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User-Oriented QoS Control Method Based on CSMA/CA for IEEE802.11 Wireless LAN System

Akira KISHIDA†a), **Masashi IWABUCHI**†, **Toshiyuki SHINTAKU**†, **Tetsu SAKATA**†, **Takefumi HIRAGURI**††, *and* **Kentaro NISHIMORI**†††, ***Members***

SUMMARY The IEEE 802.11 distributed coordinated function (DCF) adopts carrier sense multiple access with collision avoidance (CSMA/CA) as its medium access control (MAC) protocol. CSMA/CA is designed such that the transmission from any one station does not have priority over any other. In a congested environment with many DCF stations, this design makes it difficult to protect channel resources for certain stations such as when products are used for presentation at exhibitions, which should be protected based on priority. On the other hand, The IEEE 802.11 enhanced distributed channel access (EDCA) provides a quality-of-service (QoS) mechanism for DCF. However in EDCA, transmission opportunities are allocated based on not individual stations but on the defined traffic type of applications. This paper proposes a distributed dynamic resource allocation method that enables control of flexible bandwidth allocation to each specific station. The proposed method controls the priority level and can coexist with conventional CSMA/CA. Moreover, the proposed method improves the system throughput. Specifically, under the coexistence environment with DCF stations, the proposed method is able to obtain up to over 300% higher user throughput characteristic compared to the case in which the proposed method is not introduced. In addition, under non-coexistence environment, all the proposed stations achieve 70% higher throughput than DCF stations when the number of stations in a network is 50.

key words: *user-oriented, QoS, fixed backoff, CSMA/CA, IEEE802.11*

1. Introduction

Nowadays, the use of wireless local area network (WLAN) stations (STAs) such as smartphones, mobile routers, and laptop PCs is rapidly spreading. Almost all of these WLAN STAs adopt the IEEE 802.11 distributed coordinated function (DCF) [1] as the media access control (MAC) protocol. DCF employs carrier sense multiple access with collision avoidance (CSMA/CA). Frequency resources are scarce where many WLAN STAs are clustered. Hereafter, we refer to a congested situation with many WLAN STAs as a wireless dense environment (WDE). In WDE, all STAs suffer critical degradation in communication quality. This is because the number of collisions of data frames increase in proportion to the number of STAs due to CSMA/CA operation. CSMA/CA is designed in such a way that the priority for transmission from all STAs is impartial. However, to improve the user experience, there are many cases where certain STAs should be given priority. We define this priority structure as a user-oriented quality-of-service (QoS). In the following cases, protecting user-oriented QoS becomes important: the case where all STAs or access points (APs) are controlled by site owners or residents, or the case where priorities for certain STAs are obvious according to the STA service policy or regulations. The use of WLANs in offices or homes, the use for presentations at an exhibition, the use of fee-based Wi-Fi hotspots are examples of these cases. On the other hand, the IEEE802.11e enhanced distributed channel access (EDCA) provides a QoS mechanism for DCF. However, EDCA prioritizes each traffic flow based on categorized applications and not based on specific STAs. In other words, EDCA does not protect user-oriented QoS aimed at specified STAs. The priority structure protected by EDCA is defined as application-oriented QoS.

This paper proposes an effective MAC protocol based on CSMA/CA that protects user-oriented QoS for each STA. More specifically, we protect user-oriented QoS by operating CSMA/CA as a pseudo-centralized control that utilizes two kinds of fixed backoff as substitutes for random backoff. The proposed method coexists with the conventional DCF and is able to prioritize specified STAs. Thus, the proposed method is highly effective in the cases described above, and can coexist with other WLAN systems by controlling the priority between the proposed STAs and other conventional DCF STAs. Moreover, the proposed method is effective under saturation conditions, which means that STAs always have data to send. It is considered that these saturation conditions are generated frequently in a WDE.

The remainder of this paper is organized as follows. Section 2 describes the IEEE 802.11 DCF and reviews some related work. Section 3 describes the operation of the proposed method. Section 4 presents evaluation results based on computer simulations. Section 5 concludes this paper.

2. Background

2.1 IEEE802.11 MAC Protocols

The IEEE802.11 DCF based on CSMA/CA is adopted widely in WLAN STAs due to its simplicity. CSMA/CA is a contention-based MAC protocol in which the transmission from any one station does not have priority over any other. This fact implies that the DCF is not able to protect user-

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†The authors are with NTT Access Network Service Systems Laboratories, NTT Corporation, Yokosuka-shi, 239-0847 Japan.
††The author is with Nippon Institute of Technology, Saitama-ken, 345-8501 Japan.
†††The author is with Niigata University, Niigata-shi, 950-2181 Japan.
a) E-mail: kishida.akira@lab.ntt.co.jp

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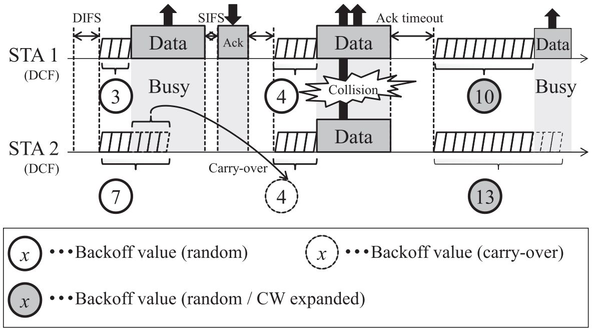


Fig. 1 Operation of CSMA/CA.

oriented QoS. Moreover, the throughput of CSMA/CA is severely degraded in a WDE due to the number of collisions generated between DCF STAs. The operation of CSMA/CA is briefly described hereafter.

Figure 1 shows the operation of CSMA/CA. In CSMA/CA, WLAN STAs autonomously decide the transmission timing. If the wireless medium (WM) is in use for a certain STA, the other STAs recognize the WM as being “busy” (carrier-sense) and refrain from transmission. Subsequently, if no other STA uses the WM, the STAs recognize the WM as being “idle” and reattempt transmission after waiting for a certain offset time period. This offset period consists of a fixed period (distributed inter-frame space: DIFS) and a random period (backoff time; decided by a random backoff value); thus the probability of a collision among STAs decreases due to the varied backoff period. This backoff period is decreased according to an elapsed slot time during the “idle” state. However, the decrement is frozen during the “busy” state and is resumed when the WM returns to the “idle” state. This mechanism ensures fairness among STAs. As a result, CSMA/CA is unable to prioritize certain STAs owing to its uniform treatment of all STAs.

The DCF adopts binary exponential backoff (BEB) to select a backoff value. The backoff value is randomly assigned from the range of the contention window (CW). In a WDE, the probability that two or more STAs select the same backoff value increases and, in such a case, a failure in transmission results due to a collision between the STAs. In particular, if the number of competing STAs that attempt transmission exceeds the CW, a collision between STAs is inevitable. Thus, the CW is increased exponentially in proportion to the number of transmission failures in order to reduce the number of collisions. At the first transmission, the CW is assigned to the initial value, $CW_{\min}$. If transmission failures continue, the CW increases exponentially up to the upper bound, $CW_{\max}$. In addition, the CW is reset to $CW_{\min}$ when the transmission succeeds. Therefore, the CW is decided based on the BEB as follows.

IF transmission succeeds,

$$\mathrm{CW} = CW_{\min} \tag{1}$$

Otherwise,

$$\mathrm{CW} = \min\left[2 \times (CW + 1)\,, CW_{\max}\right] \tag{2}$$

According to the BEB, the probability of collision decreases temporarily as the CW increases due to a transmission failure. However, the probability of collision increases again because the CW is reset to $CW_{\min}$ when the transmission succeeds. This operation degrades the throughput and delay characteristics in a WDE.

On the other hand, the IEEE 802.11 defines polling-based centralized control methods: the IEEE 802.11 point coordinated function (PCF) and the IEEE 802.11e hybrid coordination function (HCF) controlled channel access (HCCA) [1]. The system throughput characteristics of these centralized control methods are superior to those for the DCF. Moreover, these centralized operations are able to control QoS using arbitrary criteria that specify the timing of transmission. Reference [2] utilizes the existing framework of PCF and increases the flexibility of QoS by using an IEEE 802.11e-type scheduler. Reference [3] proposes an aging priority scheduling algorithm and a dynamic adaptation algorithm to vary the PCF interval based on the traffic and to reduce the overhead. Reference [4] introduces an enhanced polling scheme that manages queue control.

Although these polling-based control methods achieve good performance and QoS control, we focus on contention-based methods such as the DCF because of the inherent problem with complete polling mechanisms. This is because if there are many DCF STAs, these polling-based control methods have difficulty with flexible operation when trying to coexist with DCF STAs because those polling methods utilize the Network Allocation Vector (NAV) and the NAV prohibits any transmission of DCF STAs. In the PCF, DCF STAs cannot transmit any data frame unless this NAV period (contention free period: CFP) ends. This mechanism causes degradation in the throughput and delay characteristics for DCF STAs. Moreover, in the HCCA, the AP is required to schedule the timing and estimate the duration of transmission for each STA using procedures such as the traffic specification (TSPEC) negotiation defined in IEEE802.11e. This *a priori* procedure degrades the throughput and delay characteristics as well. In addition, most well-known WLAN STAs adopt the DCF and it is easy to implement contention-based control especially in a WDE. In the proposed method that will be explained hereafter, although the concept of its operation is based on centralized control, the actualization procedure is based on DCF. Therefore, the proposed method avoids the problems facing the complete polling-based methods described above. We aim to achieve coexistence with DCF STAs and enhance the communication quality without using the complete polling mechanisms.

Alternatively, EDCA provides a mechanism for application-oriented QoS. Access categories (ACs) are defined as a function of the QoS in EDCA and each AC has a different inter-frame space (IFS) and CW. STAs have queues corresponding to each AC, and each traffic flow is inserted into the queue corresponding to an application such as voice or video. At that point, the application and not the specific

STA is the criterion for the classification. Therefore, EDCA does not provide a user-oriented QoS mechanism that protects specific STAs.

2.2 Introduction to Conventional Methods

There are many notable studies that combat the problem described above. In [2], a user-oriented QoS protection method using EDCA is proposed. The method converts each AC corresponding to a single application into an AC corresponding to a single specified STA. This method utilizes the existing EDCA framework; however, the resulting plethora of queues for the number of STAs significantly increases the implementation costs. Moreover, the method cannot prevent collisions generated between prioritized STAs because of CSMA/CA operation. Therefore, the method does not prevent throughput degradation, especially in a WDE.

To prevent throughput degradation, other studies focus on improving CSMA/CA [6]–[12]. The main approach employed in these studies is adaptive optimization of CSMA/CA parameters such as the CW or IFS. The number of STAs ([6] and [7]), transmission rate ([8] and [9]), and frame size ([10] and [12]) are utilized to appraise metrics. The transmission history and auto rate fallback (ARF) are criteria used to adjust the optimal parameters in [10]–[12]. Most of these methods dynamically change the CW to decrease the possibility of collision. Subsequently, the CW is gradually adjusted to an appropriate value as determined by the criterion of each method. These methods can improve the system throughput without drastically changing the existing CSMA/CA. However in these methods, protection of the user-oriented QoS is difficult with coexisting conventional DCF STAs. This is because DCF STAs deprive other STAs of priority by resetting their CW to the head start value ($CW_{\min}$) after each successful transmission. Therefore, protection of user-oriented QoS is difficult with coexisting conventional DCF STAs.

Then again, [13]–[19] propose other remarkable approaches that utilize both polling-based and contention-based control. Reference [13] proposes a polling ACK mechanism to permit the designated STA to transmit without performing any contention process in the DCF. Reference [14] proposes a QoS control method by a priority-based backoff scheme to provide application-oriented QoS. Moreover, the methods in [15], [16] utilize both fixed backoff and random backoff by sending the backoff timer information together with the data or control frames destined to each given STA.

The work herein is most relevant to the work done in [17]–[19]. In [17], a method referred to as CSMA/ECA (enhanced collision avoidance) operates with pseudo-centralized control by using a fixed backoff. CSMA/ECA assigns its backoff value randomly with its first transmission as well as that for CSMA/CA. A fixed backoff value is assigned for successive transmissions. If there is no collision for the first transmission, all STAs can avoid collision on consecutive transmissions. On the other hand, if the transmission fails owing to a collision between a fixed backoff transmission and a random backoff transmission (for example, a transmission from a DCF STA), a random backoff value is assigned again for the CSMA/ECA STA. This operation further facilitates coexistence with DCF STAs. However, it is difficult to maintain pseudo-centralized control using a fixed backoff when random backoff transmissions exist because if the previous transmission fails due to a collision, a random backoff value is assigned instead of a fixed backoff value for the CSMA/ECA STA. Thus, the number of STAs using a random backoff increases and this increases the possibility of collision. Even if there are no DCF STAs, collisions between CSMA/ECA STAs cannot be eliminated because of the initial random backoff.

In this paper, we propose a flexible pseudo-centralized control method that uses two kinds of fixed backoff to protect user-oriented QoS in an environment with coexisting DCF STAs and that improves the throughput characteristics.

3. Proposed Method

3.1 Basic Operation

Figures 2 and 3 show the basic access mechanism for the proposed method and the flowchart for the proposed method respectively. The proposed method is based on CSMA/CA and the functions of the proposed method for WM listening, decreasing the backoff, and IFS parameters are the same as those for CSMA/CA. The significant difference from CSMA/CA is how the backoff value is determined. Although CSMA/CA decides the backoff value randomly within the CW range, the proposed method defines and adopts two kinds of fixed backoff values, namely, the initial backoff value (IBV) and the cyclic backoff value (CBV). The AP specifies the IBV and assigns it as the backoff value when the first transmission of each STA occurs. The IBV is a unique and non-zero value that is different for each STA. During the first transmission occurs, there is no collision between the STAs using the proposed method (hereafter proposed STAs) due to the different backoff values decided by the IBV. Afterwards, the CBV is assigned as the backoff value for each successive transmission unless a collision occurs. The CBV is also a fixed value and is specified by the AP. However, the value is common to all proposed STAs. The effect of the two kinds of fixed backoff values can be summed up as follows. The IBV establishes different offset times for each STA, while the CBV sustains the relation of the offset in a cyclic manner. This operation avoids collisions between the proposed STAs and improves the system throughput.

During the pseudo-centralized control of the proposed method, DCF STAs can execute their transmissions as usual, unlike existing centralized control methods, as illustrated in Fig. 4. This is because the proposed STAs are different from the DCF STAs only in the way they determine backoff values, while they refrain from transmissions during "busy" state according to the CSMA/CA manner. As a result, the

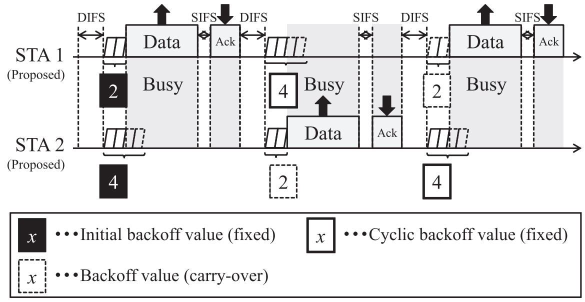


Fig. 2 Basic peration of proposed method.

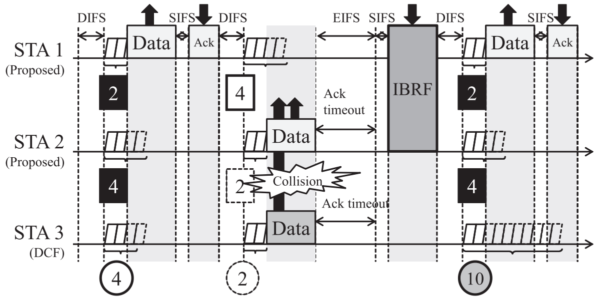


Fig. 5 Operation of proposed method with DCF STA (Collision).

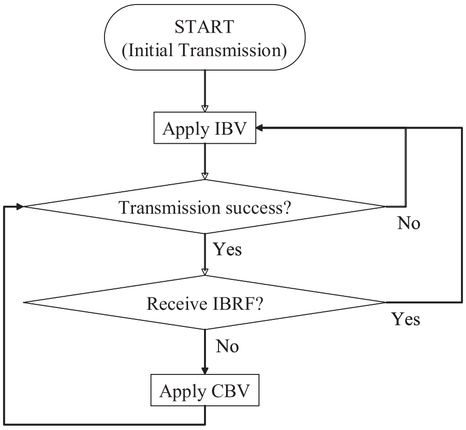


Fig. 3 Flowchart of the proposed method.

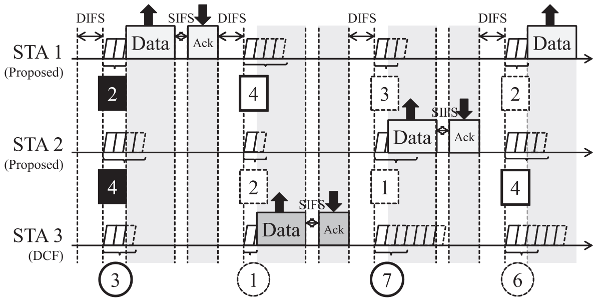


Fig. 4 Operation of proposed method with DCF STA.

periodicity of the backoff value for the proposed STAs is maintained as long as the DCF STAs assign backoff values that are different than those for the proposed STAs.

Although collision between proposed STAs can be avoided, there is a possibility that they will collide with DCF STAs. Figure 5 illustrates the operation of the proposed method when the transmission of a proposed STA collides with that of a DCF STA. In this case, all the proposed STAs reset their backoff values to each specified IBV using the "initial backoff reset frame" (IBRF). While the DCF STA expands its CW to reduce the collision probability based on the BEB, the proposed STAs resume pseudo-centralized control of the initial stage. Since the backoff values of the proposed STAs are reset to their IBV each time a collision occurs, assignment of the IBV is the key factor in deciding the user-oriented QoS level. In other words, if a low number is assigned to the IBV, the priority of proposed STA increases and vice versa. The effect of IBV and CBV is explained in Sect. 3.3.

3.2 Fixed Backoff Values

If only proposed STAs are connected to an AP, i.e., there are no DCF STAs, there is no prioritization among the STAs because the proposed method implements complete centralized operation without any collision and the chances for transmission are given in a cyclic manner. However, in a situation where a collision occurs due to DCF STAs, the backoff values for each proposed STA are reset to each specified IBV upon a collision. This behavior can be leveraged to control the user-oriented QoS. The degree of the QoS depends on the settings for the CBV and IBV.

3.2.1 Cyclic Backoff Value (CBV)

The CBV is a shared value among all proposed STAs and is assigned to consecutive transmissions as long as the previous transmission is successful. The number of CBV values should be equal to or greater than the total number of all STAs including DCF STAs. A larger CBV can better decrease the possibility of collisions between proposed STAs and DCF STAs. Conversely, if the number of CBV values is less than the total number of all STAs, a collision is inevitable due to lack of selectable backoff values. This CBV is broadcasted via a beacon frame or IBRF.

3.2.2 Initial Backoff Value (IBV)

The IBV is a unique value assigned to each proposed STA and is applied when STAs receive an IBRF from an AP. The AP informs each STA of the specified IBV using a probe response frame or data frame. At this point, the same IBV should not be assigned to different STAs. Moreover, the value of each IBV should not exceed the CBV; in other words, any IBV should be within the cycle length of the CBV. Each proposed STA that receives the IBRF immediately resets its backoff value to its assigned IBV. Therefore, STAs that have a lower IBV can obtain more chances for transmission. As a result, priority control for each proposed

STA is enabled by adjusting the IBV appropriately. In addition, the IBRF is broadcasted when the initialization of pseudo-centralized control is desired; that is, when a new STA connects to the AP or a collision occurs.

Although it is possible for proposed STAs to maintain pseudo-centralized control without any IBRF if all the proposed STAs can detect collisions and autonomously reset their backoff values to their respective IBVs, this situation may cause unconformity in the backoff resulting from the hidden terminal problem. Therefore, it is preferable to broadcast an explicit IBRF to all the proposed STAs to eliminate this problem.

Furthermore, although the proposed method is aimed at use in a WDE, it can be utilized in a non-WDE. In order to maintain the basic operation of the proposed method a CBV is assigned without transmitting any data frame if there are no data to send in the queue of the proposed STA when the proposed STA obtains a chance for transmission. However, the overhead time due to unnecessary backoff degrade the throughput and delay characteristics. Therefore, if data transmissions occur sporadically, the proposed method can quit the pseudo-centralized operation and change to CSMA/CA. This hybrid operation can cope with the case where only a specific STA has much data to send as well.

3.3 Control of User-Oriented QoS

3.3.1 System-Level User-Oriented QoS (S-QoS)

We define the priority structure between the proposed method and the conventional DCF as the system level user-oriented QoS (S-QoS). The priority structure of each proposed STA is defined as the user level user-oriented QoS (U-QoS).

There are two methods to control the S-QoS. One is to expand the range of the CBV and the other is to adjust the IBV. First, we define some variables to express the effects of these two fixed backoff values. We assume that N STAs are connected to the AP and these STAs comprise both proposed and DCF STAs. In addition, the total number of the proposed STAs is assumed to be N_p and the total number of the DCF STAs is N_c. An individual STA number, n ($n = 1, 2 \ldots N$) is given to each STA. Therefore, the AP decides the IBVs and CBV for the proposed STAs in the range of the following formulas.

$$B_c \geq N \tag{3}$$

and

$$B_c \geq B_I(n) \tag{4}$$

In (3) and (4), B_c represents the shared CBV of all the proposed STAs and B_I (n) denotes the IBV of STA n.

The effect of expanding the range of CBV is described below. The total number of candidates for the backoff value of DCF STAs that avoid collisions is B_r and is calculated as follows.

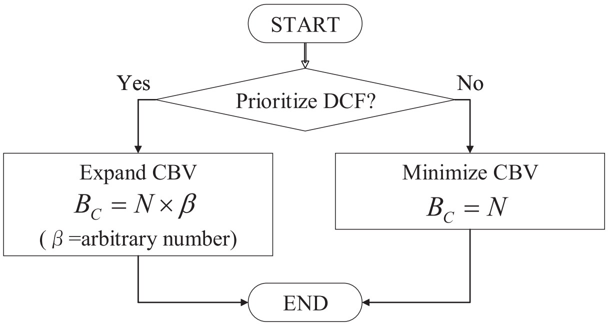


Fig. 6 Flowchart of S-QoS control (by CBV).

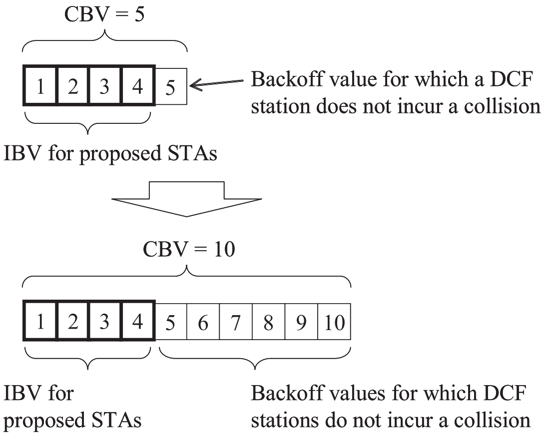


Fig. 7 Effect of expanding CBV.

$$B_r = B_c - N_P \tag{5}$$

According to (5), a larger B_c can increase B_r further. This means that the possibility of collision between the proposed STAs and DCF STAs is decreased and the DCF STAs obtain more chances for transmission in exchange for a reduction in the number of chances for transmission for the proposed STAs in proportion to B_c. Figure 6 shows the flowchart for the setting of CBV to control the S-QoS, and Fig. 7 shows an example of the effect of expanding CBV respectively. There are four proposed STAs ($N_p = 4$), one DCF STA ($N_c = 1$), and the total number of STAs is five ($N = 5$). If B_c is set to five (which, in this case, equals N), the proposed STAs receive a chance of transmission every five backoff slots if no collision occurs. This enables high-speed transmission for the proposed STAs. However, the transmission of the DCF STA collides with the transmission of the proposed STA with a probability of 4/5. If B_c is set to ten (which equals $N \times 2$), the collision probability of the DCF STA drops to 2/5 by means of degrading the efficiency and priority of the proposed STAs. In this case, the efficiency and priority of the DCF STAs are improved at the expense of the proposed STAs.

Next, we explain the method of controlling the S-QoS by adjusting IBV. Figure 8 illustrates the relationship between IBV and S-QoS. In addition, Fig. 9 shows the flowchart for the setting of IBV to control the S-QoS. As

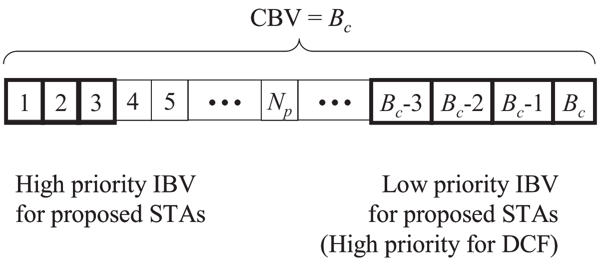


Fig. 8 Priority control by adjusting IBV.

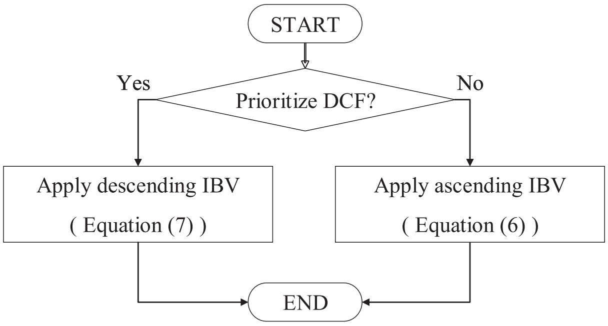


Fig. 9 Flowchart of S-QoS control (by IBV).

described in Sect. 3.2.2, a proposed STA with a lower IBV has a higher priority level. Thus, the method to assign the higher priority to the proposed STAs is to set each IBV in ascending order. Namely, each B_I (n) is assigned as follows.

$$B_I = \left\{ B_I(n) | B_I(n) = 1, 2, \cdots, N_p \right\} \tag{6}$$

In contrast, the method to prioritize DCF STAs is to set each IBV in descending order as expressed below.

$$B_I = \left\{ B_I(n) | B_I(n) = B_c, B_c - 1, \cdots, B_c - N_p + 1 \right\} \tag{7}$$

Therefore, control of the S-QoS is achieved through these two methods.

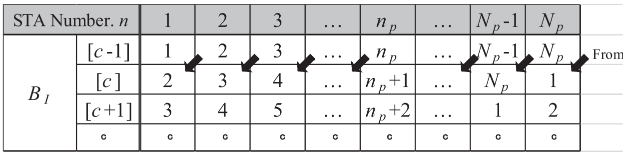
3.3.2 User-Level User-Oriented QoS (U-QoS)

The grade of the U-QoS depends on each IBV assigned to each proposed STA. For example, the allocation method in (6) divides the U-QoS into N_p classes (the same as the number of proposed STAs). Moreover, the proposed method classifies the U-QoS by arbitrary granularity. This is achieved by changing the IBV adaptively upon a collision. We assume that n_p is the individual STA number for the proposed STA and c is the number of collisions. Moreover, x represents the granularity of the U-QoS class. Then we set n_p as shown in (8) as an example.

$$n_p = 1, 2, \cdots, N_p \tag{8}$$

Therefore, the allocation method of the IBV that controls the U-QoS class between the proposed STAs is expressed as follows.

$$B_I(n_p)[c+1] = \begin{cases} B_I(n_p + x)[c] & \left(n_p + x \leq N_p\right) \\ B_I(n_p + x - N_p)[c] & \left(n_p + x > N_p\right) \end{cases} \tag{9}$$



STA Number. n		1	2	3	…	n_p	…	N_p-1	N_p	
B_I	$[c$-1]	1	2	3	…	n_p	…	N_p-1	N_p	From
	$[c]$	2	3	4	…	n_p+1	…	N_p	1	
	$[c$+1]	3	4	5	…	n_p+2	…	1	2	
	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	

Fig. 10 Assignment of IBV for user-oriented QoS (x = 1).

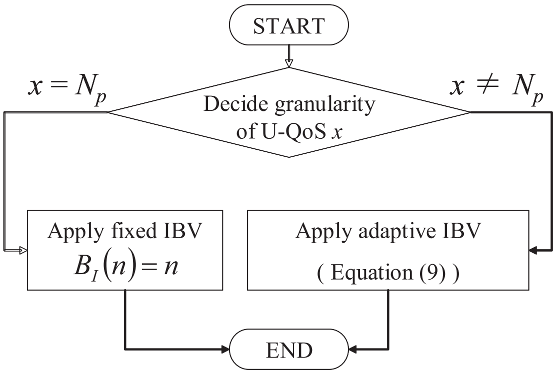


Fig. 11 Flowchart of U-QoS control (by IBV).

In (9), where B_I (n_p) $[c]$ is the IBV of the proposed STA whose number is n_p after c collisions. The IBV is assigned in turn among the proposed STAs. If x = 1, the priority of each proposed STA is removed. Figure 10 depicts an example of this operation and Fig. 11 shows the flowchart for the setting of the IBV to control U-QoS respectively.

In addition, individual U-QoS control for each STA is achieved by manually classifying groups of STAs for IBV rotation. We assume that g is the arbitrarily group number and it equals the priority rank. Each group g contains any number of STAs that is arbitrarily classified by the controller of the AP. The assignment of each IBV and its rotation rule are expressed below.

$$B_I(n_p)[c+1] = \begin{cases} B_I(n_p + 1)[c] & \left(n_p + 1 \leq n_{p(g,\max)}\right) \\ B_I(n_{p(g,\min)})[c] & \left(n_p + 1 > N_{p(g,\max)}\right) \end{cases} \tag{10}$$

where $n_{p(g,\max)}$ and $n_{p(g,\min)}$ are the maximum STA number and the minimum STA number that belong to group g, respectively. Therefore, the granularity of the U-QoS class is decided arbitrarily according to the classification number. Moreover, the priority levels of the proposed STAs that belong to the same group become the same although the difference in the priority level between each group remains. Thus, the priority level between proposed STAs (U-QoS) can be controlled by setting an appropriate IBV.

4. Performance Evaluation

To clarify the performance of the proposed method, we conducted computer simulations. First, we evaluated the maximum performance of the proposed method, DCF, and CSMA/ECA as introduced in [17]. Next, the impact of controlling the S-QoS was evaluated in an environment where the proposed and DCF STAs coexist. Finally, we verified

Table 1 Simulation parameters.

Parameter	Evaluation 1	Evaluation 2		Evaluation 3
		(i) IBV	(ii) CBV	
Number of STAs, N	1-50	50		
Proportion of proposed STAs, α	0 and 1	0 to 1	0.5	0.3
Transmission rate [Mbit/s]	54			
Data payload [byte]	1500			
Maximum retry	6			
SIFS [μs]	16			
DIFS [μs]	34			
Slot time [μs]	9			
Initial backoff value, $B_I(n)$ (Proposed only)	Equal to n		Equal to $n \times (1\text{-}5)$	Equal to n
Cyclic backoff value, $B_C(n)$ (Proposed only)	Equal to N		Equal to $N \times (1\text{-}5)$	Equal to N
CW_{min} (DCF, CSMA/ECA)	15			
CW_{max} (DCF, CSMA/ECA)	1023			
User-oriented QoS granularity x	1			1 and 5

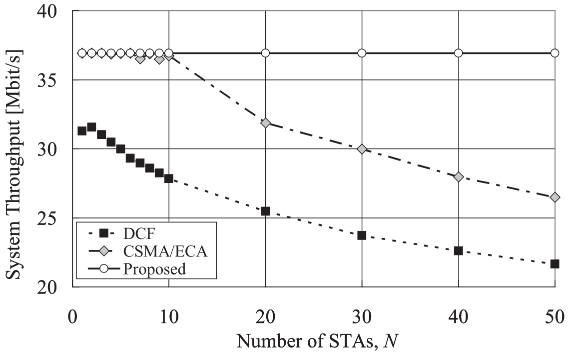


Fig. 12 System throughput vs. number of STAs.

whether or not the U-QoS can be protected in an environment where the proposed and DCF STAs coexist. The simulation parameters are listed in Table 1. Parameters such as the IFS and slot time comply with IEEE 802.11g. Moreover, these simulations were operated under saturation conditions, which mean that STAs always had data to send. Besides, these simulations were conducted with the simulation time of 20 s, and the results of these simulations are derived from the mean value of that period.

4.1 Evaluation 1: Maximum Performance

The evaluation of system throughput, average propagation delay and average number of retry attempts versus the number of STAs are discussed in this section. In this evaluation, it is assumed that all STAs obey a single method; in other words, only one type of STA exists. The system throughput represents the total throughput of N STAs. Figures 12 through 14 show the simulation results. In the environment with a few STAs, both CSMA/ECA and the proposed method improve throughput as compared to DCF. On the other hand, the effect of the improvement in CSMA/ECA is reduced according to the increase in the number of STAs. This is because CSMA/ECA adopts a random backoff after the first transmission or upon a collision. Therefore, a STA that applies a fixed backoff is forced to apply a random backoff for the next transmission due to a collision with a STA that applies a random backoff. This causes a chain of collisions. Especially if N exceeds CW, a collision is inevitable at the first transmission. Thus, the number of collisions is increased in proportion to the number of STAs.

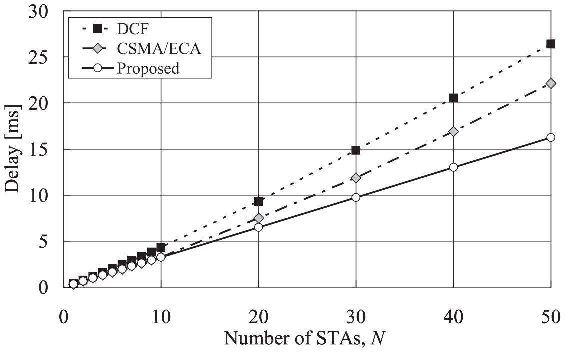


Fig. 13 Average propagation delay vs. number of STAs.

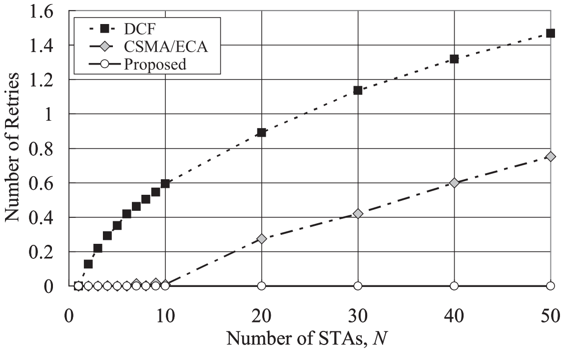


Fig. 14 Average retries vs. number of STAs.

Conversely, if there is no STA that applies random backoff, the proposed method avoids any collisions due to completely centralized operation. Thus, system throughput becomes constant regardless of N. In Fig. 12, the proposed method achieves a throughput level 70% higher than that for the DCF when N is 50, and a throughput level 40% higher than that for CSMA/ECA as well. Moreover, as shown in Fig. 13, while CSMA/ECA achieves a reduction of 20% compared to the DCF when N is 50, the proposed method reduces the propagation delay by 40% under the same conditions. Since the proposed method excludes any collision, the number of retry attempts of the proposed method becomes 0 regardless of N, as shown in Fig. 14. On the other hand, the number of retry attempts of CSMA/ECA is increased because of the chain of collisions described above when the number of STAs exceeds 20 (> CW_{min}). These results confirm the effect of collision avoidance of the proposed method and reduction in the overhead time due to pseudo-centralized control.

4.2 Evaluation 2: Performance in Environment with Coexisting Proposed and DCF STAs (Verification of S-QoS Control)

To verify the effect of controlling the priority level between the proposed method and DCF (S-QoS), we evaluated the average throughput characteristics. An environment where proposed STAs and DCF STAs coexist is assumed in this evaluation. We evaluated the average throughput of N_p for

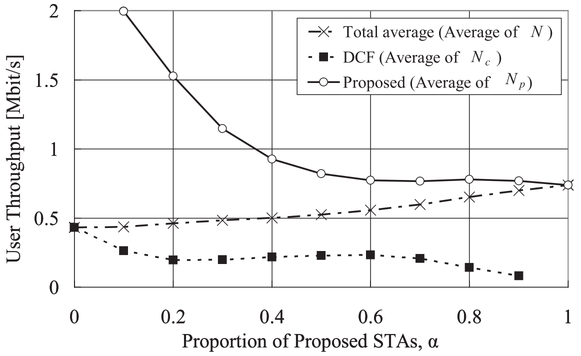


Fig. 15 Performance in coexistence environment (Proposed prioritization).

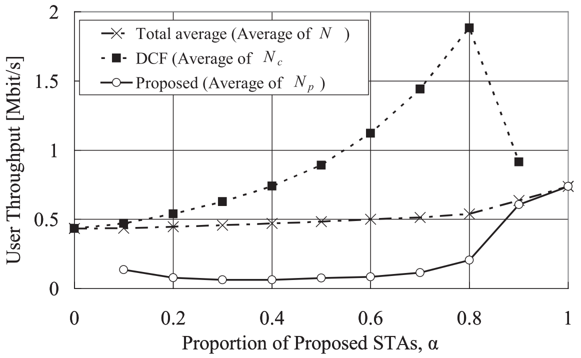


Fig. 16 Performance in coexistence environment (DCF prioritization).

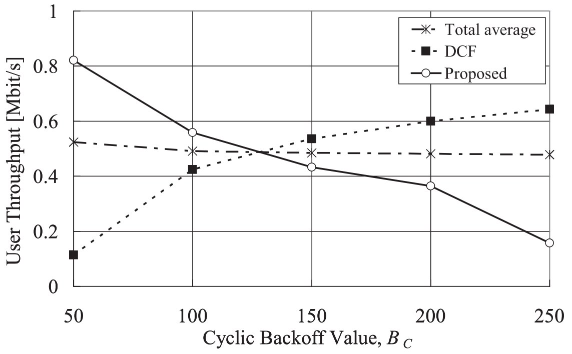


Fig. 17 S-QoS control using CBV.

proposed STAs and that of N_c for DCF STAs. The total average throughput of N is measured as well.

4.2.1 S-QoS Control Using IBV

To confirm the influence of IBV, we assign each IBV in ascending order and descending order, as expressed in (6) and (7), respectively. Figure 15 shows the simulation results when the proposed STAs are prioritized (ascending IBVs), and Fig. 16 shows the results when the DCF STAs are prioritized (descending IBVs). Hereafter, we define α as the ratio of proposed STAs to N. Terms N_p, N_c, and α have the following relationships.

$$N = N_p + N_c \tag{11}$$

$$N_p = N \times \alpha \tag{12}$$

According to the results shown in Fig. 15, the total average throughput of N is increased in proportion to α. For instance, when $\alpha = 0.3$, the throughput is approximately 10% higher than at $\alpha = 0$. This is because the probability of collision decreases for the entire system as the number of proposed STAs increases. At this time, the proposed STAs gain 160% higher throughput compared to the case where all STAs are DCF STAs (the case where the proposed method is not introduced). However, the DCF STAs suffer 50% lower throughput in this case as well. Similarly at $\alpha = 0.1$, the proposed STAs can obtain up to 300% higher throughput and the DCF STAs suffer 40% lower throughput. This is trade-off for setting a higher priority for the proposed STAs. As described in Sect. 3.3.1, the priority of the DCF STAs can be improved at the expense of the proposed STAs by setting larger IBVs. In addition, the average throughput of the proposed STAs is decreased in proportion to α. The reason for this is described hereafter. If there are only a few proposed STAs, each proposed STA is likely to collide with a DCF STA. As the proposed STAs reset their backoff value to the IBV when collision occurs, the proposed STAs obtain a chance for transmission by priority. On the other hand, if there are many proposed STAs, their average throughput decreases because all the proposed STAs have higher priority and must share a common resource.

In the case where the DCF STAs are given priority, the system throughput is approximately 5% higher at $\alpha = 0.3$ than at $\alpha = 0$, according to the results shown in Fig. 16. This implies that the improvement in the system throughput is lower than that in the case where the proposed STAs are given priority. The reason for this is that the number of chances for transmission for the proposed STAs is reduced and the effect of collision avoidance becomes smaller than that for the case in which the proposed STAs are given priority. At this time, the DCF STAs gain 40% higher throughput compared to the case in which all STAs are DCF STAs. On the other hand, the proposed STAs suffer 80% lower throughput in this case for the same reason described above.

4.2.2 S-QoS Control Using CBV

Next, to verify the impact of CBV on the S-QoS, we evaluated the average throughput of each method. In this evaluation, we fixed $\alpha = 0.5$ and arranged B_I (n) in ascending order, as expressed in (6) to give priority to the proposed STAs first. Then, we escalated B_c to gradually shift the priority to DCF STAs.

Figure 17 shows the simulation results. The results indicate that increasing the CBV can give priority to the DCF STAs while suppressing the deterioration of the system throughput. Specifically, the total average throughput of N is reduced by only 10% for $B_c = 250$, as compared to when $B_c = 50$ and the priority between the proposed STAs and DCF STAs becomes reversed.

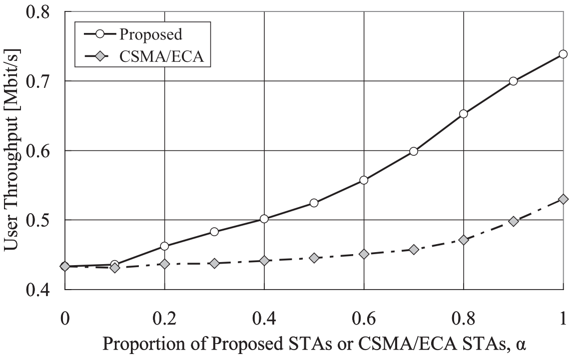


Fig. 18 Performance in coexistence environment (Proposed method vs. CSMA/ECA).

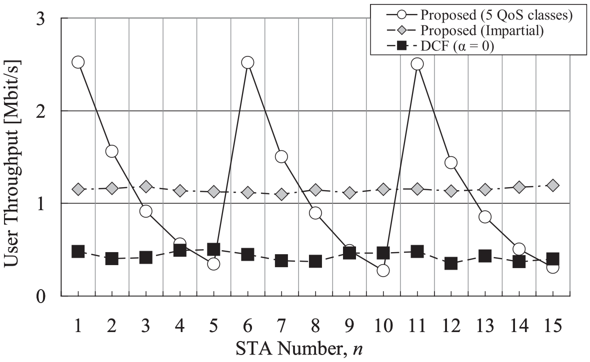


Fig. 19 U-QoS control using IBV.

4.2.3 Comparison with CSMA/ECA

This section describes a performance comparison between the proposed method and CSMA/ECA in an environment where proposed STAs and DCF STAs coexist.

Figure 18 shows the total average throughput of N versus α, which indicates the proportion of proposed STAs or CSMA/ECA STAs to N. According to the results in Fig. 18, the proposed method achieves better performance than CSMA/ECA at any α. This is because collisions between the proposed STAs are avoided by designating a fixed backoff. By contrast, collisions between CSMA/ECA STAs cannot be eliminated because of the random backoff, as described in Sect. 3.2.

4.3 Evaluation 3: Performance in Environment with Coexisting Proposed and DCF STAs (Verification of U-QoS Control)

In this section, the effect of controlling the U-QoS is evaluated. Each $B_I\ (n)$ is arranged in ascending order as expressed in (6), and two kinds of QoS classes are introduced. The classification of the QoS is executed according to (9); One experiment has five QoS classes ($x = 5$), and the other has no QoS classes ($x = 1$, impartial). In addition, we set $\alpha = 0.3$ and compared the case in which the proposed STAs are classified by QoS classes, and the case in which all STAs are DCF ($\alpha = 0$).

Figure 19 shows the throughput achieved by each STA. In Fig. 19, the STA number n_p, is represented on the horizontal axis. In the case of $x = 5$, the throughput characteristics are quantized to five QoS classes according to the results. In this simulation, the STAs numbered 1, 6, and 11 achieve the highest throughput. This is because the $B_I\ (n)$ values of these STAs change in the rotation into only three values, namely 1, 6 and 11, according to (9). The STAs that obtain the second highest throughput levels are numbers 2, 7, and 12, for the same reason described above. The $B_I\ (n)$ of these STAs also holds only three values. Moreover, the rest of the STAs comply in the same manner and are classified into each QoS class.

In addition, the results indicate that the throughput characteristic become equal in the case of $x = 1$. In this case, each $B_I\ (n)$ value from all the proposed STAs was assigned from 1 to 15 in turn to eliminate the difference in priority among the proposed STAs. Moreover, the throughput of all the proposed STAs is superior to that of the DCF STA. Therefore, we clarified that the U-QoS control is achieved by setting an appropriate IBV in turn.

5. Conclusion

In this paper, we proposed a pseudo-centralized control method based on CSMA/CA. The proposed method suppresses collisions between proposed STAs, improves the throughput characteristics and shortens the propagation delay. Moreover, the proposed method controls the user-oriented QoS by setting two kinds of fixed backoff values, namely, the IBV and CBV. If a low number is assigned to the IBV, the priority of the proposed STA increases, and vice versa. Conversely, increasing the CBV increases the priority level of the DCF STAs. In addition, the granularity of the user-oriented QoS classes can be specified by setting the appropriate IBVs. These effects are verified through computer simulations. Thus, the proposed method is highly effective in protecting the user-oriented QoS in a congested situation with many WLAN STAs. The results of computer simulations showed that the proposed method can achieve up to over 300% higher user throughput, compared to the case in which the proposed method is not introduced under the coexistence environment with DCF STAs. In addition, all the proposed STAs achieved 70% higher throughput than the DCF STAs under a non-coexistence environment.

Future research will include negotiation with neighbor-proposed APs and assignment of adequate IBVs by considering STAs connected to the neighboring APs. Moreover, although we are convinced that the hidden terminal problem can be overcome by using the Request-To-Send (RTS)/ Clear-To-Send (CTS) procedure in the proposed method, evaluations considering the problem should be introduced analytically in future research because unconformity in the IBV for proposed STAs breaks the pseudo-centralized control and degrades the throughput characteristics.

We consider that the proposed method can be improved to enable control of not only user-oriented QoS but also application-oriented QoS. In future research, we plan to investigate in detail the queuing mechanism to achieve application-oriented QoS control.

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Akira Kishida received the B.E. and M.E. degrees from Tokyo University of Agriculture and Technology, Tokyo, Japan, in 2005 and 2007, respectively. In 2007, he joined NTT Access Network Service Systems Laboratories, Nippon Telegraph and Telephone Corporation (NTT), in Japan. He is engaged in the research of MAC protocol for wireless LAN systems. His current research interests include the design and analysis of high efficient transmission protocol in a congested situation with many wireless LAN stations. He received the IEICE Young Researcher's Award in 2010.

Masashi Iwabuchi received the B.E. and M.E. degrees from Tokyo Institute of Technology, Tokyo, Japan, in 2008 and 2010, respectively. In 2010, he joined NTT Access Network Service Systems Laboratories, Nippon Telegraph and Telephone Corporation (NTT), in Japan. He is engaged in the research of MAC protocol for distributed wireless networks. His current research interests include establishment of multiplication for transmission by using both MAC and PHY cross-layer approach.

Toshiyuki Shintaku received the B.E. degrees from Tokyo University of Science, Tokyo, Japan, in 1997. In 1997, he joined Nippon Telegraph and Telephone Corporation (NTT), in Japan. He is engaged in the development for wireless LAN systems. His current research covers QoS control, reliability, and networking for wireless LAN systems.

Tetsu Sakata received the B.E. and M.E. degrees from Kyoto Institute of Technology, Kyoto, Japan, in 1986 and 1988, respectively. In 1988, he joined NTT Radio Communication Systems Laboratories, Nippon Telegraph and Telephone Corporation (NTT), in Japan. Since then he has been engaged in research and development of wireless LAN systems, digital modems, transmission power control system, and digital LSIs for satellite communications and personal communications. He is currently a Senior Research Engineer of Wireless Access Systems Project, NTT Access Network Service Systems Laboratories. He is a member of IEEE.

Takefumi Hiraguri received the M.E. and Ph.D. degree from the University of Tsukuba, Ibaraki, Japan, in 1999 and 2008, respectively. In 1999, he joined the NTT Access Network Service Systems Laboratories, Nippon Telegraph and Telephone Corporation in Japan. He has been engaged in research and development of MAC protocol for the high speed and the high communication quality in wireless LANs systems. He is now associate professor in Nippon Institute of Technology. He is a member of IEEE.

Kentaro Nishimori received the B.E., M.E. and Ph.D. degrees in electrical and computer engineering form Nagoya Institute of Technology, Nagoya, Japan in 1994, 1996 and 2003, respectively. In 1996, he joined the NTT Wireless Systems Laboratories, Nippon Telegraph and Telephone Corporation (NTT), in Japan. He was senior research engineer on NTT Network Innovation Laboratories. He is now associate professor in Niigata University. He was a visiting researcher at the Center for Teleinfrastructure (CTIF), Aalborg University, Aalborg, Denmark from Feb. 2006 to Jan. 2007. He was an Associate Editor for the Transactions on Communications for the IEICE Communications Society from May 2007 to May 2010 and Assistant Secretary of Technical Committee on Antennas and Propagation of IEICE from June 2008 to May 2010. He received the Young Engineers Award from the IEICE of Japan in 2001, Young Engineer Award from IEEE AP-S Japan Chapter in 2001, Best Paper Award of Software Radio Society in 2007 and Distinguished Service Award from the IEICE Communications Society in 2005, 2008 and 2010. His main interests are spatial signal processing including MIMO systems and interference management techniques in heterogeneous networks. He is a member of IEEE. He received IEICE Best Paper Award in 2010.