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Distributed Medium Access Control for Real-time Traffic in Wireless LANs

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Abstract Supporting real-time traffic in wireless LANs is one of the interesting QoS issues. To support real-time traffic in wireless LANs, concentrated control mechanisms using PCF of IEEE802.11 are proposed in several previous researches. Although not only a concentrated control mechanism but also a distributed control mechanism is required for flexible QoS support in wireless LANs, there is no distributed control mechanism meeting features required to realize the flexible QoS support. We clarify requirements of a distributed control mechanisms supporting real-time traffic and propose a new MAC mechanism satisfying the requirements, which provides delay fairness and delay differentiation for real-time flows. Additionally, we show that the proposed mechanism is easily embedded into a prospective service model of IEEE802.11 based wireless LAN. By simulation, we show that our mechanism achieves delay fairness and differentiation, and functions adequately to support real-time traffic in practical environments where real-time traffic and non-real-time traffic coexist in an identical wireless LAN.

Key words wireless LAN, IEEE802.11, CSMA/CA, MAC, distributed, QoS, fairness, differentiation, real-time

無線LANにおけるリアルタイムトラフィックのための分散型メディアアクセス制御

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あらまし 無線LANにおいてリアルタイムトラフィックをサポートするための手法として、IEEE802.11で規格化されているPCFを用いた集中制御方式が多数提案されている。しかし、無線LANにおいて柔軟なQoSサポートを行うためには、集中制御だけでなく分散制御も必要である。本稿では、無線LANにおけるリアルタイムトラフィックのための分散制御方式に対する要求事項を示し、その要求事項を満たす分散型メディアアクセス制御方式を提案する。また、提案方式がIEEE802.11ベースの無線LANにおいて想定されるQoSサポートの実現に適していることを述べ、更に、提案方式をシミュレーションにより評価する。

キーワード 無線LAN, IEEE802.11, CSMA/CA, MAC, 分散, QoS, 公平性, 差別化, リアルタイム

1. Introduction

Recently, wireless LANs have become widely used to access the Internet and real-time applications such as telecommunications and videoconferences become to use the Internet. In the future, we foresee, these applications will widely use wireless LANs to access the Internet. Therefore, supporting real-time traffic in wireless LANs is an interesting QoS issue.

To support real-time traffic in wireless LANs, concentrated control mechanisms are utilized in several previous researches [1]～[5]. The mechanisms proposed in [1]～[5] use PCF (Point Coordination Function) of IEEE802.11 [6] to support real-time traffic. Although these mechanisms can provide bounded delay service, they increase implementation complexities of access points and real-time stations(1). Additionally, they can be used only in infrastructure mode of IEEE802.11 owing to being based on PCF; they cannot be used in ad hoc mode. On the other hand, distributed control mechanisms do not require such implementation complexities and can be used even in ad hoc mode. So, a distributed control mechanism supporting real-time traffic is required.

Stations contend for transmission opportunities in a distributed control mechanism, while stations are given them by an access point in a concentrated control mechanism. To give the finite transmission opportunities to flows(2) having various features, distributed control mechanisms provide fairness and differentiation for flows. In multi-class service, fairness shall be provided for flows belonging to the same service class and differentiation shall be provided for flows belonging to different service classes. Take into account that real-time applications are sensitive to delay rather than throughput, we believe that fairness provided for real-time flows should be delay fairness and that differentiation provided for real-time flows should be delay differentiation.

Distributed control mechanisms supporting real-time traffic in wireless LANs are proposed in previous researches [7]～[9]. The mechanisms proposed in [7]～[9] use DCF or another access control method. Although these mechanisms provide higher-priority service for real-time traffic by differentiating real-time traffic from non-real-time traffic, they can provide nether delay fairness nor delay differentiation.

In this paper, we propose a new distributed MAC mechanism that provides delay fairness and differentiation for real-time flows and can be easily embedded into IEEE802.11 based wireless LAN. To achieve delay fairness, we introduce a backoff algorithm that controls backoff time based on waiting-time—the time a frame has experienced since it was enqueued in the link interface queue. To achieve delay differentiation, we introduce weighting parameter into the backoff algorithm. Additionally, we show that the proposed distributed MAC is effectually embedded into to a prospective service model of IEEE802.11 based wireless LAN. By simulation, we confirm that our mechanism functions adequately for supporting real-time traffic in wireless LANs.

The structure of the paper is as follows. In Sect. 2., we briefly introduce IEEE802.11 standard, focusing on DCF and PCF. In Sect. 3., we discuss the previous researches aiming at supporting real-time traffic in wireless LANs. Then, in Sect. 4., we identify the requirements of a distributed MAC mechanism for real-time

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(1) : We use the word "real-time station" as a station generating real-time traffic.

(2) : The word "flow" shall not mean "traffic". A flow is composed of frames transmitted by a station. Traffic may be composed of some flows or may be a part of a flow.

traffic, propose a distributed MAC satisfying the requirements, and explain how it support real-time traffic in a prospective service model of IEEE802.11 based wireless LAN. We evaluate the proposed mechanism by simulation in Sect. 5.. Finally, we conclude this paper in Sect. 6..

2. IEEE802.11 Standard

IEEE802.11 standard describes MAC layer and physical layer specifications for IEEE802.11 wireless LAN [6]. Two access control methods are defined in the MAC layer specifications. One is DCF (Distributed Coordination Function), and the other is PCF (Point Coordination Function).

2.1 DCF

DCF (Distributed Coordination Function) is a distributed control method based on CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance). DCF must be implemented in all IEEE802.11 stations. In DCF, if a station has frames to be transmitted, the station decides backoff time of the frame, which is used to resolve contention. Backoff time is decided using a backoff algorithm. DCF adopts BEB (Binary Exponential Backoff) as a backoff algorithm. In BEB, backoff time is decided using the following expressions:

$$CW := (CW_{min} + 1)2^{RC} - 1 \quad (1)$$

$$CW := min(CW, CW_{max}) \quad (2)$$

$$B := \lfloor CW \times rand() \rfloor (\text{slots}) \quad (3)$$

where CW is contention window; RC is retransmission count of a frame, which is 0 when the frame is to be transmitted at the first time and is n when the frame is to be retransmitted at the n-th time; CW_{min} is the minimum value of CW, which is equal to CW when $RC = 0$; CW_{max} is the maximum value of CW; $min(a, b)$ is the function that returns the smaller number of a and b; $rand()$ is the function that returns a value chosen randomly from the interval from 0 to 1; $\lfloor n \rfloor$ is the largest integer less than or equal to n; B is backoff time; and $:=$ is the assignment operator. Backoff time is decremented by a station only while the station determines the medium to be idle for a time interval greater than a DIFS (DCF Interframe Space; IFSs are detailed in Table 1). When the backoff time becomes 0, the station transmits a frame. After transmitting the frame, the station repeats the above procedures for the next frame with reset RC if it receives the ACK frame for the transmitted frame, and it repeats the above procedures for the same frame with incremented RC if it does not receive the ACK frame.

2.2 PCF

PCF (Point Coordination Function) is the concentrated control method that is the optional function only usable in infrastructure mode of IEEE802.11 wireless LAN. In PCF, an access point manages the right of transmission during CFP (Contention Free Period), which periodically starts when the access point transmits a beacon frame and finishes when the access point transmits a CF-End frame. During CFP, stations can transmit frames only when polled by an access point. Stations to be polled are described in a polling list, and an access point manages the list and polls the stations according to the list. During CFP, frames are transmitted at the intervals of SIFS (Short Interframe Space) or PIFS (PCF Interframe Space). When CFP is terminated by an access point, CP (Contention Period) starts and the medium is controlled by DCF until CFP starts again.

3. Related Work

To support real-time traffic in wireless LANs, concentrated control mechanisms are utilized in several previous researches [1]~[5]. The mechanisms proposed in [1]~[5] use PCF (Point Coordination Function) to support real-time traffic. Although these mechanisms can provide bounded delay service, procedures required by them, e.g. admission control, resource reservation, polling scheduling, increase implementation complexities of access points and real-time stations. Additionally, they can be used only in infrastructure mode of IEEE802.11 owing to being based on PCF; they cannot be used in ad hoc mode.

On the other hand, distributed control mechanisms are utilized in previous researches [7]~[9] to support real-time traffic in wireless LANs. The mechanisms proposed in [7], [8] use DCF. these mechanisms let CW_{min} of real-time flows be smaller than that of non-real-time flows in CDF, real-time traffic and non-real-time traffic are differentiated; the transmission priority of real-time traffic is higher than that of non-real-time traffic. However, they can provide nether delay fairness nor delay differentiation, because DCF gives transmission opportunities to flows regardless of how long flows are kept waiting to transmit frames. The mechanism proposed in [9] uses another access control method to support real-time traffic, while it uses DCF to support non-real-time traffic. The method used for real-time traffic lets real-time flows transmit a frame when a PDFS interval has passed after the medium became idle. In IEEE 802.11 standard, however, frames may be transmitted at the PIFS intervals during CFP. Therefore, this mechanism cannot coexist with PCF; it is used only in ad hoc mode or in infrastructure mode not using PCF.

EDCF (Enhanced DCF) [10] is one of the other distributed control mechanisms that can be utilized to support real-time traffic in IEEE802.11 wireless LAN. EDCF is a distributed MAC protocol under standardization by IEEE802.11 task group e, which standardizes MAC protocols for supporting QoS in IEEE802.11 wireless LAN. In EDCF, 8 traffic categories are defined. In an EDCF station, every traffic category has its own priority, queue and protocol parameters, e.g. CW_{min}. In EDCF, if two or more traffic categories attempt to transmit a frame concurrently in a station, the traffic category of the highest priority may transmit and the other traffic categories should retransmit. Except this point, every traffic category contends for the medium by using DCF independently of other traffic categories in a station. In addition, all the traffic categories have the following relashionship:

$$IFS[i] < IFS[j] (0 \leqq i < j \leqq 7) \quad (4)$$

$$CW_{min}[i] \leqq CW_{min}[j] (0 \leqq i < j \leqq 7) \quad (5)$$

where $IFS[i]$ is the IFS of traffic category i and $CW_{min}[i]$ is CW_{min} of traffic category i. Thus, EDCF can differentiate the traffic categories. EDCF can differentiate real-time traffic from non-real-time traffic by having real-time traffic and non-real-time traffic belong to different traffic categories. However, EDCF itself cannot achieve delay fairness among flows of a same traffic category. So, delay fairness among real-time flows cannot be achieved by EDCF.

4. Distributed MAC for Real-time Traffic

4.1 Requirements

A distributed MAC mechanism supporting real-time traffic in wireless LANs should satisfy the following requirements:

- Delay fairness: A distributed control mechanism is required to give the finite transmission opportunities to flows fairly. In addition, delay is very important factor to be considered for real-time traffic, because real-time applications are sensitive to delay rather than throughput. Thus, all the real-time flows supported by a distributed MAC should be provided with delay fairness.
- Delay differentiation: Delay differentiation is useful to support real-time flows according to their QoS requirements. Real-time applications have different level of requirements on delay according to the characteristics of them. For example, voice requires tighter delay than moving picture, and interactive communication requires tighter delay than one-way communication.

Besides, from the viewpoint of practicability, a distributed MAC mechanism supporting real-time traffic is desired to have the following features:

- Coexistence with PCF: Because a concentrated control mechanism, e.g. [1]~[5], can provide high quality service such as bounded delay service, a distributed MAC for supporting real-time traffic is desired to be able to coexist with PCF. The coexistence enables flexible service, where a concentrated control mech-

Table 1 IFSs defined in IEEE802.11 standard

IFS	frames using the IFS	relationship with SIFS
SIFS (Short IFS)	an ACK frame, a CTS frame, the second or subsequent frame of a fragment burst, a frame responding to a polling frame during CFP, a frame transmitted by an access point during CFP	
PIFS (PCF IFS)	a frame transmitted by an access point during CFP	$PIFS = SIFS + SLOTTIME$
DIFS (DCF IFS)	a frame during CP	$DIFS = SIFS + 2SLOTTIME$

IFS (interframe space) is the time interval between frames. Every frame uses an IFS as the time interval during which the frame must wait before transmitted.

anism using PCF supports real-time stations requiring bounded delay service while a distributed control mechanism supports real-time stations not requiring bounded delay service or incapable of giving the bounded delay service.

- Coexistence with a MAC mechanism for non-real-time traffic: Because real-time traffic and non-real-time traffic coexists in a practical wireless LAN, a MAC mechanism of wireless LANs is required to support both real-time traffic and non-real-time traffic. Now, DCF of IEEE802.11 is the most widely used wireless LAN protocol and the standard for non-real-time traffic. Therefore, a MAC mechanism for real-time traffic is required to coexist a MAC mechanism for non-real-time traffic such as DCF.

4.2 Approach

To meet the requirements described in Sect. 4.1, we propose a new MAC mechanism. DCF cannot support delay fairness or differentiation, because BEB—the backoff algorithm used in DCF—decides backoff time of a frame regardless of how long the frame is kept waiting to be transmitted. Then, to achieve delay fairness, we introduce "waiting-time" defined as the time a frame has experienced since it was enqueued in the link interface queue, and we give smaller backoff time to a frame having larger waiting-time. To achieve delay differentiation, we also introduce weighting parameter used to adjust backoff time independently of waiting-time, and give different waiting parameters to differentiated frames.

Although our mechanism adopts the new backoff algorithm as in the above description, our mechanism and DCF are the same except a backoff algorithm. Our mechanism does not strictly conformable to IEEE802.11 standard, but it can coexist with PCF because frame transmission in the mechanism strictly obeys DIFS interval. In addition, a differentiated MAC mechanism, e.g. EDCF [10], enables it to coexist with another MAC mechanism for non-real-time traffic such as DCF.

4.3 Algorithm

In this section, we present our distributed MAC mechanism for real-time traffic in wireless LANs. It adopts the backoff algorithm presented by the following expressions:

$$CW := (CW_{min} + 1)2^{RC} - 1 \qquad (6)$$

$$CW := min(CW, CW_{max}) \qquad (7)$$

$$B := \lfloor CW \times rand() \rfloor \qquad (8)$$

$$B := \lfloor B \cdot K/(t/w) \rfloor \qquad (9)$$

$$B := max(B, B_{min}) \qquad (10)$$

$$B := min(B, B_{max}) \qquad (11)$$

where t is waiting-time, K is a constant the value of which is the same in any station, w is a weighting parameter the value of which may vary in every station, B_{min} is the minimum value of B, B_{max} is the maximum value of B, and $max(a,b)$ is the function that returns the larger number of a and b.

This backoff algorithm is composed of 2 steps. In the first step, the BEB procedure decides B according to the expressions (6), (7) and (8). (6), (7) and (8) are equivalent to (1), (2) and (3), respectively. We utilize the contention resolution functionality of BEB in this step. In the second step, B is adjusted according to the expressions (9), (10) and (11). This step decides B to be inversely proportional to t, whereby a frame of larger waiting-time has higher transmission priority. That is, this step supports delay fairness. In addition, by making stations have different w values, this step can support delay differentiation. Expressions (10) and (11) limit B in the range from B_{min} to B_{max}. Except a backoff algorithm, our mechanism and DCF is the same. Figure 1 presents the proposed distributed MAC in detail.

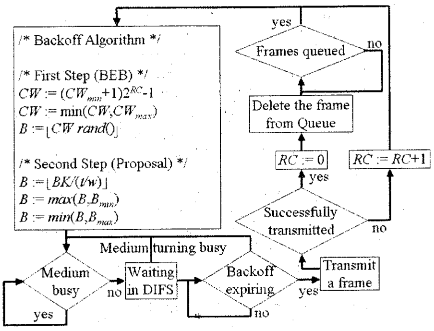


Figure 1 The flowchart of the distributed MAC for real-time traffic

4.4 Application of the proposed MAC to IEEE802.11 based wireless LAN service

In this section, we present a prospective service model of IEEE802.11 based wireless LAN and explain that the proposed distributed MAC is easily embedded into the model.

In the future, wireless LANs are expected to support both real-time flows and non-real-time flows according to their QoS requirements. To realize the future wireless LANs, multiple service classes should be supported and configured in wireless LANs according to Table 2.

The first class is supported by a concentrated control mechanism and used to provide bounded delay service for flows belonging to the class. The service of this class is useful for real-time flows requiring bounded delay service. PCF is useful to support the first class, because many concentrated control mechanisms using PCF are proposed and effectiveness of the mechanisms is confirmed in [1]~[5].

The second class is supported by a distributed control mechanism and used to provide delay fairness for flows belonging to the class. The service of this class is useful for real-time flows not requiring such high quality service as bounded delay or incapable of giving bounded delay service. This class may have several subclasses, the number of which is M in Table 2. In this case, this class provides delay fairness for flows belonging to the same subclass and provides delay differentiation for flows belonging to different subclasses. The proposed mechanism is useful to support delay fairness and delay differentiation in the second class. In the proposed mechanism, by making flows belonging to the same subclass have the same w value and making flows belonging to different subclasses have different w values, the service of the second class is realized.

The third class is supported by a distributed control mechanism and used to provide throughput fairness for flows belonging to the class. The service of this class is useful for non-real-time flows. This class may have several subclass, the number of which is N in Table 2. In this case, this class provides throughput fairness for flows belonging to the same subclass and provides throughput differentiation for flows belonging to different subclasses. EDCF is appropriate to support the differentiation among the subclasses of the third class, because EDCF is the differentiation mecha-

Table 2 A prospective service model of wireless LAN

class	sub-	service: in the subclass	service: among the subclasses	how controlled	for which traffic	implementation exemplum	
1		bounded delay		concentrated	real-time	PCF	
2	1	delay fairness	delay differentiation	distributed		EDCF	Traffic Category (Proposal)
	:	:					:
	M	delay fairness					Traffic Category (Proposal)
3	1	throughput fairness	throughput differentiation		non-real-time		Traffic Category (DCF or DFS)
	:	:					:
	N	throughput fairness					Traffic Category (DCF or DFS)

nism strictly compatible with DCF and it is a part of prospective IEEE802.11e standard. Additionally, EDCF is useful to differentiate the second class and the third class. However, EDCF itself cannot strictly support throughput fairness because it uses BEB as a backoff algorithm. This problem is easily solved by replacing BEB with the backoff algorithm proposed in DFS (Distributed Fair Scheduling) [11], which support throughput fairness.

The whole service of the model is realized only in infrastructure mode. However, all the classes except the first class can be supported even in ad hoc mode because they are supported by a distributed control mechanism. Without a distributed control mechanism supporting real-time traffic, real-time traffic in ad hoc mode cannot be supported. Taking this fact into account, such a mechanism as uses distributed control is very useful.

5. Simulation and Evaluation

In this section, we evaluate the proposed MAC mechanism by simulation. Figure 2 shows the simulation environments, where n senders transmit frames destined for an identical receiver at constant bit rate and every station is not a hidden terminal to any other station. The transmission in the environments is typical of uplink transmission to an access point in infrastructure mode, but the simulation results are valid even for more general environments where several receivers exists in ad hoc mode, because the contention occurs among senders and is irrelevant to receivers in the assumed environments. We use Configuration 1-4 as simulation configurations to evaluate delay fairness, delay differentiation, and so on. While the configuration common to all the simulations is shown in Fig. 2, The configurations varying in each simulation is shown in Table 3, Table 5, Table 7 and Table 8.

To make the simulation data reliable, each simulation runs for 10 seconds, which is the time span satisfactory to derive the reliable results, and each simulation data in this section are composed of delays, fairness indexes and/or drop rates averaged for the 10 seconds. Because there is no prior distributed MAC mechanism supporting delay fairness, we evaluate the proposed MAC mainly by comparing the simulation results of the proposed MAC with those of DCF.

In this paper, we use fairness index [12] to evaluate accuracy of delay fairness and differentiation. Fairness index is defined by the following qeuation:

$$fairness\ index = \frac{(\sum_{i=1}^{n} d_i/w_i)^2}{n\sum_{i=1}^{n}(d_i/w_i)^2} \qquad (12)$$

where n is the number of senders. d_i is the delay of sender i, and w_i is the weight of sender i. Fairness index is greater than 0, and less than or equal to 1. It approaches to 1 as d_1/w_1, d_2/w_2, $\cdots$, d_n/w_n are becoming the same.

5.1 Delay fairness and differentiation

5.1.1 Delay fairness

To evaluate the fairness of the proposed MAC mechanism, we use Configuration 1, described in Table 3, as a simulation configuration. In the configuration, n senders all implement the proposed MAC mechanism and have the parameters in the table. For the purpose of the comparison of the proposed MAC and DCF, we have all the senders implement DCF too. In the case, they have the parameters in the table except K, B_{min}, B_{max} and w. Figure 3 shows the delay characteristics obtained in the simulation of Configuration 1. The figure shows simulation results in the case where the n sender all implement the proposed MAC or in the case where the n senders all implement DCF. The lines of "min" present delays of the sender having the smallest delay of the n senders, the lines of "max" present delays of the sender having the largest delay of the n senders, and the lines of "ave" present the average values of the delays of the n senders. Both in the proposed mechanism and in DCF, if $n \leqq 6$, all the senders experience little delay because the medium load is light. On the other hand, if $n \geqq 7$, the average delay of the n senders increases as n grows larger. Additionally, there are two features when $n \geqq 7$. One is that the average delay in the proposed mechanism is smaller than that in DCF. The other is that the difference between the maximum delay and the minimum delay in the proposed mechanism is much smaller than that in DCF. In other words, the proposed MAC is a better mechanism to achieve low delay and delay fairness than DCF. This advantage is derived from our original procedure (9), where larger waiting-time leads to smaller backoff time.

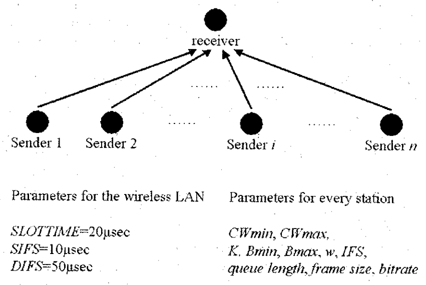


Figure 2 Simulation environments

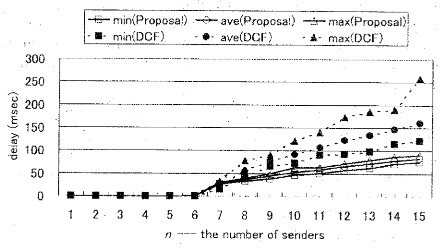


Figure 3 Delay — Configuration 1

Table 4 shows the fairness indexes when $n \geqq 7$ in Configuration 1. Fairness indexes in the proposed mechanism are all over 99% and approach to 1.

5.1.2 Delay differentiation

To evaluate the differentiation of the proposed MAC mechanism, we use Configuration 2, described in Table 5, as a simulation configuration. In the configuration, n senders all implement the proposed MAC mechanism. Sender i ($1 \leqq i \leqq 4$) is a H-sender, which is a sender with higher priority, while sender i ($i \geqq 5$) is

Table 3 Configuration 1

sender	CW_{min}	CW_{max}	K	B_{min}	B_{max}	w	IFS	*queue length*	*frame size*	*bitrate*
1–n	31	1023	0.005	1	1023	1	$DIFS$	16KByte	1024byte	1000kbps

Table 4 Fairness index — Configuration 1

n	7	8	9	10	11	12	13	14	15
fairness index (%)	99.8	99.7	99.6	99.0	99.6	99.7	99.5	99.7	99.7

Table 5 Configuration 2

sender	CW_{min}	CW_{max}	K	B_{min}	B_{max}	w	IFS	*queue length*	*frame size*	*bitrate*
1-4 (H)	31	1023	0.005	1	1023	1	$DIFS$	16KByte	1024byte	1000kbps
5–n (L)	31	1023	0.005	1	1023	2	$DIFS$	16KByte	1024byte	1000kbps

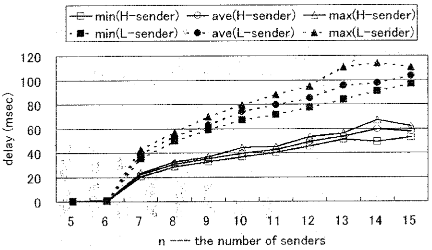


Figure 4 Delay — Configuration 2

a L-sender, which is a sender with lower priority. H-senders and L-senders are differentiated using weighting parameter w. Except w, there is no difference between the configuration of H-senders and that of L-senders. Figure 4 shows the delay characteristics obtained in the simulation of Configuration 2. The lines of "min(H-sender)" present delays of the H-sender having the smallest delay of the 4 H-senders, the lines of "max" present delays of the H-sender having the largest delay of the 4 H-senders, and the lines of "ave" present the average values of the delays of the 4 H-senders. Similarly, the lines of "min(L-sender)" present delays of the L-sender having the smallest delay of the $n-4$ L-senders, the lines of "max" present delays of the L-sender having the largest delay of the $n-4$ L-senders, and the lines of "ave" present the average values of the delays of the $n-4$ L-senders. Both in the proposed mechanism and in DCF, if $n \leqq 6$, all the senders experience little delay because the medium load is light. If $n \geqq 7$, on the other hand, both the average delay of H-senders and that of L-senders increase as n grows larger. The differentiation between the H-senders and the L-senders is achieved, because the maximum delay of the H-senders is kept being smaller than the minimum delay of the L-senders.

Moreover, by using fairness index, the accuracy of fairness and differentiation can be evaluated. Table 6 shows the fairness indexes when $n \geqq 7$ in Configuration 2. The fairness indexes in Table 6 are as large as those in Table 4, and they are greater than 99%. These simulation results confirm that the fairness of the senders having the same w value and the differentiation of the senders having different w values has adequate accuracy.

5. 1. 3 Impacts on delay fairness

Generally, parameters of a station, e.g. *queue length*, *frame size*, *bitrate*, may be different from those of another station, because stations may have different implementations, applications have different characteristics, and Internet users have different preferences. Delay fairness is desired to be achieved regardless of these varieties.

To investigate how *queue length*, *frame size* and *bitrate* impact on delay fairness, we measured delays in the simulation environments of Configuration 3 described in Table 7, and calculated fairness indexes from the delays. In the configuration, both the 2 senders implement the proposed MAC mechanism or both the 2 senders implement DCF, and while sender 1 has no variable parameter, sender 2 has 3 variable parameters—b, l, r. The values of the other parameters of sender 2 are equal to those of sender 1. Figure 5 presents the delays and the fairness indexes. Figure 5(a) shows that fairness index is largest when $b = 16$ and deteriorated as b is away from 16 both in the case of the proposed MAC and in the case of DCF. Figure 5(b) shows that fairness index is largest when $l = 1024$ and deteriorated as l is away from 1024 both in the 2 cases. From these results, difference between the queue lengths of senders and difference between the frame sizes of senders impact on delay fairness. On the other hand, Fig. 5(c) shows that the sender of larger r experiences longer delay both in the case of the proposed mechanism and in the case of DCF when the medium is not saturated ($r < 4000$). This is because sender 2 is light loaded and can transmit with little waiting. Although a MAC mechanism forcing longer delay on light-loaded stations could achieve higher accuracy of fairness, it is not an appropriate solution. Figure 5(c) also shows that delay fairness is achieved regardless of r when the medium is saturated ($r \geqq 4000$).

From the above discussion, we found that these 3 parameters—*queue length*, *frame size*, *bitrate*—have an impact on delay fairness. However, the proposed MAC can be widely effective in suppressing the impact, because the proposed MAC dynamically controls transmission priorities according to waiting-time. In Fig. 5, the fairness indexes in the proposed mechanism are larger than those in the DCF in every configuration of Configuration 3. In the case of DCF, delay fairness conspicuously collapses when $b \leqq 8$, $l \leqq 256$, $l \geqq 1792$ or $r \leqq 3200$. The proposed MAC is effective especially in these cases.

5. 2 Coexistence with other mechanisms

To evaluate the performance of the proposed MAC coexisting with DCF, we use Configuration 4 described in Table 8. In the configuration, sender i ($1 \leqq i \leqq 4$) implementing the proposed MAC mechanism—we call it R-sender—is a real-time station, and sender i ($5 \leqq i \leqq n$) implementing DCF—we call it NR-sender—is a non-real-time station. While R-senders transmit frames at constant bit rate, NR-senders transmit frames at enough high rate to saturate the medium. Figure 6 shows that the average drop rate of the 4 R-senders is so small in spite of the increase of NR-senders; the rate is under 1% when the number of NR-senders is up to 15. Additionally, the fairness index of the 4 R-senders is so high regardless of the number of NR-senders; the index is over 90% regardless of the number of NR-senders and is often over 95%. Although fairness indexes in this case are a few percents smaller than those in the case where only the proposed MAC mechanism works presented in Table 4 or Table 6, these results illustrate the proposed MAC mechanism can support real-time traffic even in the environments where another MAC mechanism coexists.

6. Conclusion

In this paper, we specified requirements of a distributed control mechanism supporting real-time traffic in wireless LANs—providing delay fairness, providing delay differentiation, coexisting with PCF and a mechanism for non-real-time traffic. Later we proposed a new MAC mechanism satisfying the requirements. Additionally, we showed that the proposed MAC mechanism is easily embedded into a prospective service model of IEEE802.11 based wireless LAN.

We evaluated the proposed MAC mechanism by simulation. We

Table 6 Fairness index — Configuration 2

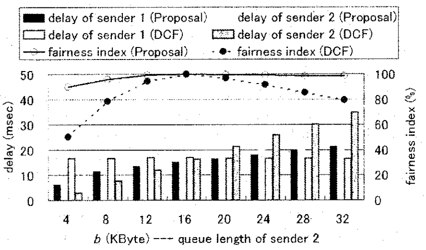
n	7	8	9	10	11	12	13	14	15
fairness index (%)	99.0	99.2	99.3	99.4	99.5	99.0	99.1	99.3	99.5

Table 7 Configuration 3

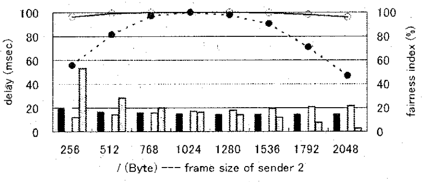
sender	CW_{min}	CW_{max}	K	B_{min}	B_{max}	w	IFS	*queue length*	*frame size*	*bitrate*
1	31	1023	0.005	1	1023	1	$DIFS$	16KByte	1024byte	5000kbps
2	31	1023	0.005	1	1023	1	$DIFS$	bKByte	$l$byte	$r$kbps

Table 8 Configuration 4

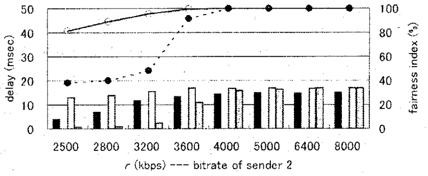
sender	CW_{min}	CW_{max}	K	B_{min}	B_{max}	w	IFS	*queue length*	*frame size*	*bitrate*
1–4 (Proposal)	15	1023	0.005	1	1023	1	$DIFS$	16KByte	512byte	500kbps
5–n (DCF)	31	1023	—	—	—	—	70μsec	16KByte	1500byte	—



$l = 1024$, $r = 5000$
(a) Impact of queue length



$b = 16$, $r = 5000$
(b) Impact of frame size



$b = 16$, $l = 1024$
(c) Impact of bitrate

Figure 5 Delay and fairness index — Configuration 3

confirmed that our mechanism can provide delay fairness and differentiation with high accuracy not achieved by DCF. We also confirmed that our mechanism supports delay fairness and low drop rate for real-time flows in the environments where not only real-time traffic but also non-real-time traffic is supported in an identical wireless LAN.

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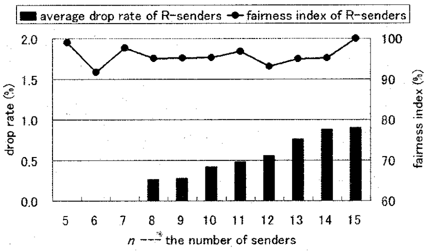

Figure 6 Drop rate and fairness index — Configuration 4