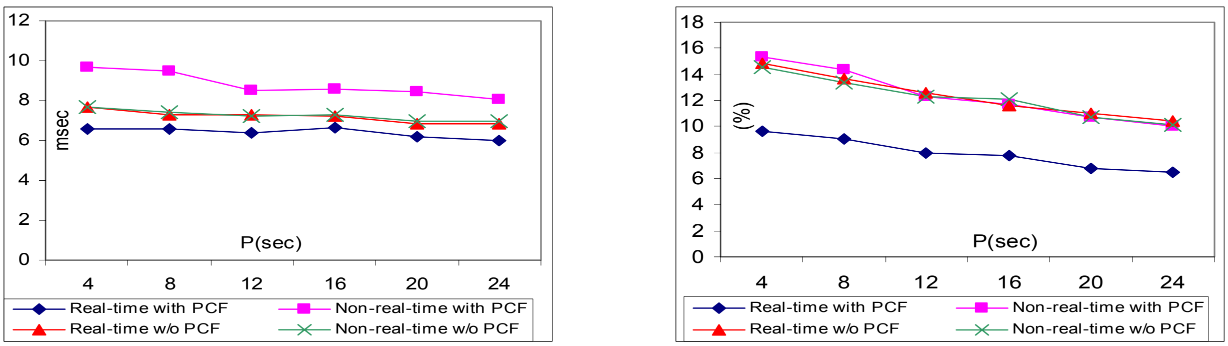
(A) Average Delay **(B) Discard Ratio**

Figure 6 Effect of transmission range (λ=1, S=1, P=4, N=40, L=1000)



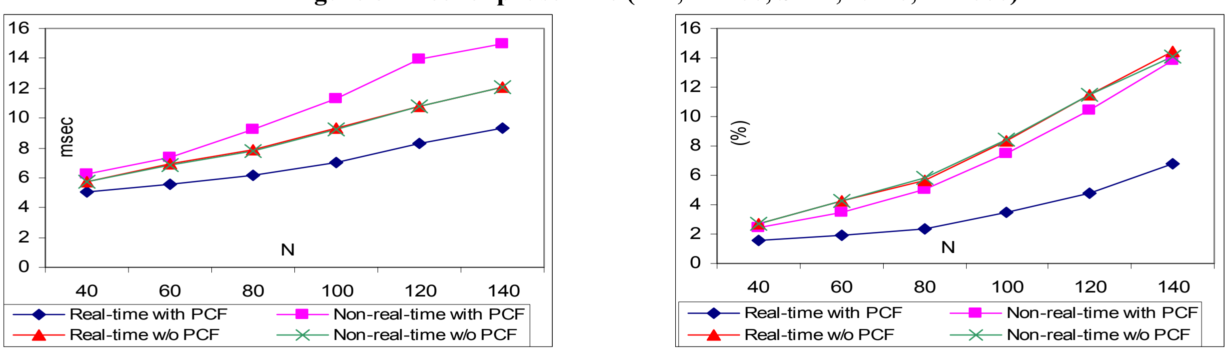
(A) Average Delay **(B) Discard Ratio**

Figure 7 Effect of mobile speed (λ=2, R=100, P=4, N=40, L=1000)



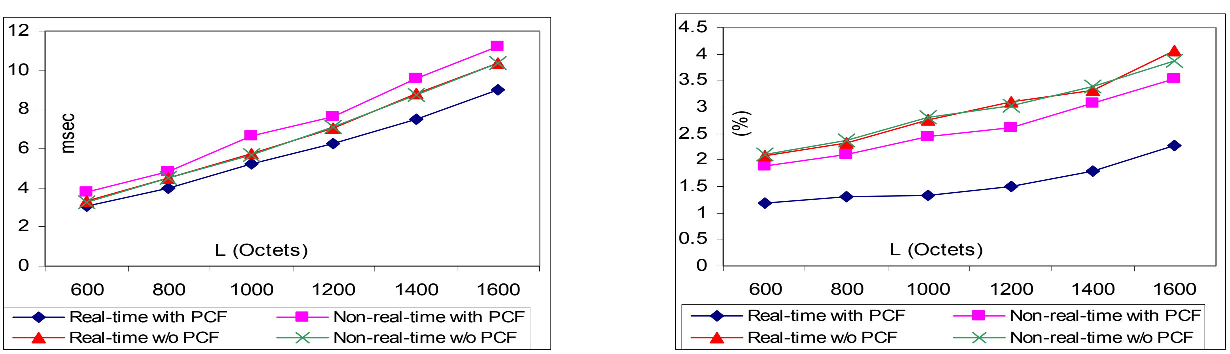
(A) Average Delay **(B) Discard Ratio**

Figure 8 Effect of pause time (λ=2, R=100, S=11, N=40, L=1000)



(A) Average Delay **(B) Discard Ratio**

Figure 9 Effect of number of MT's (λ=1, R=100, S=1, P=4, L=1000)



(A) Average Delay **(B) Discard Ratio**

Figure 10 Effect of packet size (λ=1, R=100, S=1, P=4, N=40)

5. CONCLUSION

In this paper, an efficient and on-the-fly infrastructure is created using our proposed Mobile Point Coordinators (MPC) protocol. Based on this protocol, we have also developed an efficient MAC protocol, namely MPC-MAC. Our MAC protocol extends the IEEE 802.11 standard for use in multi hop wireless ad-hoc networks implementing both the DCF and PCF modes of operation. The goal, and also the challenge, is to achieve QoS delivery and priority access for real-time traffic in ad-hoc wireless environments while maintaining backward compatibility with the IEEE 802.11 standard.

In our MPC infrastructure-creation protocol, some of the mobile nodes, based on an agreed-upon policy, are elected as MPCs and become in charge of all, or a subset, of the neighboring nodes located within their wireless communication range of association, known as the MPC range. With the "large communication range but small cluster range" concept in our MPC creation scheme, we can overcome, or at least ease, some of the problems caused by utilizing the MTs as BSs. In our proposed scheme, when two neighboring MPCs are more than one hop apart, both can initiate the PCF period at the same time without resulting in collisions. The neighboring MPCs will be farther away than the registered MT's MPC, and thus less inter-cluster interference results. We were also able to overcome the natural shortage of effective coordination methods between neighboring MPCs, which cannot conventionally communicate via any wired/wireless interconnection network, unlike BSs. Also, in a small cluster, when an MPC is shut down during the PCF period, the node that replaces it will be capable of communicating with all the cluster members. The cluster is small enough that any two nodes within the cluster can communicate directly. The small cluster range also eases the problems created by mobility: all the nodes registered to an MPC are located close to the MPC, and a registered MT has enough time to inform the MPC of its re-association before it moves out of its communication range.

We developed a packet-level simulator to test the performance of the MPC-MAC protocol in a wireless ad-hoc environment. The results were compared with the peer-to-peer mode of the IEEE 802-11 standard, which implements the CSMA/CA DCF. We have conducted experiments to observe the effects of mobility (including speed and pause period), packet arrival rate, packet length, and nodal density (including radio transmission range and number of nodes), on the performance of our protocol. It was shown that, our MPC-MAC has a positive effect on real-time packets by decreasing the average delay and discard rate. On the whole, the system performance of our MPC-MAC is improved compared to peer-to peer IEEE 802.11, especially when the mobility is greater. More importantly it achieves QoS performance for real-time traffic by enhancing their average delays and discard ratios.

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