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Differentiated cooperative multiple access for multimedia communications over fading wireless networks

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Abstract: The quality of service (QoS) support for multimedia communications faces a big challenge in a fading wireless network. On one hand, conventional automatic repeat request (ARQ) schemes are not effective for small-scale fading channels with correlated errors due to consecutive retransmission failures. On the other hand, large-scale fading due to propagation loss or shadowing severely limits transmission range. A novel differentiated cooperative medium access control (MAC) protocol, called DC-MAC, is proposed to enhance the QoS support for multimedia communications while supporting service differentiation based on the IEEE 802.11e architecture. By enabling cooperative ARQ, the retransmission is initiated from an appropriate transmission queue of an appropriate relay node instead of the original source. Since unnecessary and useless retransmissions may intensify the node contention and degrade the system performance contrarily, a novel negative acknowledgement feedback mechanism is introduced for loss distinguishing and channel estimation such that cooperative retransmission will be employed only when necessary and only by competent nodes. Extensive simulations are conducted on the OPNET platform to analyse the performances of DC-MAC under both small-scale and large-scale fading. Simulation results show that the proposed scheme significantly improves the performances of both multimedia applications and best-effort data applications in terms of throughput, delay and coverage with moderate user contention.

1 Introduction

With the increasing popularity of multimedia applications over wireless links, quality of service (QoS) support has become a critical demand for next generation wireless networks. The recent IEEE 802.11e enhanced distributed channel access (EDCA) function [1], which is the QoS enhancement version of the basic 802.11 distributed coordination function (DCF) [2], provides service differentiation with a priority-based medium access mechanism. A link layer automatic repeat request (ARQ) scheme is used to retransmit the corrupted packets due to channel errors or collisions. Retries will continue until either the corresponding acknowledgement (ACK) is received or the retry count reaches a predefined limit. However, this scheme may not be effective under a small-scale fading channel with correlated errors, where there is a high probability that bad channel condition continues for a certain period when a transmission error occurs. For a mobile travelling at 1 m/s with RF frequency 2.4 GHz, which corresponds to a wireless local area network (WLAN) type scenario, the maximum Doppler frequency is around 8 Hz. Assuming a Ricean fading channel with the factor K of 5, at the normalised threshold of 0 dB, the average fade duration is 97.6 ms. At a data rate of 11 Mbps, a 1000 byte frame takes only 0.73 ms. Even after taking all the overheads into account, the average fade duration is on the order of multiple frame transmission times. In this case, conventional ARQ schemes based on time diversity cannot help since a transmitter sees only a single realisation of the channel within its retransmission duration. The frame drop rate and delay will considerably increase because of consecutive retransmission failures and the bandwidth is wasted from a system point of view since useless messages occupy the channel. On the other hand, mobile users locating at the edges of a network may have to adopt a very low rate because of large-scale fading. The low-rate transmissions occupying long duration may severely deteriorate the QoS performances of both themselves and other users [3].

Cooperative communication is becoming a promising technology for wireless networks [4] by exploiting multipath fading instead of mitigating its impact. Single antenna devices can share their antennas in a cooperative manner to emulate a multi-input multi-output system and exploit the spatial diversity benefits traditionally realised by an antenna array hosted on a single device. Inspired by the idea of cooperative diversity, cooperative ARQ has been shown to be an effective technology to improve the reliability of wireless links [5–7]. A retransmission could be initiated from a relay node that overheard the information packet instead of the original source. Since signals from different locations undergo independent fading gains, the retransmission success probability can be greatly increased by exploiting this spatial diversity. In [5], a simple but effective ARQ scheme called node-cooperative stop and wait is proposed to reduce the average duration of retransmission trials. Significant performance improvement has been shown for a single sender–receiver pair by an analytical model based on a two-state Markov process. A cross-layer relaying protocol based on hybrid ARQ with incremental redundancy, termed hybrid-ARQ-based intra-cluster geographic relaying (HARBINGER), is proposed in [6]. The nodes decoding the data use global positioning system to identify their positions relative to the destination and the one closest to the destination will relay the frame. In [7], a cooperative communication medium access control (MAC) is proposed to improve link reliability for WLANs. Two transmission queues are maintained in each node. One is the data queue for its own outgoing data and another is the partner queue to buffer the copy of the overheard frames to be retransmitted. A higher priority is given to the partner queue such that the cooperative retransmission can occur before the original source retransmits. To the best of our knowledge, there is no scheme considering the QoS support for multimedia communications with differentiated services. Furthermore, a practical and effective protocol and a system-level investigation are lacking in the literature. From a system perspective, retransmissions from relays may equivalently increase the number of competing nodes in a system and thus may degrade the system performance if inappropriately employed. In addition, a distributed coordination mechanism is needed to solve the relay collision problem since there may be several nodes that can serve as relays. The benefit of cooperative diversity can be reflected only if an appropriate protocol has been designed carefully.

In this paper, we propose a novel differentiated cooperative MAC (DC-MAC) for multimedia communications over fading wireless networks based on the IEEE 802.11e architecture. A differentiated cooperative ARQ mechanism is employed to improve the performances of both multimedia applications and best-effort data applications while supporting service differentiation under both small-scale and large-scale fading. The contributions of this paper are as follows:

- First, the corrupted frames will be retransmitted by a relay node based on their priorities. It is shown that changing retransmission priority at a relay node can change the relative performance ratio between the sources with different traffic classes and thus introduce a new degree of freedom for protocol design.

- Second, a novel negative acknowledgement (NAK) feedback mechanism for loss distinguishing and channel estimation is introduced such that cooperative retransmission will be employed only when necessary and only by competent nodes.

- Last, but not least, while most of work [5–7] concentrated on numerical analysis for a single pair of source-destination nodes, we implement the whole protocol on the OPNET platform [8], investigate the system-level performances and consider several practical issues such as sequence control and duplicate detection.

2 Background

2.1 Principles of IEEE 802.11e EDCA

The IEEE 802.11e EDCA [1] is the QoS enhancement version of the basic 802.11 DCF [2]. In EDCA, eight priorities are supported and mapped into four access categories (ACs) at each station as shown in Fig. 1. Each AC has an associated transmission queue and contends for the transmission opportunity (TXOP[AC]) using a set of EDCA parameters: the arbitration interframe space (AIFS[AC]), minimum contention window size (CW_{min}[AC]), maximum contention window size (CW_{max}[AC]) and maximum retry limit (M_{retry}[AC]). When a high-layer frame arrives, it will be buffered in a corresponding transmission queue based on its priority. A frame of a given AC has to wait for an AIFS[AC] period and after that it enters a slotted backoff procedure for collision avoidance. A backoff counter is uniformly selected in

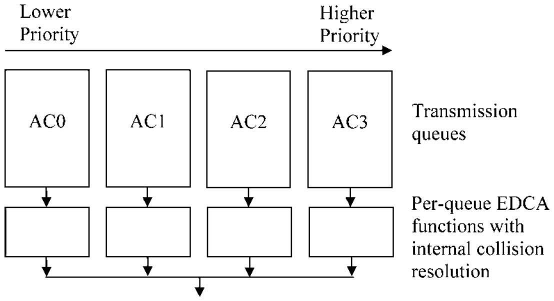

Figure 1 *Transmission queue model in the IEEE 802.11e*

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the range $[0, \mathrm{CW}_j[\mathrm{AC}]]$, where $\mathrm{CW}_j[\mathrm{AC}] = \min[2^j \times (\mathrm{CW}_{\min}[\mathrm{AC}] + 1) - 1, \mathrm{CW}_{\max}[\mathrm{AC}]]$ and j is the number of the unsuccessful transmission attempts. The backoff counter decrements as long as the channel is sensed idle for a slot time σ, otherwise it freezes. When the backoff counter reaches 0, a transmission is initiated. A simple stop-and-wait ARQ scheme is employed for error control. If no ACK frame is received within a certain time, the data frame will be retransmitted by entering the next backoff stage. The backoff procedure ends at the point that either the frame has been successfully transmitted or the maximum retry limit $M_{\mathrm{retry}}[\mathrm{AC}]$ has been reached. Since multiple ACs contend within a station, an internal collision may occur in EDCA. In that case, the AC of highest priority will transmit, whereas other ACs involved in the collision will enter another backoff. To deal with the hidden node problem and avoid the collisions of long data frames, a request-to-send/clear-to-send (RTS/CTS) mechanism can be optionally employed. The short RTS/CTS frames are exchanged prior to the actual exchange of data.

2.2 *Cooperative communication*

The basic idea behind cooperative communication can be tracked back to the seminal work of Cover and Gamal on the information theoretic analysis of the relay channel in [9]. Based on the work on the relay channel, Sendonaris *et al.* [10, 11] presented an information theoretic analysis and a code division multiple access implementation with user cooperation. In contrast to the concept of the relaying channel, each user can act as an information source and a relay for other users. It was shown that cooperation is beneficial in terms of system throughput, transmission reliability and cell coverage. Laneman *et al.* [12] proposed several repetition-based cooperative schemes for a half-duplex single relay system. Relays amplify their received signals or fully decode and repeat information. The authors referred to them as amplify-and-forward and decode-and-forward, respectively. It was shown that high diversity gain can be achieved at a loss of spectral efficiency as each relay needs an orthogonal channel for repetition. To improve bandwidth efficiency and incorporate more relays, distributed space–time coding was studied in [13] to allow all the relays to transmit on the same channel.

To date, most of work in cooperative communication focuses on physical layer point-to-point link performance investigation and optimisation in terms of outage probability without considering in much detail how to coordinate node cooperation in practical systems beyond physical layer until very recently [14–16]. Two similar MAC protocols, cooperative MAC (CoopMAC) [14] and relay-enabled DCF [15] have been proposed to enhance the multi-rate capability of the IEEE 802.11 protocol by taking the advantage of MAC layer relaying. A slow node, instead of sending its packets at a low rate to a receiver directly, proactively chooses a ‘helper’ that is located between the sender and the receiver and is able to transmit at a higher rate in a two-hop manner. To adapt to dynamical channel condition and network topology and take advantage of cooperative diversity gain, the authors [16] proposed a cooperative relay-based auto-rate MAC with reactive relay selection. The receiver can combine the packets from both the sender and the relay such that a higher rate can be supported due to diversity gain. In this paper, we focus on improving link reliability for mixed multimedia and data traffic without considering rate adaption.

3 Differentiated CoopMAC

Our proposed scheme is based on the IEEE 802.11e EDCA architecture and thus can be easily integrated into current systems. Without changing the original stop-and-wait ARQ scheme in a source, the neighbouring nodes overhearing the frames will help in retransmissions and thus our scheme falls into the category of decode-and-forward transmission [4]. Without loss of generality, we consider two traffic classes in this paper: one is best-effort data traffic and the other is real-time multimedia traffic. For simplicity, we consider only one frame transmission in each TXOP. Also we consider the basic access method without RTS/CTS in this paper, although our scheme can be easily extended to that case.

3.1 *Transmission queue model*

Based on the architecture of the 802.11e EDCA, our new transmission queue model is shown in Fig. 2. There are two queues at each station for its own best-effort (Own Class 1) and real-time traffic (Own Class 2), respectively. In addition, there is a partner queue for each traffic category. To support cooperative retransmission, each partner queue should be assigned to a higher priority than its corresponding own queue for retransmissions in order to avoid wasting the bandwidth by useless retransmission from the original source and reduce the retransmission delay. To support the QoS of real-time traffic, the priority of the partner queue for best-effort traffic should be set between the ones of two own queues. In this way, the benefit of cooperative retransmission can be exploited and meanwhile the service differentiation is supported. This model corresponds to the four transmission queue architecture in

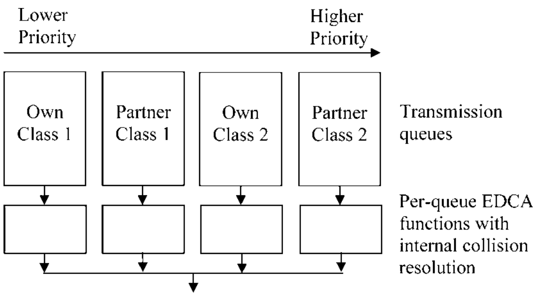

Figure 2 *Transmission queue model in DC-MAC*

the 802.11e EDCA except that two queues are used here for relaying overheard frames. Each queue has a set of its own medium access parameters and all the original regulations in the 802.11e EDCA are inherited, for example, internal collision resolution. Therefore our scheme can be easily integrated to the current deployed 802.11e WLANs.

3.2 Loss distinguishing and channel estimation

Since retransmissions from the partners may cause increased network load and thus intensify the station competition, it should be employed only when necessary. The missing of an ACK frame may be caused by either collision with other frames or transmission error over wireless link. A loss-distinguishing mechanism is essential for the system performance. The partners should not retransmit the lost frame due to collision since this will further intensify the competition. The original source has the capability of taking care of the retransmission by itself. In addition, up-to-date channel state information between the destination and itself is needed by a partner to determine if it has the capability to help retransmission. Without this information, a useless retransmission from a partner may intensify the relay competition and waste the bandwidth.

A novel NAK control frame is proposed here to solve the above two problems all at once. In the 802.11e protocol, each data frame consists of three basic components: an MAC header, a variable length frame body and a frame check sequence (FCS). The MAC header comprises frame control, duration, address, sequence control and QoS control information. The FCS is calculated over all the fields of the MAC header and the frame body to determine if a received frame has been successfully decoded. Since the MAC header alone is much shorter than the whole frame, it has a higher probability to be decoded. In addition, the MAC header can be transmitted at a lower rate compared with the frame body to further improve its reliability. By observing the content of the MAC header, a node will know if it is the intended receiver and who the sender is. On the other hand, in a fully connected topology without hidden nodes where collision occurs only when more than one node send data in the same slot, both the header and the frame body will be corrupted because of frame collision. This observation has been used to design a loss-distinguishable MAC in [17] without considering cooperation. In our proposed protocol, a header check sequence (HCS) is added immediately after an MAC header to verify the correctness of the MAC header, as shown in Fig. 3*a*. An NAK frame is proposed to indicate the occurrence of an unsuccessful transmission due to fading channel, which has the same format as the ACK frame except the frame type, as shown in Fig. 3*b*. Algorithm 1 (Fig. 4) describes the loss-distinguishing and channel-estimation mechanism using the NAK frame, where $\mathrm{SNR}_{\mathrm{NAK}}$ denotes the sensed signal-to-noise ratio (SNR) of the NAK frame and $\mathrm{SNR}_{\mathrm{th}}$ (R) denotes the required SNR threshold to support a data rate R. The potential partners will set a timer for each overheard data frame. An overhead data frame will be buffered in the corresponding partner queue for cooperative retransmission only if an NAK frame with good enough SNR is received before the timer expires. Note that NAK will not waste additional bandwidth as channel has been reserved by the

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Algorithm 1: Loss distinguishing and channel estimation

Receiver:
IF   HCS of data frame is correct,
        IF      FCS of date frame is correct, an ACK is sent back;
        ELSE    A NAK is sent back;
ELSE   Keep silent.

Sender:
IF   ACK is received, initiate a new backoff for the next data frame;
IF   NAK is received OR nothing is received, double contention window
     and go to the next stage backoff.

Potential Relays:
IF   Data frame is received, start a timer;
     IF   ACK is received OR timer expires, drop the received data frame;
     IF   NAK is received,
          IF      $SNR_{NAK} > SNR_{th}(R)$, enqueue the received data frame;
          ELSE    Drop the received data frame.
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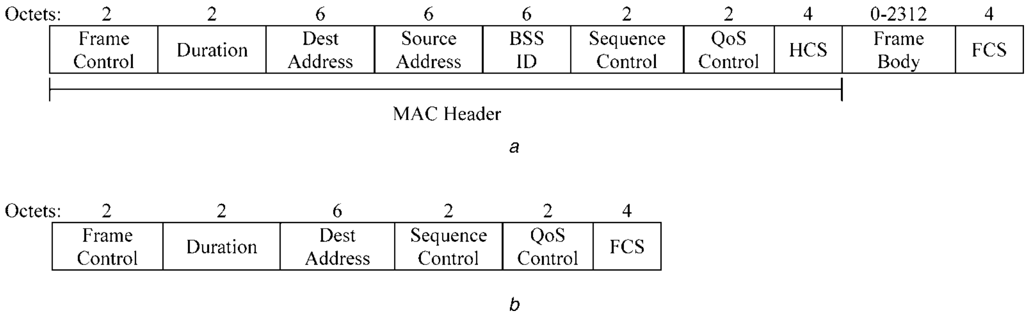
Figure 4 *Loss-distinguishing and channel-estimation mechanism*



Octets:	2	2	6	6	6	2	2	4	0-2312	4
	Frame Control	Duration	Dest Address	Source Address	BSS ID	Sequence Control	QoS Control	HCS	Frame Body	FCS

a

Octets:	2	2	6	2	2	4
	Frame Control	Duration	Dest Address	Sequence Control	QoS Control	FCS

b

Figure 3 *Frame format in DC-MAC*

a Data frame
b ACK/NAK frame

data frame for possible ACK transmission according to the 802.11e standard.

3.3 Frame transmission sequence

An example of frame transmission sequence is shown in Fig. 5. When a source transmits a data frame to a destination, some neighbour nodes may overhear this frame because of the broadcast nature of the wireless medium. Based on the regulation in Section 3.2, the destination will respond with an ACK or NAK frame or keep silent, which, respectively, indicates the occurrence of a successful frame transmission, an unsuccessful transmission due to fading channel or an unsuccessful transmission due to frame collision. The neighbour nodes will help in retransmissions only if an NAK frame with good enough SNR is received. The overheard data frame including its original head information will be buffered in the corresponding partner queue based on its priority. If the backoff counter of one partner queue reaches 0, the frame at the head of this queue will be transmitted with the original source address in the MAC header. The destination will treat the frame from a relay as the one from the original source and respond with an ACK or NAK frame destined to the original source or keep silent. The queue statuses at each node are updated in a real-time manner on hearing the ACK or NAK frames. Any node receiving the ACK will check its corresponding queue (own queue for the source and partner queue for the neighbour nodes) and flush out the corresponding data. Any node except the source receiving the NAK will sense the signal strength of the NAK and flush out the corresponding data in the corresponding partner queue if its signal strength is no longer good enough. If neither ACK nor NAK is received by the current node in relaying, it will double its contention window and enter another backoff stage as a frame collision occurs. The number of retry attempts for a frame in a partner queue should be small to avoid burdening the network load.

3.4 Sequence control and duplicate detection

Owing to the distributed nature of the protocol, an efficient and reliable mechanism is needed to keep the information in each node up to date, avoid redundant retransmissions and enable duplicate detection. For instance, some relay nodes may still try to transmit the out-of-date frames that have been received by the destination because of the loss of the ACK frame. The source may inappropriately drop the data frame on receiving the out-of-date ACK frame.

In the IEEE 802.11e standard, each data frame is assigned a sequence number from a receiver and priority specific counter. This number remains constant in all the retransmissions and increments by 1 for the next frame belonging to the same priority/receiver pair. The receiver will determine the received frame to be a duplicate if its sequence information matches the most recent catch entry. In the proposed scheme, a sender may receive an ACK frame at its own backoff stage and thus it has to be aware of the validity and the object to be acknowledged of this ACK frame. Two new fields are included in an ACK frame as shown in Fig. 3*b*: acknowledged QoS control and sequence control field, which are used to identify the traffic priority and the sequence control information of the data frame to be acknowledged, respectively. When a node receives an ACK frame destined to it, it will check the cached sequence number of the data frame to be retransmitted of the corresponding transmission queue. If the sequence number in ACK matches the cached one, the corresponding data frame is acknowledged. Otherwise, the ACK frame is determined to be out of date and is dropped. In addition, to avoid redundant retransmission, each partner will replace the old frame with the new one if a data frame with the latest sequence number is overheard from the same sender. In practical implementation, a sequence number is produced from a single module-4096

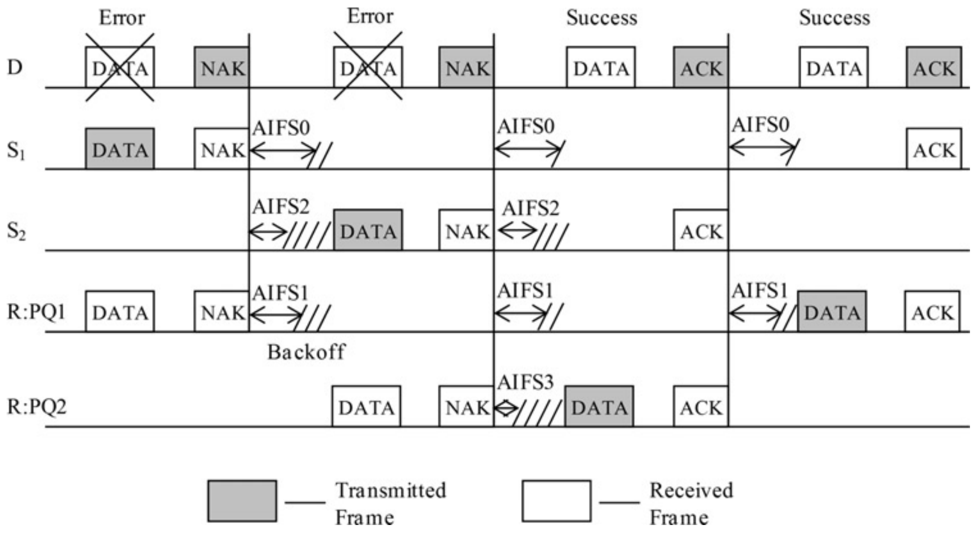


Figure 5 *Frame transmission sequence in DC-MAC*

counter [1]. A small window W_{seq} is used to determine which frame is the latest one by considering the possibility that the sequence number may be wrapped around. Frame a will be determined to be the latest compared with frame b if

$$\begin{aligned}&\mathrm{seq}(a) > \mathrm{seq}(b) \quad \text{and} \quad \mathrm{seq}(a) - \mathrm{seq}(b) < W_{\mathrm{seq}} \quad \text{or} \\ &\mathrm{seq}(a) < \mathrm{seq}(b) \quad \text{and} \quad \mathrm{seq}(a) - \mathrm{seq}(b) < W_{\mathrm{seq}} - 4096\end{aligned} \tag{1}$$

4 Performance evaluation

We implement the proposed protocol in OPNET simulator 11.5 [8]. Extensive simulation studies are conducted to compare the performance of DC-MAC with the original 802.11e EDCA and to identify the effects of the key parameters of DC-MAC. In our simulations, we have assumed two types of traffic flows: video streams and background UDP traffic, which are transmitted from own queue 2 (AC2) and own queue 1 (AC0), respectively. The set of prioritised access parameters used in simulations are shown in Table 1. For purpose of comparison, the default parameters defined in OPNET are used for both own queues. The basic 802.11 parameters used in simulations are shown in Table 2.

The free space model [18] is used to model the large-scale fading. The reception power $P_{\mathrm{r}}(d)$ at a distance d is given by

$$P_{\mathrm{r}}(d) = P_{\mathrm{t}} G_{\mathrm{t}} G_{\mathrm{r}} \left(\frac{\lambda}{4\pi d}\right)^2 \tag{2}$$

where P_{t} is the transmission power, G_{t} and G_{r} are the transmit and receive antenna gain, respectively, ($G_{\mathrm{t}} = G_{\mathrm{r}} = 1$ in this paper) and λ is the wavelength of the carrier wave. For small-scale fading, the channel simulation model proposed in [19] is incorporated into OPNET 11.5 to simulate a Ricean fading channel. The average fade duration (the average period of time for which the normalised signal envelope is below a specified level ρ) is given by

$$\bar{\tau} = \frac{1 - Q\left(\sqrt{2K}, \sqrt{2(K+1)\rho^2}\right)}{\sqrt{2\pi(K+1)} f_m \rho e^{-K-(K+1)\rho^2} I_0\left(2\rho\sqrt{K(K+1)}\right)} \tag{3}$$

where K is the Ricean factor, f_{m} is the maximum Doppler frequency, $Q(a,b)$ is the Marcum Q function and I_0 is the modified Bessel function of the first kind, zero order. If the maximum velocity of the objects in the considered environment is 1 m/s, which corresponds to a WLAN-type scenario, the maximum Doppler frequency is around 8 Hz. Assuming that the Ricean factor K is 5, at the normalised threshold of 0 dB, the average fade duration is 97.6 ms.

Table 2 The set of basic 802.11 parameters used in simulations

Modulation	DPSK, CCK
data frame rate	11 Mbps
control frame rate	1 Mbps
transmission power	0 dBm
receiver sensitivity	−95 dBm
background noise	−88 dBm
SIFS	10 µs
slot time	10 µs
PHY preamble and header	192 bit
MAC header	240 bit
ACK/NAK	144 bit
payload	1000 byte

For each simulation, the following performance metrics are evaluated:

- Throughput: Total data traffic in bits/s successfully received and forwarded to the higher layer by each AC.

- MAC delay: From the time a frame arrives at the head of the transmission queue to the time it is successfully transmitted or dropped by the MAC.

4.1 *Infrastructure scenario*

We first simulate an IEEE 802.11b WLAN consisting of an access point (AP), several stations with uplink traffic and 20 idle stations that may potentially act as relays. All the idle stations are randomly distributed within a circle of radius 120 m, whereas the AP is located at the centre of this

Table 1 The set of prioritised access parameters used in simulations

Queue	AIFS	$\mathrm{CW}_{\mathrm{min}}$	$\mathrm{CW}_{\mathrm{max}}$	M_{retry}
own class 1 (AC0)	7	31	1023	7
partner class 1 (AC1)	2	CW_1	$2^2 \times (\mathrm{CW}_1 + 1) - 1$	2
own class 2 (AC2)	2	15	31	7
partner class 2 (AC3)	2	CW_2	$2^2 \times (\mathrm{CW}_2 + 1) - 1$	2

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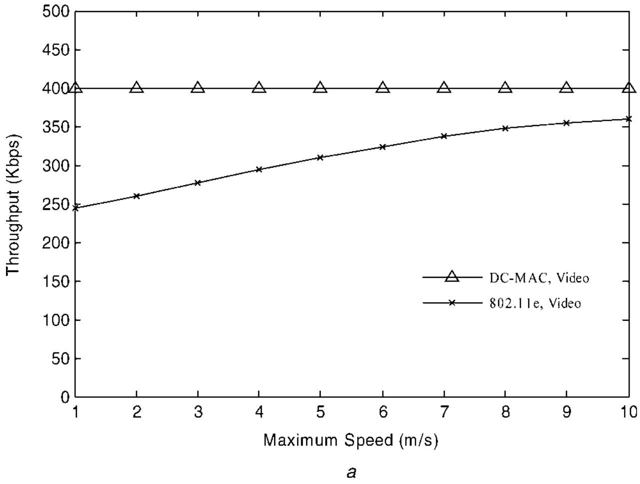
circle. By this simple scenario, we investigate the impact of channel coherence time and the impact of retransmission priorities at relays in DC-MAC.

The channel coherence time is inversely proportional to the maximum Doppler shift and determined by the maximum velocity of objects in the environment. To clarify the effects of different aspects separately, we only consider one station with uplink video traffic travelling along a straight line to and from the AP at a constant speed of v m/s in an oscillatory motion. The distance between them varies between 80 and 120 m. The traffic is generated at a rate of 400 Kbps, with a packet size of 1000 bytes, which models a normal video flow in real world. Idle stations move randomly within the circle according to the random waypoint model [20] with a speed uniformly distributed in [0, v m/s]. Pause time between moves is set to be 0 s. We set the initial contention window size for relaying $CW_2 = 15$. As shown in Fig. 6, DC-MAC outperforms 802.11e in terms of both throughput and MAC delay across all the channel conditions. In particular, the performance improvement of DC-MAC is more obvious under a slow fading channel. When $v = 1$ m/s, 38% frames are dropped in 802.11e because of exceeded retransmission threshold. A transmitter can only see a single realisation of the channel within its retransmission duration, and thus the ARQ scheme based on time diversity cannot help. DC-MAC solves this problem by exploiting spatial diversity. Facilitated by real-time channel estimation in DC-MAC, a very high retransmission success probability can be achieved by retransmitting the frames from a competent relay.



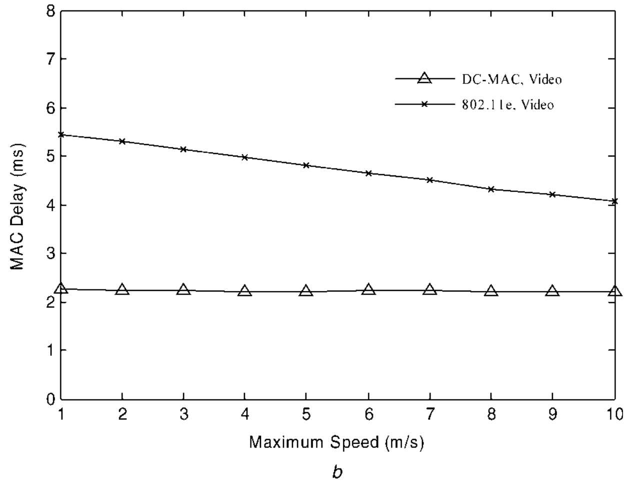


Figure 6 *Impact of channel coherence time*

a Throughput
b MAC delay

To clarify the effects of retransmission priorities at relays and prevent the starvation of low-priority traffic at high loads of high-priority traffic [21], we consider a mixed traffic scenario where four stations with uplink background UDP traffic and one station with uplink video traffic are symmetrically placed on the circle. Idle stations move continuously and randomly within the circle at a constant speed of 1 m/s. To clearly show the performance differences, each flow is saturated, that is, it always has a frame awaiting transmission. For purposes of comparison, we set the same AIFS value for both partner queues and thus the retransmission priorities at relays are determined by $CW_{\min}$. We can see in Fig. 7 that the sizes of $CW_{\min}$ at relays for different traffic classes can significantly affect the relative performance ratio of these traffic classes. When CW_2 is fixed, the performance of video flow is improved as CW_1 increases, whereas the performance of background UDP flow is reduced. When CW_1 is fixed, the performance of background UDP flow is improved as CW_2 increases, whereas the performance of video flow is reduced except for $CW_2 = 15$. At the extreme case ($CW_1 = 7$, 15 or 31, $CW_2 = 255$), the performance of video flow in DC-MAC is worse than that in 802.11e. On one hand, since relays have to compete with each other to forward the frames, a too-small contention window may result in considerable transmission collisions negatively affecting the performance; On the other hand, a too big contention window may enable the retransmission from the original source occurring before cooperative retransmissions and thus the bandwidth is wasted by useless retransmissions. The fast cooperative retransmissions from background UDP flow resulting from a small CW_1 may reduce the transmission opportunities of video flow. For the MAC delay performance, the crossing point of the curve DC-MAC ($CW_2 = 255$) and 802.11e in Fig. 7*c* is delayed a little compared with that of the throughput curves in Fig. 7*a*, because the retransmissions from relays equivalently increase the number of maximum retry limit M_{retry} at a source. The throughput can be further enhanced at the cost of the increased MAC delay. It is shown that when appropriate access parameters are applied, the performances of both multimedia flow and background UDP flow are significantly improved while service differentiation is supported. With the setting of $CW_1 = 31$ and $CW_2 = 15$, compared with 802.11e, DC-MAC can increase the video and the background throughput by 76 and 57%, respectively, and reduce the video and the

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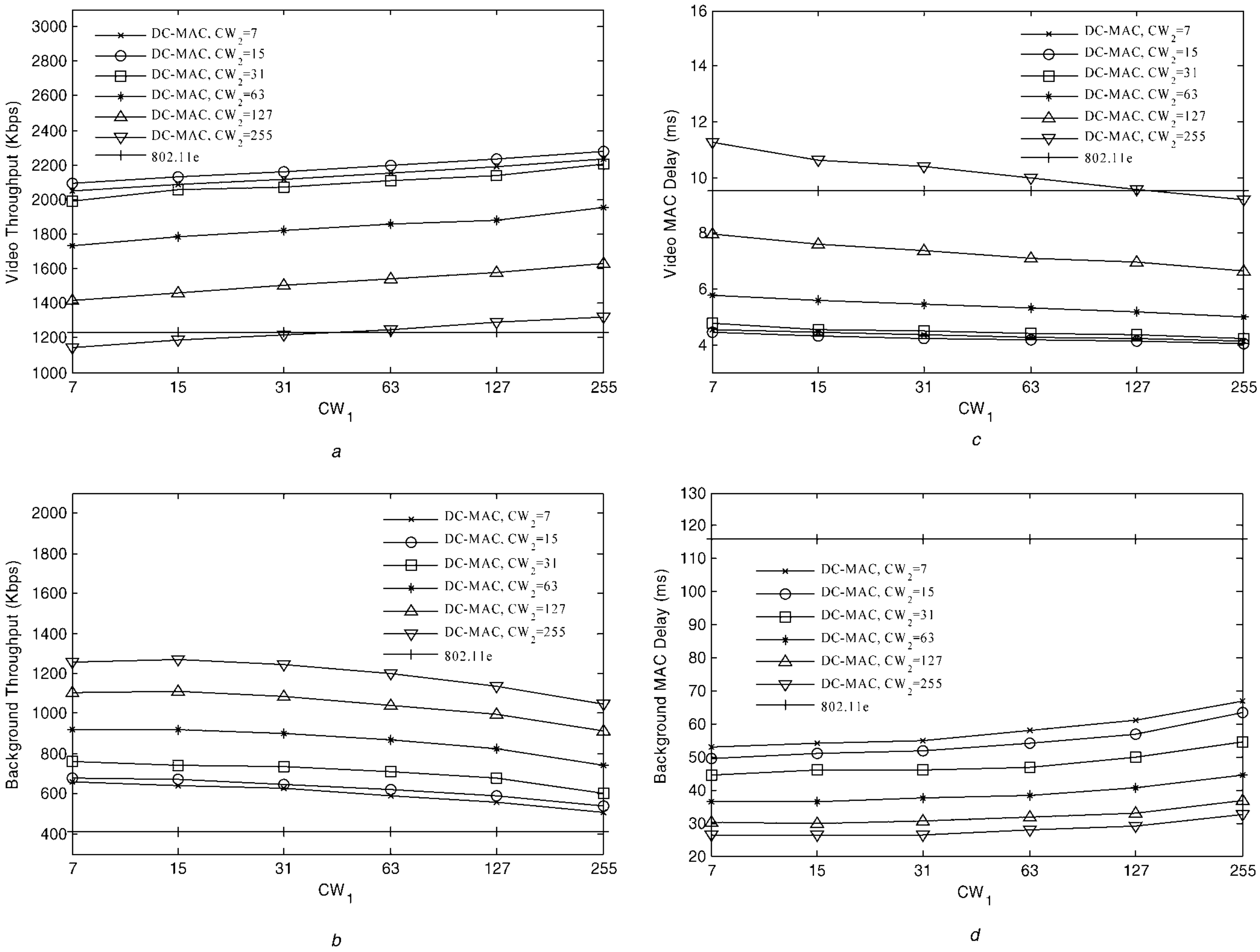

a

c

b

d

Figure 7 *Impact of CW_{min} at relays*

a Throughput of video traffic
b Throughput of background traffic
c MAC delay of video traffic
d MAC delay of background traffic

background MAC delay by 56 and 55%, respectively. Note that the same CW_{min} size for an own queue and its partner queue does not mean the same retransmission priority since the contention window size will be doubled at a source after its first transmission failure. In the following, we choose $CW_1 = 31$ and $CW_2 = 15$ as the default values and will show that this setting can adapt to a wide range of network scenarios.

4.2 Random ad hoc scenario

We then evaluate the performances in random *ad hoc* topologies to investigate the impact of different environmental parameters. The results are presented for varied number of potential relays, varied number of flows and varied network ranges. For describing simplicity, we set a reference scenario where the network area is 200 m × 200 m and 50 nodes are randomly distributed within this area. There are five video flows and five background UDP flows. Each video flow is generated at a rate of 400 Kbps while each background UDP flow is saturated. The environmental object speed is 1 m/s. In the following, we will vary one setting while making others fixed.

First, we investigate the proposed scheme with varied number of potential relays. A two-faced effect is conceptually comprehensible: on one hand, few nodes in the considered area may cause little cooperation opportunity limiting the performance gain; on the other hand, too many nodes overhearing and retransmitting the frames may intensify the node contention leading to high frame collision probability. We can see in Fig. 8 that the number of potential relays is sufficient to support all the video flows when there are only 20 nodes totally in this area. When the number of nodes in the area exceeds 50, the performance of background UDP flows is reduced due to increased retransmission collisions. The throughput demand of the video flows can always be satisfied due to service differentiation mechanism, although the MAC delay increases a little. An adaptive mechanism to adjust

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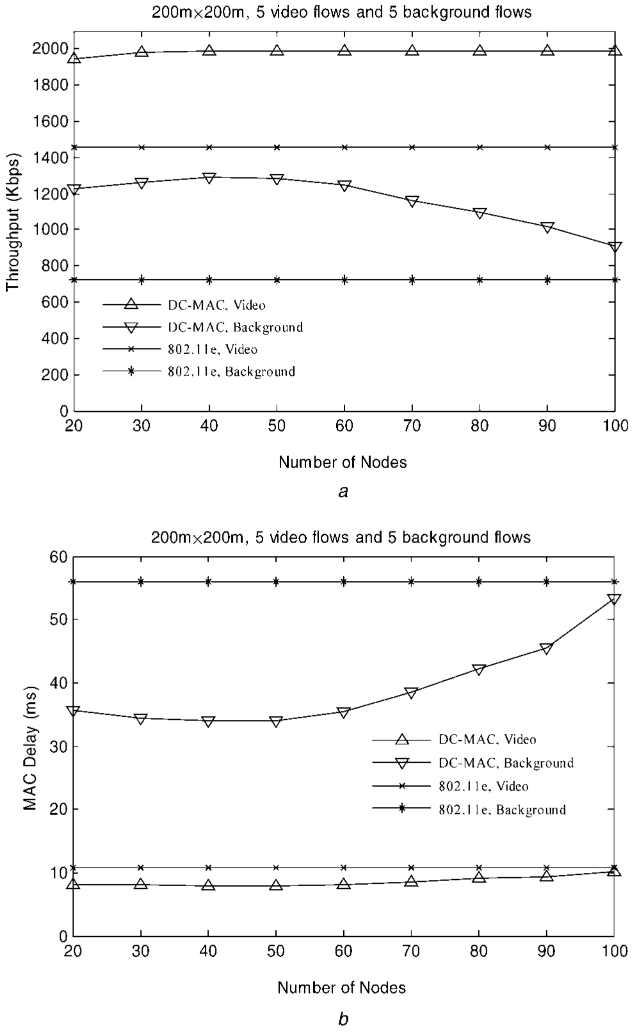

Figure 8 *Impact of number of potential relays*

a Throughput
b MAC delay

the number of potential relays is essential but beyond the scope of this paper.

Second, we investigate the proposed scheme with varied number of video flows. As shown in Fig. 9, when the number of video flows is moderate, the performances of both video flows and background UDP flows are significantly improved by cooperative retransmissions. When the number of video flows is big, the starvation of background traffic occurs due to the original 802.11e EDCA mechanism. As the number of video flows increases, the performance of DC-MAC may be worse than that of 802.11e. The reason is 2-fold: firstly, for 802.11e, when many stations intend to access the channel, each station has to wait a long time for its next retransmission, which actually decorrelates the fading process and improves the retransmission success probability; secondly, for DC-MAC, each flow may have a set of relays competing with each other and the contention will be significantly intensified when the number of flows is big.

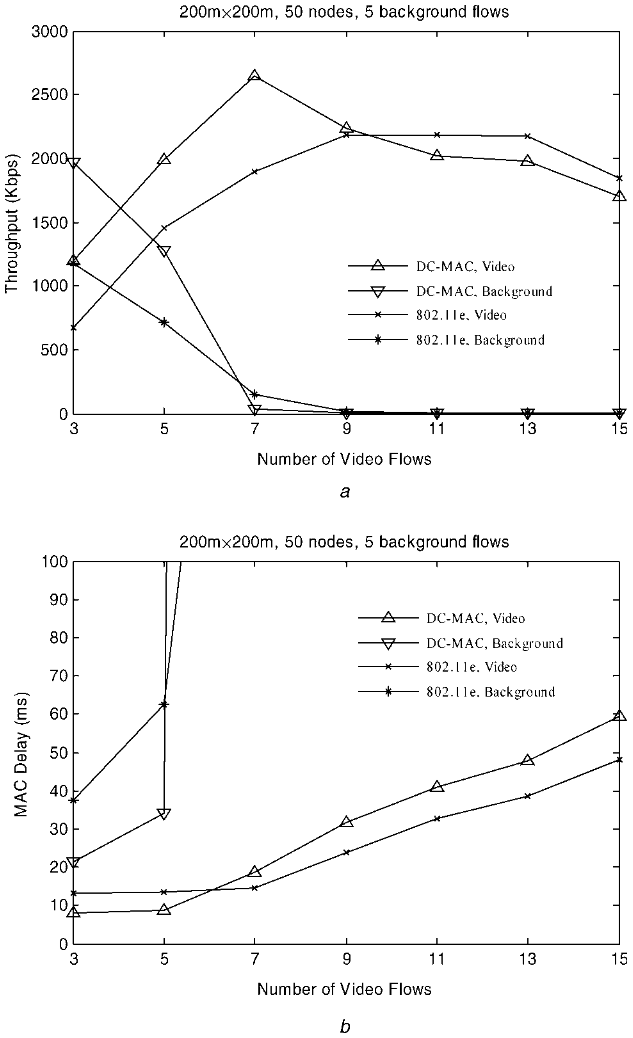

Figure 9 *Impact of number of flows*

a Throughput
b MAC delay

Third, we investigate the proposed scheme with varied network ranges. We increase both network area edges from 50 to 250 m, and all the stations remain randomly distributed within the considered area. We can see in Fig. 10 that when the network range is small, both schemes have similar performance because of high transmission success rate and the performance of 802.11e is even better since DC-MAC introduces extra overhead and relay retransmission collisions. As the network range increases, the performance of 802.11e will reduce rapidly because of large-scale fading. With the help of relays, the QoS demand of the video flows can be satisfied when the network area is up to 200 m × 200 m. As the network range further increases, the performances of both schemes will reduce since the decoding probability of the MAC header in DC-MAC is reduced. However, the performance gain ratio (the ratio of the performance difference between the two schemes over the performance of 802.11e) continuously increases up to 41% for video and 108% for background UDP traffic in terms of throughput and 26%

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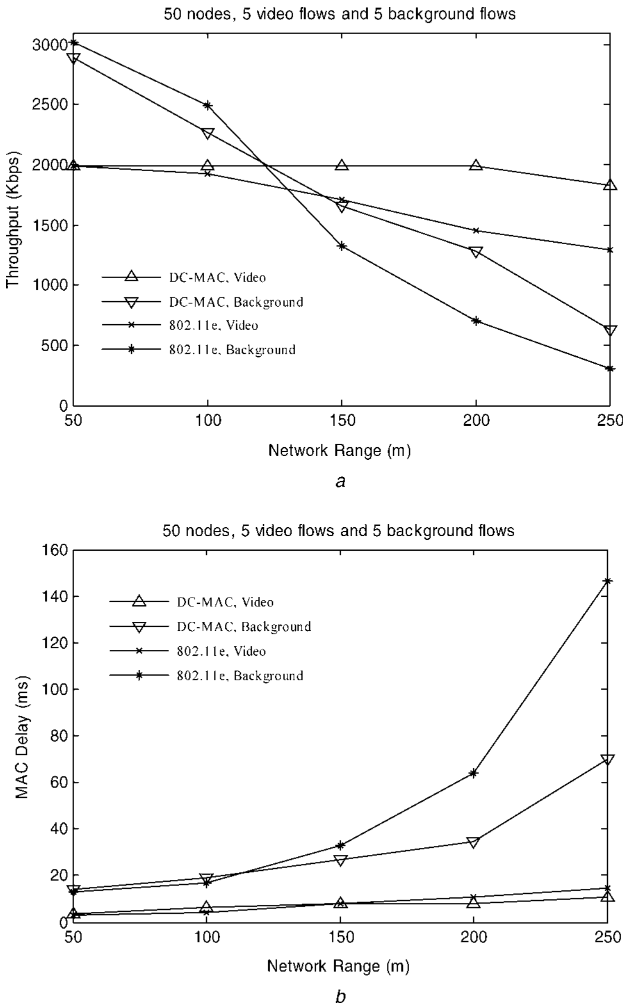

Figure 10 *Impact of network range*

a Throughput
b MAC delay

for video and 52% for background UDP traffic in terms of MAC delay, when the network area is 250 m × 250 m. Our proposed scheme can significantly increase the coverage with a high data rate.

5 Conclusion

In this paper, we have proposed a novel DC-MAC to enhance the QoS support for multimedia communications while supporting service-differentiation over fading wireless networks based on the IEEE 802.11e architecture. To combat small-scale fading with bursty errors and limited high-rate transmission range due to large-scale fading, cooperative ARQ is enabled to initiate a retransmission from an appropriate transmission queue of an appropriate relay node instead of the original source. A novel NAK feedback mechanism is introduced for loss distinguishing and channel estimation such that cooperative retransmissions will be employed only when necessary and only by competent nodes. We have carried out extensive simulations to analyse the impact of key protocol parameters and environmental parameters over the performance of the proposed scheme based on the OPNET platform. Simulation results show that compared with the 802.11e EDCA, the proposed scheme significantly improves the performances of both multimedia applications and best-effort data applications in terms of throughput, delay and coverage with moderate user contention. For future work, an adaptive mechanism to adjust the number of potential relays and minimise the relay contention needs to be investigated. We also would like to implement our proposed protocol on a testbed and evaluate its performance in a realistic environment.

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