A Priority MAC Protocol to Support Real-time Multimedia Traffic in Ad Hoc Networks

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Abstract
Carrier sense multiple access and its variants have been widely used in mobile ad hoc networks. However, such access cannot guarantee the quality of real-time traffic. This paper presents a distributed medium access control protocol that provides priority based multimedia access to wireless ad hoc networks. First, a priority classification scheme is used to distinguish the higher-priority frames (real-time frames) and lower-priority frames (data frames). Stations with the same priority frames are then individually assigned a unique identifier number by an initialization scheme. Finally, stations transmit their frames in turn according to their identity numbers. Simulation results indicate that our protocol has bounded real-time frame delay and high channel utilization.

1 INTRODUCTION
A wireless network configuration that has received increasing attention recently is called the mobile ad hoc network (MANET) [8]. A MANET is formed by a cluster of mobile stations and can be quickly deployed without any established infrastructure or centralized administration. MANETs are applied in areas where infrastructure networks are difficult or impossible to build (e.g., fleets on oceans, armies on the march, battle fields, festival field grounds, and historic sites).

Support of sufficient quality is critical for multimedia services in wireless communication systems. This work considers MAC (Medium Access Control) in MANETs. A MAC protocol should address resolving the potential contention and collision while using the communication medium [1, 6, 2, 3]. Most MAC protocols can be divided into two categories: centralized and distributed access schemes. The centralized access scheme [2] requires centralized administration to coordinate the transmission in the wireless network. Some centralized schemes, such as time division multiple access (TDMA), frequency division multiple access (FDMA) and code division multiple access (CDMA), stations must reserve time slots, frequencies or codes to transmit their data. Another centralized scheme, called polling, also requires a centralized administrator to manage the transmission of the stations. The coordinator polls each station individually to ask whether they wish to send data frames.

Traditional, centralized access schemes are inappropriate for MANETs since they involve no central administrator. Distributed access schemes, such as Aloha, CSMA, MACA [7], MACAW [1], and FAMA [6], may be more suitable for MANETs since they are mainly contention-based. Standard IEEE 802.11 MAC protocol provides two media access methods: the distributed coordination function (DCF) and point coordination function (PCF). The DCF protocol operates on ad hoc networks and infrastructure wireless local area networks (WLANs) [4], but PCF protocol operates only on infrastructure WLANs. The fundamental access method of the IEEE 802.11 MAC is the DCF, also known as carrier sense multiple access with collision avoidance (CSMA/CA), which supports asynchronous data transfer on a best effort basis.

The standard IEEE 802.11 MAC protocol for MANET only operates in DCF mode and does not provide a priority scheme that supports quality of service (QoS) guarantees. All real-time traffic, such as video and voice, require time-bounded service and a bandwidth guarantee, but still contends fairly with traditional data traffic, such as text and e-mail, for the media. A simple priority scheme modifying the CSMA/CA protocol during the contention period has been proposed in [5]. The authors modify the backoff scheme such that the higher-priority traffic has the shorter backoff time. The priority media access is controlled through the use of different interframe space (IFS) intervals, such as SIFS, PIFS, and DIFS, between the transmission frames. A station using a shorter IFS has a higher priority. This approach does not avoid some exceptional conditions. A collision will occur whenever more than one station's timer expires simultaneously, and each station will retransmit its frame at the next backoff period. The
backoff time’s threshold depends on the number of retransmissions, so more backoff time is computed when more retransmissions occur. Stations with higher-priority traffic probably have the longer backoff time and do not transmit their frames first.

The authors in [11] presented another priority scheme, called the black-burst (BB) contention mechanism. The scheme modifies the CSMA protocol to provide real-time access in a MANET. With this mechanism, real-time traffic waits only until a channel becomes idle for a PIFS period and then contends for the channel. A station that wants to transmit a real-time frame must contend for a channel with pulses of energy. The period of BB is proportional to the time that the station has been waiting for the channel to become idle. After transmitting its BB, the station waits for an ‘observation’ time to determine whether any other station is transmitting a longer BB. If the channel is perceived to be idle after this ‘observation’ time, then the station begins to transmit its frame. However, it will waste considerable channel bandwidth in sending bursts of energy for each frame.

A DBASE protocol was proposed in [10]. This protocol also supports multimedia traffic in wireless ad hoc networks. Real-time traffic waits for a shorter IFS period than does non-real-time traffic to contend the channel. The DBASE also uses the back-off scheme to contend the channel, but the maximum size of the contention window is smaller than for non-real-time traffic. A station that successfully contends for a channel will join a reservation table and will not need to contend the medium further throughout the whole session. DBASE uses a repetition interval, \( D_{\text{max}} \), which specifies the smallest maximal tolerance delay of all active real-time connections. Real-time stations in the reservation table will transmit frames in turn during the \( D_{\text{max}} \) period. If the channel is idle for a DIFS period, non-real-time stations can contend for the channel until the \( D_{\text{max}} \) period is over. The small size of the contention window for real-time traffic means that much time is spent in contending the channel under a heavy load. In addition, the DBASE assumed a long period of DIFS (=110 µs) that degrades the channel utilization.

This paper presents a distributed MAC protocol. First, a priority classification scheme is used to distinguish higher-priority frames (real-time traffic) from lower-priority frames (data traffic). Stations with frames of the same priority are then individually assigned a unique identity number (ID) by an initialization scheme. Finally, the stations transmit their frames consecutively according to their ID numbers. Simulation results show that the performance of our protocol is superior to that of IEEE 802.11 in the DCF mode.

2 PRELIMINARY

This section introduces an initialization protocol [9], which will be used in our protocol with a minor modification. The proposed initialization protocol assigns to each of the \( n \) stations a distinct ID number from 1 to \( n \), where \( n \) indicates the number of stations in a MANET. The authors of [9] assumed that each station has collision detection (CD) capability. The following section introduces the initialization scheme without CD. A station with CD capability can detect three states of the radio channel immediately following a data transmission. 'Single' indicates exactly one transmission in the channel; 'Null' means no transmission in the channel; 'Collision' represents at least two transmissions in the channel.

The initialization protocol assumed that stations have no priority in contention. The contest is fair. The idea behind the initialization protocol is to construct a full binary tree called a contention tree. All stations that want to contend for a channel first send a request message on a single common channel. If only one station wants to contend, it can obtain an ID number. If a collision occurs, each station flips a fair coin (the probability of heads or tails is fifty percent). Some stations flipping 'heads' will be assigned to the left subtree, such that they continue to contend for the channel in the next round. Stations flipping 'tails', however, are assigned to the right subtree, and must wait until all the stations in the left subtree obtain a unique ID number, before they can also contend.

Fig. 1: A contention tree for five stations.

Fig. 1, for example, shows a contention tree for five stations, \( A, B, C, D, \) and \( E \). In the first contention round, all stations send a request message simultaneously and thus the sent messages collide with each other. Each station flips a fair coin and is then added to the left or right subtree. In Fig. 1, stations \( A \) and \( B \) flip 'heads', and so are added to the left subtree. In the second round, stations \( A \) and \( B \) continue to contend the channel and a collision occurs again. Both stations \( A \) and \( B \) flip 'heads' again. They continue to contend the channel and collide in the third round. At the end of third round, station \( A \) flips 'head' and station \( B \) flips 'tail'. In round 4, only station \( A \) sends the request message to contend for the channel. Hence, station \( A \) obtains a unique ID number = 1. In round 5, only station \( B \) contends for the channel and obtains a unique ID number = 2. No station contends for the channel during round 6. The left subtree of the root is completed at this time, after which stations
$C, D,$ and $E$ contend for the channel. They proceed recursively to complete the right subtree of the root. Each station obtains a unique ID number after the contention period. Note that, the collision detection capability allows determination of whether a given node is an internal node or a leaf ("Leaf" means that only one station will contend for a channel and obtains a unique ID number).

3 PRIORITY BASED MAC PROTOCOL

This section presents the priority based MAC protocol. Multiple-priority traffic is allowed; that is, higher-priority frames with a bounded delay can be transmitted before lower-priority frames. Stations with the same priority frames are each assigned a unique ID number. The stations transmit their frames in the order of their ID numbers. A station determines that a medium is idle by using the carrier sense function for an interframe space (IFS). Three IFS intervals are used in our protocols- the short IFS (SIFS), the PCF IFS (PIFS), and the DCF IFS (DIFS). The standard specification of the IEEE 802.11 is considered and the periods of PIFS and DIFS are assumed to equal three and five times that of SIFS, respectively.

3.1 A Priority Classification Scheme

A priority classification scheme is applied to distinguish the higher-priority frames from the lower-priority frames. Stations with higher-priority frames are allowed to contend the free channel first. Stations with lower-priority frames are blocked until all the higher-priority stations have completely transmitted their frames. Assume that all data frames can be divided into $m$ types of priority. The $m$th type has the highest priority $D_m$, and the first type has the lowest priority $D_1$. Thus, the priority order is $D_m > D_{m-1} > \cdots > D_2 > D_1$. The black-burst (BB) scheme proposed in [11] is used to distinguish the priorities of the stations. The period (transmission time) of BB is proportional to the priority, such that the stations with a higher priority have a longer BB. The period of $BB_m = m * t_{\text{unit}}$. $t_{\text{unit}}$ is the BB unit time, $m$ is the priority of the frame. Therefore, if the priority of a station is 1 then the period of $BB_1 = t_{\text{unit}}$ and if the priority of a station is 2 then the period of $BB_2 = 2 * t_{\text{unit}}$. Fig. 2 gives an overview of our priority MAC protocol.

![Fig. 2: An overview of our priority MAC protocol.](image)

**Priority Classification Scheme:**

**Step 1:** A station that wants to transmit a frame will first sense the status of the channel. If the channel is busy, the station will wait until it becomes idle for a DIFS period and then will enter the priority contention period.

**Step 2:** During the priority contention period, a station that wants to contend for the channel must send out a BB signal to block the channel according to its priority. The station that has the higher-priority frame emits the longer time of BB signal.

**Step 3:** The station will sense the channel status after completely sending out its BB signal. The station has the highest priority if the channel is idle. It waits until the channel becomes idle for a PIFS period and enters the ID initialization scheme. However, the station has a lower priority if the channel is blocked from other stations. It must wait until next channel becomes idle for a DIFS period, and then proceeds to Step 2 to contend the channel again.

An illustrative example that demonstrates this scheme is described as follows. Three types of priority are assumed to be among 10 stations that desire to contend for a common channel. Five stations have the highest priority, three stations are second, and the rest are the lowest priority. All stations enter the network and execute the priority classification scheme at the same time. During the BB contention period, five stations with the highest priority transmit the longest BB time and they proceed to the ID initialization phase. The other lower-priority stations must wait until the highest priority stations have finished transmitting their frames, before they can again contend for the channel.

3.2 An ID Initialization Scheme

The ID initialization scheme is based on the initialization protocol [9], which was presented in Section 2. Each station is assumed to possess the CD capability. The last subsection considers the ID initialization scheme without CD capability. In the initialization scheme, each station senses the channel status after a request message is broadcast. If the channel status is 'Collision', a fair coin decides whether the station sends a request message again in the next round. If the channel status is 'Single', a unique ID number is obtained. If the channel status is 'Null', the station does nothing. An illustrative example that demonstrates the effectiveness of the ID initialization scheme is shown below.

After the priority classification phase, assume that stations $A, B, C, D,$ and $E$ have the highest priority and perform the ID initialization as shown in Fig. 3. The contention tree of Fig. 3 corresponds to Fig. 1. The ID initialization phase terminates when each station possesses an ID number.

In our protocol, the synchronization among stations is controlled by using the different IFS intervals. After waiting for the channel to become idle for a DIFS period, the stations can undergo the priority
classification to contend for the free channel. Stations with higher priority wait for a PIFS time and enter the ID initialization, during which an SIFS period separates consecutive rounds. However, the presence of contiguous 'Null' states during the ID initialization will make the channel idle period above the DIFS period. Such a situation causes confusion and failure of the ID initialization because the stations that do not proceed through ID initialization phase will enter the priority classification phase and emit a BB signal. This problem can be solved as follows. A 'Reset' action is performed when a station executing the ID initialization scheme detects that the channel is idle for two consecutive SIFS periods. In the next round, the stations without ID number construct a new contention tree to contend for the ID numbers. The ID initialization scheme typically constructs more than one tree until all stations have obtained their ID numbers. For example, in Fig. 4, station $B$ obtains an ID number $= 2$ in round 8. However, no station broadcasts the request message in rounds 9 and 10. Stations $C, D,$ and $E$, which have no ID numbers, construct another contention tree after two SIFS periods. Finally, stations $C, D$ and $E$ obtain a unique ID number in rounds 14, 16 and 17, respectively.

The following description explains why the 'Reset' action is performed after the stations detect two contiguous 'Null' rounds (two SIFS periods). Consider a case as shown in Fig. 5. Each station obtains an ID number in round 13, and detects two contiguous

'Null' states in rounds 14 and 15. Another 'Null' round is detected in round 16 since every station has an ID number and thus need not to send a request message. Hence, the ID initialization is terminated in round 16. After waiting for another SIFS period, all stations transmit their frames in order of ID numbers. The total idle time of the channel equals four SIFS periods (< DIFS time), i.e., the maximum tolerable idle time.

This priority MAC protocol allows a new station to contend for a channel during the initialization phase. A new station that enters the network and wishes to contend for a channel will first sense the channel status. If the channel is not free, the station attempts to listen for the request message broadcast by some station. The new station can enter the ID initialization phase in the next round if its priority equals that of the station that has successfully broadcast the request message. The new station can copy the local variables used in the ID initialization scheme from the request message. Fig. 6 presents the frame format of the request message, 'REQ'. The format of the 'REQ' frame is similar to that of 'RTS' frame of IEEE 802.11. 'TA' is the transmitter address; 'RA' is the receiver address; and 'CRC' is used for error checking. A field is added to store the five variables used in the ID initialization scheme. Variable $P$ represents the priority of stations. The other four variables, $L, l, N$, and $flag$ are explained in ID initialization protocol.

ID Initialization Scheme:
All stations maintain four variables, $l, L, N,$ and $flag$. Initially, set $l ← 1$, $L ← 1$, $N ← 1$, and

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**Fig. 3:** The execution steps of initialization scheme for five stations.

**Fig. 4:** An example of constructing two contention trees.

**Fig. 5:** A special case of contention trees.

**Fig. 6:** The REQ frame format.
flag ← 0. Let $P_L$ denote a group of stations whose local variable $l$ equals $L$. The variable flag is used to sense two contiguous 'Null' states.

While $L ≥ 1$
do
All stations in $P_L$ send 'REQ' frame on the channel and sense the following channel status.

Case 1: 'Collision'
All stations set $L ← L + 1$ and $flag ← 0$.

Case 2: 'Single'
The unique station in $P_L$ that broadcasts 'REQ' message successfully sets $ID ← N$. The other stations set $N ← N + 1$, $L ← L - 1$, and $flag ← 0$.

Case 3: 'Null'
All stations set $flag ← flag + 1$ and check the following cases:

Case 3.1: $flag = 1$
All stations set $L ← L - 1$.

Case 3.2: $flag = 2$
Station without ID number resets its local variables, $l ← 1$, $L ← 1$, and $flag ← 0$.

End While

3.3 Transmission Scheme
Each active station has a unique ID number after the ID initialization scheme has been applied. In the transmission phase, all active stations can transmit data frames in the order of their ID numbers. Each station can raise a piggyback flag to transmit multiple data frames in a round-robin manner. Two variables are used to control the transmission of multiple data frames. Let $N_{count}$ denote the ID of a station currently transmitting a data frame. Let $P_{count}$ be the number of stations which still have frames in their buffers and desire to transmit data frames in the next transmission cycle. The transmission scheme with piggyback information is presented as follows.

Transmission Scheme:
$N$ is the number of active stations with an ID number.

While my buffer is not empty do
$N_{count} ← 1$ and $P_{count} ← 0$.

While $N_{count} ≤ N$ do
If my ID = $N_{count}$ Then
Send data frame on the channel.
If piggyback flag = 1 Then
The sender sets its $ID ← P_{count} + 1$.
The other stations set $P_{count} ← P_{count} + 1$.
Else
The sender sets its $ID ← 0$ and
leaves the protocol.
End If
End If
$N_{count} ← N_{count} + 1$.
End While

$N ← P_{count}$.
End While

In the following, an example is used to illustrate this scheme. Assume that five stations $A, B, C, D,$ and $E$ have ID numbers 1, 2, 3, 4, and 5, respectively. In $N_{count} = 1$, station $A$ can transmit its frame. If station $A$ still has frames in its buffer, it will set the piggyback flag = 1 in the sent message and reset its ID number = $P_{count} = 1$. After transmitting their frames once, the five stations will change their ID numbers according to their buffers status. If a station has no frame to transmit from the buffer, its ID number is set to zero and it leaves the protocol. However, if a stations still has frames in the buffer, it will reset its ID number = $P_{count}$. This example assumes only three stations, $A, C,$ and $E$, still want to transmit again, and that they change their ID numbers from 1, 3, and 5 to 1, 2, and 3, respectively.

3.4 The ID Initialization Scheme Without CD
The above initialization scheme assumes that the stations have CD capability. This assumption is impractical for wireless ad hoc networks. The authors of [9] proposed a scheme to initialize an ad hoc network that does not have CD capability. Without CD capability, all stations can detect two states of the radio channel at the end of data transmission. 'Noise' indicates either no transmission or a collision in the channel and 'Single' indicates a single transmission in the channel. First, a leader is elected from the ad hoc network. The leader is used to distinguish the 'Collision' and 'Null' states from the 'Noise' state. For example, if the channel status of round $k$ is 'Single', the leader does nothing and all stations proceed to the subsequent round. Otherwise, the channel status of round $k$ is 'Noise', the leader and the stations which broadcast in round $k$, broadcast a request message again in round $k + 1$. During round $k + 1$, all stations sense the channel status. If the channel status is 'Single', only leader broadcasts in this round. Accordingly, no station broadcasts in round $k$ and the channel status is 'Null'. If the channel status is 'Noise', at least two stations broadcast a request message in round $k$ and the channel status is 'Collision'. In such an environment, the leader always broadcasts a message following a 'Null' or 'Collision' round. Therefore, in the ID initialization phase, two 'Null' rounds never occur contiguously and only one contention tree is constructed in the initialization phase. The next section simulates the model of ad hoc networks with CD and without CD capabilities.

4 SIMULATION RESULTS
This section evaluates the performance of our priority MAC protocol. The simulation model is built in a fully connected ad hoc network. The channel rate is assumed to be 11 Mbps and each frame size is 256 bytes. The following three types of traffic are considered to investigate the performance of multiple priority multimedia traffic.

• Pure Data Traffic: The arrival of data frames from
each station follows a Poisson distribution.

- Voice Traffic: The voice traffic is usually considered to be constant bit rate (CBR) traffic. The data rate of voice traffic is assumed to be 64Kbps. Voice traffic has a maximum tolerance delay time of 25 ms. Frames of voice traffic that are not successfully transmitted within its maximum tolerance are assumed to be lost.

- Video Traffic: The video traffic is considered to be variable bit rate (VBR) traffic. Frames of video traffic also have a maximum tolerance delay time of 75 ms. The bit rates of VBR are exponentially distributed. Table 1 summarizes the parameters used in the simulation.

Assume video traffic has the highest priority; voice traffic is second, and pure data traffic has the lowest priority. Video and voice are real-time traffic with maximum tolerable delays. The transmission rates of the three types of traffic are mixed in the ratio, 1 : 1 : 1. Three performance measurements used in our simulation are defined below.

- Throughput: Throughput is defined as the channel rates that can be used to transmit multimedia frames by stations. The cost of contention is excluded from the throughput.

- Average frame delay: The period from a frame’s arrival at the system to its complete transmission.

- Frame loss probability: The frame loss probability is the fraction of discarded frames due to the delay constraint for real-time traffic.

![Fig. 7: The throughput of three MAC protocols under various transmission load.](image)

![Fig. 8: The throughput of three types of traffic for our protocol with CD.](image)

![Fig. 9: Average frame delay of three types of traffic for our protocol with CD.](image)

The performances of the priority MAC protocols are compared with that of the DCF protocol of the IEEE 802.11 standard. Fig. 7 shows the throughput of three MAC protocols. The protocols presented here have better throughput and channel utilization than the DCF protocol as the offered load is heavy.

Our MAC protocol with CD has a throughput approaching 8 Mbps but protocol without CD exhibits a slightly lower throughput. The throughput of the DCF protocol is around 6 Mbps. In our protocols, each station can transmit its frames from the buffer in a round-robin manner. They thus have a low channel contention overhead.

### Table 1: Simulation parameters

<table>
<thead>
<tr>
<th>Channel parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel rate</td>
<td>11 Mbps</td>
</tr>
<tr>
<td>SIFS period</td>
<td>10 (\mu s)</td>
</tr>
<tr>
<td>PIFS period</td>
<td>30 (\mu s)</td>
</tr>
<tr>
<td>DIFS period</td>
<td>50 (\mu s)</td>
</tr>
<tr>
<td>Slot time</td>
<td>20 (\mu s)</td>
</tr>
<tr>
<td>Min. backoff window size</td>
<td>32</td>
</tr>
<tr>
<td>Max. backoff window size</td>
<td>1024</td>
</tr>
<tr>
<td>Length of control frame REQ</td>
<td>240 bit</td>
</tr>
<tr>
<td>Length of data frame</td>
<td>256 bytes</td>
</tr>
<tr>
<td>Voice source rate (CBR)</td>
<td>64 Kbps</td>
</tr>
<tr>
<td>Voice max. tolerable delay</td>
<td>25 ms</td>
</tr>
<tr>
<td>Video source rate (VBR)</td>
<td></td>
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<tr>
<td>Maximum bit rate</td>
<td>420Kbps</td>
</tr>
<tr>
<td>Average bit rate</td>
<td>230Kbps</td>
</tr>
<tr>
<td>Minimum bit rate</td>
<td>120Kbps</td>
</tr>
<tr>
<td>Video max. tolerable delay</td>
<td>75 ms</td>
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</table>
Fig. 9 shows the average frame delay for three types of data traffic under our MAC protocol with CD. Real-time frames present a shorter delay time than pure data frame since they have a higher priority. Note that, the frame delay time considers only the successfully transmitted frames. The average delay of real-time traffic decreases when the traffic load is heavy, because pure data frames have less chance to transmit its frames.

Fig. 10: Average frame delay for three different MAC protocols.

Fig. 10 shows the average frame delay of our MAC protocols and the DCF protocol. The frame delay of the DCF protocol is longer than that of our protocols. In our priority protocols, the lower-priority stations cannot contend for the channel against the higher-priority stations. The number of stations contending the free channel is thus reduced as is the contention overhead.

Fig. 11: Frames loss probability for real-time traffic.

Fig. 11 shows the frame loss probability with our protocols and the DCF protocol. The loss of the video traffic is close to zero as video traffic has the highest priority. The frames loss probability of our protocols is less than that of the DCF protocol with real-time traffic. Therefore, our protocol is better suited to supporting multimedia traffic than is DCF protocol.

5 CONCLUSIONS
The standard IEEE 802.11 DCF protocol does not provide a priority scheme to support real-time multimedia access. This paper proposes a novel priority MAC protocol to support multimedia traffic in wireless ad hoc networks. First, a priority classification phase distinguishes the higher-priority from the lower-priority frames. Second, the stations with frames of the same priority are assigned consecutive ID numbers by an ID initialization phase with CD and no-CD assumptions. Finally, the stations transmit their frames in turn according to their ID numbers. A piggyback flag is used to transmit the frames in a round-robin fashion. Simulation results demonstrate that the performance of our protocols is superior to that of the DCF protocol.

References