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A Priority Control Method for Media Access Control Method SP-MAC to Improve Throughput of Bidirectional Flows**

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SUMMARY In IEEE802.11 Wireless Local Area Networks (WLANs), frame collisions occur drastically when the number of wireless terminals connecting to the same Access Point (AP) increases. It causes the decrease of the total throughput of all terminals. To solve this issue, the authors have proposed a new media access control (MAC) method, Synchronized Phase MAC (SP-MAC), based on the synchronization phenomena of coupled oscillators. We have addressed the network environment in which only uplink flows from the wireless terminal to an AP exist. However, it is necessary to take into consideration of the real network environment in which uplink and downlink flows are generated simultaneously. If many bidirectional data flows exist in the WLAN, the AP receives many frames from both uplink and downlink by collision avoidance of SP-MAC. As a result, the total throughput decreases by buffer overflow in the AP. In this paper, we propose a priority control method based on SP-MAC for avoiding the buffer overflow in the AP under the bidirectional environment. Also, we show that the proposed method has an effect for improving buffer overflow in the AP and total throughput by the simulation.

key words: *wireless LAN, media access control, synchronization phenomena of coupled oscillators, Kuramoto-model, priority*

1. Introduction

Wireless Local Area Networks (WLANs) has been increased because it can be introduced at lower costs compared to wired LANs as they can be configured without hard-wiring between terminals and Access Points (APs). Furthermore, the terminals in the transmission area of the AP can access the Internet regardless of their location if APs have access to the Internet. Moreover, network devises (smartphones, laptops, tablets, etc.) have been spreading explosively and various applications are communicated over the WLAN. So far, the Internet access services via WLANs was typically unidirectional (client/server model) such as an e-mail, web-browsing. With the advent of highly functional network devises and various network services, however, many users have come to be able to use bidirectional (i.e., concurrence of UpLink (UL) and DownLink (DL) flows) network services, such as cloud services (Dropbox [2], Microsoft OneDrive [3], etc.) and IP telephones based on Voice over Internet Protocol (VoIP).

In order to improve the utilization efficiency for bidirectional network services in WLANs, various studies have proposed solutions. [4] proposed a new bidirectional data transfer method to improve the network performance over multi-rate WLANs environment, and [5] described an analytic model to understand the performance of the bidirectional Media Access Control (MAC) frame aggregation. [6] showed the bidirectional MAC protocol for cognitive radio network and showed its protocol increased the network goodput by simulation results. In [7], network performances (throughput, congestion level) were investigated in multi-channel MAC protocol with bidirectional flow control. Here, the unfairness of the transmission opportunity between UL and DL flow has been pointed out for the network environment with the bidirectional flows in the WLAN [8]: UL flows can obtain significantly greater throughput than the competing DL flows. Some studies [9]–[14] evaluated the method to solve the unfairness between UL and DL flow.

One of the issue of the WLAN is an improvement of utilization efficiency for the bandwidth. That is, to propose an efficient MAC protocol is important issue. One of the famous WLAN standards is IEEE 802.11 [15], which refers to the existing MAC and PHYsical (PHY) layer functions. Generally, IEEE802.11 uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) for a MAC method. In CSMA/CA, however, when the number of terminals connected to the same AP increases, data frame collisions often occur among the terminals [16]. It causes the degradation of the total throughput of all terminals (utilization efficiency for the bandwidth). To improve the total throughput of terminals by avoiding data frame collisions, a novel MAC method, Synchronized Phase MAC (SP-MAC) [17]–[19], based on the synchronization phenomena of coupled oscillators [20] has been proposed. [17]–[19] have showed that SP-MAC can improve the total throughput by reducing data frame collisions drastically. Note that previous studies [17]–[19] used the network model that receivers are connected to the router via wired LAN.

However, the characteristics of SP-MAC in multiple bidirectional communication environment are unclear. This is because [17]–[19] considered the network environment in which only UL flows exist. Here, in multiple

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bidirectional communication environment, wireless terminals send data to an AP, and vice versa. This shows that data from/to the wireless terminals go through the AP. Moreover, there is a possibility that the AP occurs buffer overflow by many data arrived from each link. Here, from the characteristic of SP-MAC, each of the wireless terminals obtains the same transmission opportunity as the AP [17]. In other word, the AP has only the same channel resource as one of the wireless terminals. On the other hand, the wireless terminals send data to the AP efficiently by collision avoidance of SP-MAC. Thus, in original SP-MAC, the AP receives many data from the wireless terminals. Therefore, under the above situation, we expect that the buffer overflow in the AP occurs easier than CSMA/CA. For specific examples, when the number of the wireless terminals is 20, a channel resource of WLAN is shared by 20 wireless terminals and an AP. If transmission opportunity among nodes which include the wireless terminals and the AP is fair, the AP uses a channel resource as one terminal. Similarly, each of the wireless terminals uses the channel resource as one terminal. Here, the AP not only receives from 20 wireless terminals but also sends to 20 wireless terminals. This shows that the AP cannot transmit data sufficiently without using the channel resource equivalent to 20 wireless terminals. However, because the AP does not actually have the channel resource equivalent to 20 wireless terminals, the buffer overflow in the AP occurs easier than CSMA/CA. From the above reason, we must reduce the buffer overflow in the AP. Note that SP-MAC has a remarkable potential ability to restrain for data frame collisions which is one of reasons for decrease of a total throughput in the WLAN [17]–[19]. On multiple bidirectional communication environment in the WLAN, not only the buffer overflows in the AP but also the data frame collisions must be solved. Thus, this paper is to enhance for original SP-MAC.

In order to achieve the above objective, this paper proposes a priority control method based on SP-MAC for avoiding the buffer overflow under the bidirectional communication environment. Note that this paper assumes that receivers in the network are connected to the AP. Next, in order to clarify the effectiveness of the proposal, this paper compares the performance between the proposal and previous methods including CSMA/CA (typical contention based MAC protocol) and original SP-MAC (previous proposal).

In summary, the technical challenge of this paper is to add the priority control mechanism that the terminal increases/decreases transmission opportunity of the data frame to original SP-MAC. In addition, the academic contribution of this paper is to reduce not only the data frame collisions but also the buffer overflow in the AP by the proposed priority control of SP-MAC for improving the total throughput.

2. Related Works

In this section, we present an overview of CSMA/CA and the synchronization phenomena of coupled oscillators by which our proposed method is inspired.

2.1 CSMA/CA

CSMA/CA is a MAC protocol for IEEE802.11 WLANs. In CSMA/CA, each wireless terminal individually determines the timing of data transmission, and if a channel becomes idle when a data frame arrives in the transmission queue, it defers to Distributed coordination function Inter Frame Space (DIFS) time. Then, if the channel remains idle after DIFS, CSMA/CA waits for the back-off time, which is randomly calculated using a Contention Window (CW). Subsequently, if the channel remains idle after the back-off time, the terminal sends the data frame. The back-off time is determined using Eq. (1), which is independently calculated by each terminal.

$$\text{Backoff} = \mathit{Random}() \times \text{SlotTime}. \tag{1}$$

In Eq. (1), *Random*() and SlotTime indicate a random integer derived from a discrete uniform distribution [0, CW] and the slot time interval specified in IEEE 802.11, respectively. At this point, the initial CW is set to CW_{min}. If a collision causes the data frame transmission to fail, then the terminal again sets the back-off time using Eq. (1). In this case, the CW becomes twice the previous value, and the upper bound is CW_{max}. If the retransmission exceeds the maximum retry limit (usually seven), the terminal discards the data frame.

Here, CSMA/CA is designed to achieve that all terminals connected to the AP can obtain the transmission opportunity fairly. Thus, APs access the channel with the same priority as wireless terminals in the WLANs, even if APs aggregate several DL flows. It leads to unfairness between UL and DL flows. For example, let assume an AP aggregates μ DL flows and the AP connects ν wireless terminals. If the traffic is saturated, the available bandwidth is shared equally among terminals. Therefore, the throughput of an UL flow is μ times as large as that of a DL flow [8].

2.2 Synchronization Phenomena of Coupled Oscillators

Synchronization is the phenomena caused by multiple oscillators with different periods transform incoherent rhythms into synchronized ones with each interaction. These phenomena are also observed in nature such as the synchronous flashing of fireflies [21] and the synchronization of metronomes [22]. These synchronized oscillators are called coupled oscillators. During the synchronization, the phase differences and frequencies of all the coupled oscillators converge at certain values. Several studies [20], [23]–[25] discuss the synchronization phenomena, and have proposed mathematical models for these phenomena. One of the typical models is the *Kuramoto model* [20]. In this paper, we explain the synchronization of N coupled oscillators using the Kuramoto model.

In the Kuramoto model, the i-th oscillator runs independently at its own natural frequency ω_i and interacts with all others. Then, the i-th oscillator's phase θ_i ($0 < \theta \leq 2\pi$) is calculated using Eq. (2).

$$\frac{d\theta_i}{dt} = \omega_i + \frac{K}{N}\sum_{j=1}^{N}\sin(\theta_j - \theta_i) \quad (i = 1, 2, \cdots, N). \tag{2}$$

In Eq. (2), K (> 0) indicates coupling strength and the second term is an interaction term. Note that the interaction term is standardized by K/N to be independent of system size N. The occurrence conditions of synchronization phenomena have been discussed in [20].

3. SP-MAC: Media Access Control Method Based on the Synchronization Phenomena of Coupled Oscillators

This section gives an overview of our SP-MAC and the problem of SP-MAC when bidirectional flows exist.

3.1 Overview of SP-MAC

SP-MAC uses the synchronized phase with phase shifting based on Eq. (2) to set the back-off time rather than using a random integer in CSMA/CA. Here, we explain the purpose of using the synchronized phases with phase shifting. Figure 1 shows an example of cosine curves that result when four oscillators synchronize with phase shifting. Each cosine curve indicates the phase of each oscillator. When all the oscillators synchronize with phase shifting, each oscillator has a different $\cos\theta_i(t)$ at time t. After a certain time Δt passes ($t + \Delta t$), the relationship of $\cos\theta_i(t)$ changes; for example, $\cos\theta_1(t) > \cos\theta_4(t)$ and $\cos\theta_1(t+\Delta t) < \cos\theta_4(t+\Delta t)$. Therefore, it is expected that SP-MAC can avoid the overlap of back-off time among terminals using these synchronized phases with phase shifting. Also, SP-MAC assigns the transmission opportunity fairly to each terminal, because the terminal which obtains the transmission opportunity changes according to the time evolution. In this paper, SP-MAC sets the following preconditions:

- The number of wireless terminals does not change after data transmission begins.
- The AP and all wireless terminals do not move.
- The AP and all wireless terminals do not use the RTS/CTS function.
- The AP and all wireless terminals implement SP-MAC.

Note that the behavior between SP-MAC and CSMA/CA differs only in the calculation of the back-off time of terminals.

In SP-MAC, the AP determines the natural frequency ω_i (i is a node ID) and coupling strength K that satisfy the synchronizing condition according to N_c prior to starting transmission. Note that N_c is the number of connectable terminals for the AP. To satisfy the condition that each oscillator synchronizes with phase shifting, SP-MAC adopts a different ω_i for each wireless terminal (i.e., no overlap occurs among all ω_i). Next, the AP sets an ID i ($1 \leq i \leq N_c$) for each wireless terminal and applies ω_i and an initial phase

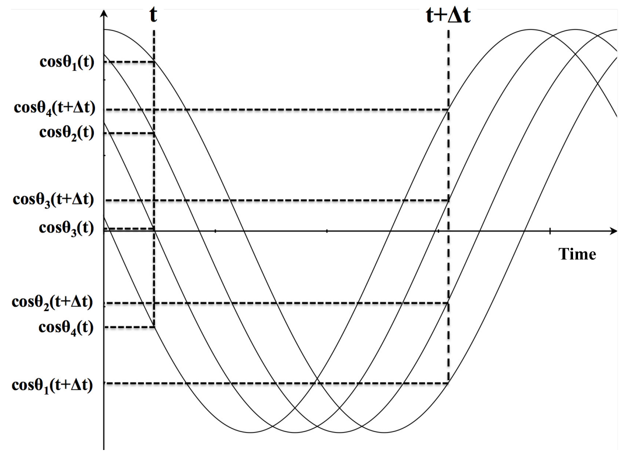

Fig. 1 Example: cosine curves of synchronized oscillators with phase shifting.

$\theta_i(0)$ to the i-th wireless terminal. Each initial phase $\theta_i(0)$ has a different value to avoid collision at the beginning of the data transmission. Then, using a beacon, the AP sends the control parameters i, $\theta_i(0)$, ω_i, K, a control interval Δt, and N_c for all wireless terminals. After receiving the beacon, each wireless terminal immediately begins calculation of the phase using the control parameters. Next, the wireless terminal calculates the phase $\theta_i(t)$ for all ID i using Eq. (2) for every Δt. The calculation of the phase continues while the terminal connects to the AP, even if no transmission data exist. When the wireless terminal wants to send a data frame at time t, it calculates the back-off time (Backoff) using Eq. (3) and phase $\theta_i(t)$ for each ID i. Then, the wireless terminal sends the data frame in the same manner as CSMA/CA. Here, about a oscillator i and other oscillator j, when the value $\cos\theta_i(t)$ equals to the value $\cos\theta_j(t)$, data frame collisions occur. However, [17] shows that the data frame collisions of SP-MAC are sufficiently lower than that of CSMA/CA. Also, because [17] confirmed that the collision by the situation is rare case, the throughput degradation is negligible. If the wireless terminal detects data frame collisions, it calculates a new back-off time using Eq. (3) and the phase parameter at the time when the sender retransmits.

$$\text{Backoff} = ((|\cos\theta_i(t)| \times \alpha) \bmod N_c) \times \text{SlotTime}. \tag{3}$$

In Eq. (3), slot time and α are the slot time interval specified in IEEE 802.11 and a coefficient to obtain the normalized phase, respectively. Note that α is set to 100 [17] because of setting the time scale of the back-off time equal to the one used with the CSMA/CA. Here, because SP-MAC is based on the original CSMA/CA (i.e., only the calculation of back-off time at the wireless terminal is different), it can be used for an environment where both the SP-MAC terminals and the original CSMA/CA terminals exist [18]. Also, the term modN_c sets the back-off time based on the number of terminals. Here, N_c is independent of α. This calculation part contributes to efficient determination of the back-off time and marked improvement of the total throughput.

Next, we discuss a problem of SP-MAC in a WLAN environment with bidirectional flows. [17]–[19] showed that SP-MAC can avoid the data frame collisions drastically under the network environment with only UL flows. If bidirectional flows exist in the WLANs, the AP receives many data frames from both UL senders and DL senders. As mentioned above, SP-MAC is implemented in not only wireless terminals but also the AP. In this situation, the transmission opportunity of the AP is same as that of terminals in SP-MAC because of the characteristics of SP-MAC although the AP must relay the multiple flows. Thus, we expect the buffer overflow occurs more significantly. In case that a terminal uses TCP as the transport protocol, a continuous TCP-ACK segment losses is a serious problem because it causes the degradation of the total throughput drastically. In order to address this problem, it is necessary to propose a priority control method that gives the high transmission opportunity for the AP and avoids occurrence of the buffer overflow in the AP. In next section, we explain our proposed priority control method for AP.

4. Priority Control Method for AP Based on SP-MAC

This section proposes a priority control method for the AP based on SP-MAC to deal with the problem (see Sect. 3) of the original SP-MAC with directional flows. Advantage of our priority control method is that extension of the original SP-MAC is very simple and the AP can get higher transmission opportunity compared with wireless terminals: we add a new parameter amplitude (*Amp*) related with the maximum back-off time for SP-MAC. Note that *Amp* is a real number. In the proposed method, the back-off time is calculated by

$$\text{Backoff} = ((|\cos\theta_i(t)|\times\alpha) \bmod N_c)\times Amp\times \text{SlotTime}. \quad (4)$$

From Eq. (3) and Eq. (4), the proposed method is the same as the original SP-MAC if *Amp* is equal to 1. As the value of *Amp* is smaller (or larger) than 1, on the other hand, the range of the back-off time (i.e., the difference between the maximum back-off time and minimum back-off time) is smaller (or larger) than that of original SP-MAC. If we set the smaller value as *Amp* of the back-off time calculation implemented in the AP, we expect that the AP can preferentially send data frames compared with the wireless terminals. As a result, the total throughput of all wireless terminals can be improved significantly owing to reduction of the buffer overflow in the AP.

5. Evaluation

In this section, we evaluate characteristics of our proposal, comparing with the original SP-MAC and CSMA/CA by using network simulator ns2 [26]. Moreover, we discuss the effectiveness of our priority control method for network performance from simulation results.

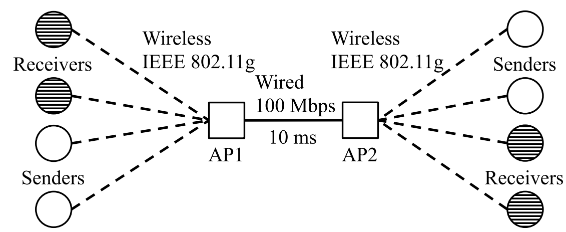

Fig. 2 Network model for the evaluation.

Table 1 The protocols for each layer.

Application	CBR (30Mbps), FTP
Transport	UDP, CUBIC-TCP
MAC	CSMA/CA, original SP-MAC, Proposal

5.1 Simulation Environment

Firstly, we explain a simulation environment. Figure 2 shows the simulation model: this network used IEEE802.11g (PHY) [27] for the wireless LAN environment, and all wireless terminals and APs implement SP-MAC. The propagation model is Two-ray ground reflection model. We assumed that none of the terminals were moved. To avoid the exposed node problem, in Fig. 2, AP1 gets enough distance from AP2. Each sender generates a single flow. The senders connected to AP1 and AP2 send data to the receivers connected to AP2 and AP1, respectively. The number of flows for each direction is equal. For example, when the number of flows is 10, each AP has 5 senders and 5 receivers. Also, Table 1 shows the remaining protocols for each layer.

Note that we consider UDP and TCP as the transport protocols. For UDP, the application protocol is Constant Bit Rate (CBR 30 Mbps), and for TCP, it is File Transfer Protocol (FTP). In these applications, the segment size is 1000 bytes. The TCP version is CUBIC-TCP [28], which is the standard for Linux and Android OS.

In this simulation, the number of flows (nodes) is varied from 10 to 40 and simulation time is 60 sec. In SP-MAC, the initial phase of the *i*-th terminal $\theta_i(0)$ and natural frequency ω_i were set to non-overlapped values in the ranges $(0, 1.0)$ and $[0, 2.0]$, respectively. Also, *Amp* for all APs is changed from 0.01 to 1 in Eq. (4). *Amp* for all terminals are set with $Amp = 1$ in Eq. (4). Here, once *Amp* is set, it is not changed during the simulation period. Then, we set the coupling strength K to $4\pi^{-1} + 1$ [1] in order to generate the synchronized phenomena [20]. The control interval Δt is set to 10 ms. We set the parameter of Eq. (3) N_c to 100. Note that the purpose of this study is to investigate whether SP-MAC can be applied to an environment in which bidirectional flows exist. Therefore, we consider an evaluation under a simple environment where the number of terminals is fixed for the passage of time. Thus, in this study, we set the parameter N_c to 100 under the consideration of the new entries of terminals. Also, a previous work [19] shows the characteristics at the environment when the N_c set to 100.

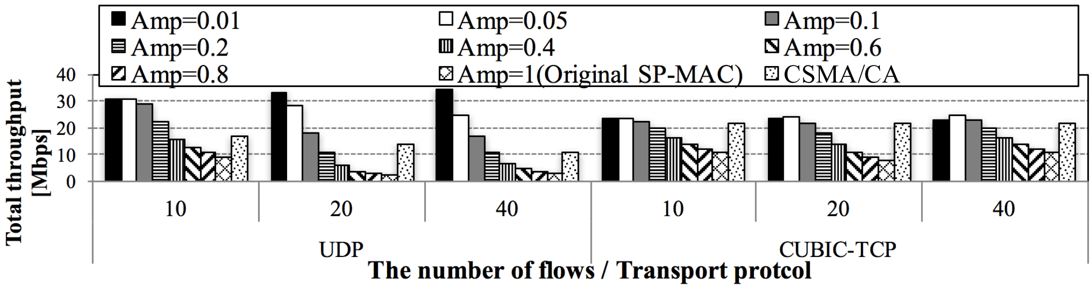

Fig. 3 Total throughput for each *Amp* value and number of flows.

5.2 Evaluation Results

This section shows a relationship between the performance of proposal and *Amp*.

5.2.1 Total Throughput of Terminals for Parameter *Amp*

Figure 3 shows the relationship between total throughput and each value of *Amp* when the number of flows is 10, 20 or 40. In this figure, the result for CSMA/CA and original SP-MAC (i.e., *Amp* is 1) is also described for reference. The left half and right half part in the figure denote results for UDP and CUBIC-TCP, respectively.

From Fig. 3, the trend of the total throughput is similar to one another regardless of the transport protocol and the number of flows: the total throughput of original SP-MAC is rather smaller than that of CSMA/CA, and the total throughput becomes larger as parameter *Amp* becomes smaller. These results mean that the original SP-MAC is totally useless under the network environment in which the bidirectional flows exist and it is necessary to modify the original SP-MAC in order to improve the total throughput. If the value of *Amp* of our priority control method is very small 0.01, the total throughput increases significantly compared with that of the original SP-MAC and CSMA/CA. Here, let us have the numerical discussion for our priority control method: we found that the total throughput of priority SP-MAC ($Amp = 0.01$) for UDP and CUBIC-TCP increased by approximately 30 Mbps and 17 Mbps, respectively, compared with original SP-MAC when number of flows is 40. Compared with CSMA/CA, on the other hand, the total throughput of priority SP-MAC ($Amp = 0.01$) for UDP and CUBIC-TCP increased by approximately 24 Mbps and 5 Mbps, respectively. Thus, we confirmed that to apply the smaller *Amp* to the back-off time calculation of the AP leads to great improvement of the total throughput.

5.2.2 Number of Data Frame Collisions for Parameter *Amp*

Table 2 and Table 3 show the relationship between each *Amp* and the number of data frame collisions for UDP and CUBIC-TCP, respectively. In this evaluation, we focus on the result of CSMA/CA, Original SP-MAC ($Amp = 1$), and our proposal when *Amp* is equal to 0.01. Here, the data frame collisions include the collisions of TCP-ACK as well as Data segment of TCP (TCP-Data). These results show that original SP-MAC can reduce data frame collisions more effectively than CSMA/CA. Therefore, the drastic degradation of the total throughput for original SP-MAC is not caused by data frame collisions. We can see from Table 2 that the number of collisions has a nearly same value for various values of *Amp* in the case of UDP. From Table 3, on the other hand, the smaller the value of *Amp* is, the larger the number of collisions for the CUBIC-TCP flows becomes, that is, this result has an opposite aspect for results of Fig. 3. It means that a petty increase of data frame collisions does not affect the total throughput. In any case, the number of collisions for SP-MAC is negligibly small (several tens) as compared with one (from 10^4 to 10^6) for CSMA/CA. Therefore, our priority control method maintains the advantage of the original SP-MAC which is an effective avoidance of data frame collisions using the synchronization phase.

Table 2 Number of data frame collisions for each number of flows (UDP).

\ *Amp* The number of flows	0.01	1.0 (Ori. SP-MAC)	CSMA/CA
10	1	2	94417
20	5	6	154212
40	20	24	223653

Table 3 Number of data frame collisions for each number of flows (CUBIC-TCP).

\ *Amp* The number of flows	0.01	1.0 (Ori. SP-MAC)	CSMA/CA
10	19	0	15696
20	40	1	19517
40	62	8	21379

5.2.3 Number of Dropped Packets by Buffer Overflow in APs

Firstly, we show the relationship between each value of parameter *Amp* and the number of dropped packets by buffer overflow in both APs. Table 4 and Table 5 denote results for UDP and CUBIC-TCP, respectively. Firstly, when comparing original SP-MAC with CSMA/CA using UDP for

Table 4 Number of dropped packets for each number of flows (UDP).

\ *Amp* The number of flows	0.01	1.0 (Ori. SP-MAC)	CSMA/CA
10	0	289322	183209
20	0	443801	205661
40	0	460883	210716

Table 5 Number of dropped packets for each number of flows (CUBIC-TCP).

\ *Amp* The number of flows	0.01	1.0 (Ori. SP-MAC)	CSMA/CA
10	0	1613	3434
20	0	1585	3801
40	1	5168	5231

the transport protocol, we can see from results of Table 4 that the number of dropped packets by buffer overflow with original SP-MAC is approximately twice that of CSMA/CA. This is because original SP-MAC avoids data frame collisions effectively even when bidirectional flows exist, as a result, the APs receive many more data packets in comparison with CSMA/CA. Furthermore, because original SP-MAC provides a same communication opportunity for each terminal and the APs, the buffer overflow occurs frequently in the APs and the throughput of original SP-MAC is decreased drastically. From Table 5, on the other hand, when the terminals use CUBIC-TCP, the number of dropped packets by buffer overflows of original SP-MAC becomes about a half of or equal to that of CSMA/CA, because the congestion control of CUBIC-TCP regulates the amount of transmitted data to avoid buffer overflow. Therefore, for CUBIC-TCP, the direct cause of the throughput degradation of original SP-MAC is not the occurrence of buffer overflow.

Secondly, we discuss results comparing our priority control method ($Amp = 0.01$) with the original SP-MAC ($Amp = 1$). From Fig. 3, the total throughput of all terminal can be maximized when Amp is 0.01. When the terminals use UDP, the smaller the number of dropped packets by buffer overflow becomes, the smaller the value of Amp becomes. Especially, when Amp is equal to 0.01, there is no dropped packets. Furthermore, for CUBIC-TCP, the number of dropped packets by buffer overflows in case Amp is equal to 0.01 is 0 or 1 that is very small compared with original SP-MAC ($Amp = 1$), because the transmission opportunity of the AP has increased by the priority control. Thus, the total throughput of all terminals increases drastically, when our priority control uses smaller Amp that is equal to 0.01.

5.2.4 The Fairness Among Flows from the Point of View of Segment Types

In this section, we clarify the relationship between the buffer overflow of APs and the fairness among flows while giving the details of the number of dropped packets by buffer overflows for segment types.

Table 6 shows the number of the dropped packets for each segment type (TCP-Data and TCP-ACK), when the number of flows is 10, 20 and 40. We can see from this table that the number of the dropped TCP-ACK is about three times larger than one of TCP-Data for CSMA/CA and original SP-MAC in case the number of flows is 10. This is caused by the unfairness of transmission rate between APs in the presence of the bidirectional flows.

Table 6 The number of TCP-ACK and TCP-Data segments which overflowed the buffer of APs.

The number of flows	Segment types	MAC protocol		
		Proposal (Amp = 0.01)	Ori.SP-MAC (Amp = 1.0)	CSMA/CA
10	TCP-Data	0	489	616
	TCP-ACK	0	1124	2817
20	TCP-Data	0	1026	1085
	TCP-ACK	0	559	2716
40	TCP-Data	0	2496	2355
	TCP-ACK	0	2671	2876

Here, we explain the reason why the unfairness between APs occurs, considering the case that congestion control operates in each terminal, when bidirectional flows exist. We assume that the congestion window size of some terminal is increasing gradually and the transmission rate becomes larger. Let AP1 be the AP that connects the terminal, and AP2 be the other AP that is a relay point.

AP2 sends frequently to receivers the TCP-Data which AP2 has received from AP1. The transmission rate of senders which connects to AP2 cannot increase, because AP2 is engaged in sending the data which is received from AP1. The difference for the transmission rate of terminals which connects to AP1 or AP2 leads to the difference of transmission rate between APs. Thus, the difference of transmission rate between APs cause the bias of the transmission frequency of TCP-ACK from receivers. When bidirectional flows exist, in order to eliminate the unfairness of the transmission rate between APs, it is necessary to equalize the amount of the transmission data per a unit time between the UL and the DL. The difference of the amount of transmission data per a unit time between the UL and the DL depends on the MAC method. In case of CSMA/CA, the backoff time increases according to increase of the value of CW when the transmission fails. Therefore, when some terminal transmits data at high frequency, the backoff time of the AP which connects to the terminal becomes larger than that of the given terminal, as a result, the difference of the amount of transmission data per a unit time between the UL flow and the DL flow occurs. In case of SP-MAC, because it assigns fair transmission opportunity between terminal and AP, the difference of the amount of transmission data also occurs. In case that $Amp = 0.01$ for SP-MAC, on the other hand, the larger total throughput is obtained because the transmission frequency of the AP becomes higher than that of each terminal.

Next, we confirm the total congestion window size of wireless terminals that connects to each AP and evaluate the unfairness between APs. Figures 4, 5 and 6 are the time evolution of the total congestion window size of wireless terminals for CSMA/CA, original SP-MAC ($Amp = 1$) and

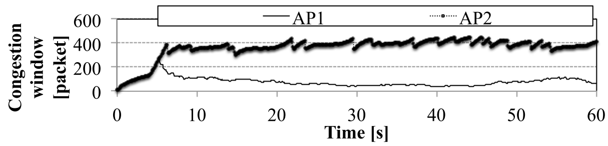

Fig. 4 The total congestion window size of all wireless terminals of connected each APs (CSMA/CA).

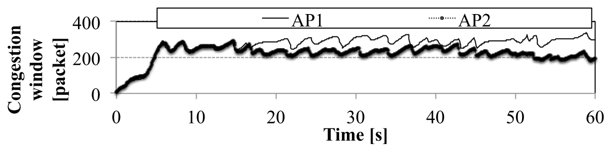

Fig. 5 The total congestion window size of all wireless terminals of connected each APs (*Amp* = 1: original SP-MAC).

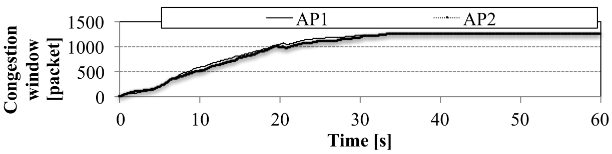

Fig. 6 The total congestion window size of all wireless terminals of connected each APs (*Amp* = 0.01).

SP-MAC (*Amp* = 0.01), respectively. From these figures, we can confirm the unfairness of the total congestion window size for CSMA/CA and original SP-MAC (*Amp* = 1), but the time evolution of the total congestion window size for the proposal (Fig. 6) is almost the same between AP1 and AP2. We can see from Table 6 that the difference of the number of dropped packets between TCP-Data and TCP-ACK becomes smaller according to increase of the number of flows. This is because increase of the number of the flows causes operation of the congestion control for each of terminals, following the frequent occurrence of the buffer overflow in APs.

When we focus on results of original SP-MAC (*Amp* = 1), the larger the number of flows becomes, the larger the number of dropped packets of TCP-Data becomes. However, the total number of the dropped packets of TCP-Data and TCP-ACK is almost the same between the number of flows 10 and 20. When the number of flows increases from 10 to 20, the congestion control for each sender operates powerfully. On the other hand, the number of dropped packets of both TCP-Data and TCP-ACK increases when the number of flows is 40 and *Amp* = 1. This is because the occurrence of buffer overflow increases without being able to avoid congestion absolutely in AP only by the congestion control of each terminal.

5.2.5 Total Throughput of all APs for the Parameter *Amp*

In this section, to clarify the reason of the total throughput degradation in CUBIC-TCP, we evaluated the time change of the total throughput. We compare the result of original SP-MAC and the one of CSMA/CA firstly. Figure 7 shows

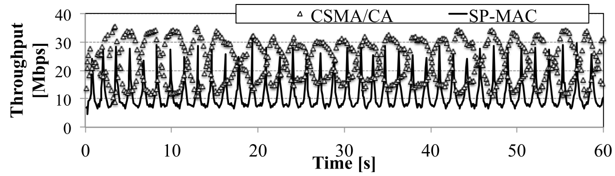

Fig. 7 Time evolution of the total throughput for both AP's when the terminals use CUBIC-TCP (CSMA/CA, original SP-MAC).

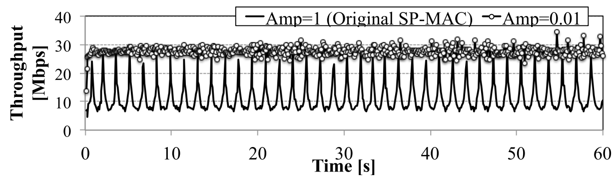

Fig. 8 Time evolution of total throughput for all APs for each *Amp* value when the terminals use CUBIC -TCP (*Amp* = 1: original SP-MAC, *Amp* = 0.01).

the time evolution of total throughput for all APs. Note that Fig. 7 shows the results when the number of flows is 40 and the terminals use CUBIC-TCP. The horizontal and vertical axes show the time and total throughput of both APs, respectively. From Fig. 7, the total throughput has large variation when all wireless terminals and APs use CSMA/CA. For the case with original SP-MAC, the total throughput changed periodically because the back-off time of original SP-MAC is determined by the cosine wave (Eq. (3)). Moreover, because original SP-MAC assigns channel access for each terminal and the AP fairly, the access timing of both the AP and terminals dynamically changes. Thus, the AP cannot send data frames efficiently when the cosine value (back-off time) is large. Therefore, the total throughput of APs decreases. This situation decreases the amount of transmitted TCP-Data and TCP-ACK packets. TCP cannot transmit new TCP-Data packets if TCP-ACK packets do not arrive. Therefore, if the throughput of the AP decreases, throughput degradation of the transport layer occurs.

We then discuss the result of proposal secondly. Figure 8 shows the time evolution of the total throughput for all APs when the number of flows is 40 and the terminals use CUBIC-TCP. From Fig. 8, the total throughput of *Amp* = 0.01 is higher and more stable than that of the original SP-MAC (*Amp* is 1) because the range of the back-off time for APs is less than that of the terminals by decreasing *Amp*. As a result, the total throughput of all APs is independent of time. Thus, TCP-Data and TCP-ACK packets in the AP are transmitted efficiently, and the total throughput of all wireless terminals improves significantly. For example, when the number of flows is 40 and the terminals use UDP, the average throughput of *Amp* = 0.01 and *Amp* = 1 is 34.3 Mbps and 3.1 Mbps, respectively. In contrast, when the terminals use CUBIC-TCP, the average throughput of *Amp* = 0.01 and *Amp* = 1 is 27.6 Mbps and 11.5 Mbps, respectively.

From the above results, we confirm that the proposed method can avoid data frame collisions, dropped packets by buffer overflow, and congestion in the AP. As a result, the total throughput improves significantly even if bidirectional flows exist.

5.2.6 Fairness between UL and DL

In Sect. 5.2.1, we confirmed that the proposal can obtain higher throughput than that of CSMA/CA. Here, from Sect. 2.1, the communication priority of AP is same as wireless terminals in CSMA/CA. Therefore, the throughput between UL from terminal to AP and DL from AP to terminal becomes unfair. However, in the proposal, the AP can obtain higher transmission priority than that of terminals. That is, the proposal can improve the fairness of throughput between UL and DL. This section clarifies the fairness of throughput between UL and DL at the AP in case of TCP traffic.

Figure 9 shows the throughput of UL and DL at AP1 when the terminals use CUBIC-TCP. Here, the throughput of UL includes the total traffic from all wireless terminals connecting to AP1. Also, Fig. 10 plots the ratio of DL throughput to UL one at AP1. Note that the throughput of UL and DL becomes fair when the ratio becomes close to 1. From Fig. 9, the proposal obtains higher throughput in both UL and DL than that of CSMA/CA and original SP-MAC (existing MAC protocols). Furthermore, from Fig. 10, the proposal can obtain higher fairness than the existing MAC protocols. On the other hand, the throughput between UL and DL is unfair in CSMA/CA of all cases and original SP-MAC of 10 flows case. As mentioned in Sect. 2.1, because CSMA/CA terminals and AP have same transmission opportunity, the throughput between UL and DL becomes unfair. Next, in original SP-MAC, the throughput between UL and DL is unfair because of same reason of CSMA/CA when the number of flows is 10. However, when the number of flows becomes larger, original SP-MAC improves the fairness of the throughput. In this case, because the packet losses by buffer overflow occur in AP, the throughput of all terminals decreases by retransmission control and congestion one of TCP. As a result, since the total traffic of UL becomes smaller, the throughput between UL and DL becomes fair in this environment. Finally, in case of proposal, the AP obtains higher transmission opportunity than terminals. Therefore, the fairness of throughput between UL and DL improves drastically.

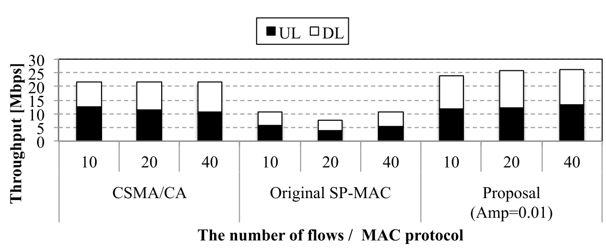

Fig. 9 The throughput of UL and DL at AP1 (CUBIC-TCP).

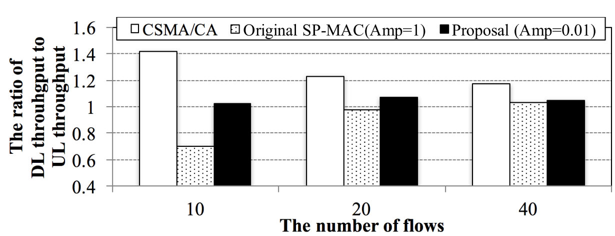

Fig. 10 The ratio of DL throughput to UL one at AP1 (CUBIC-TCP).

6. Conclusion

In WLANs based on the IEEE 802.11 standard, when the number of wireless terminals connecting to an AP increases, the total throughput of all wireless terminals decreases because of data frame collisions. To address this problem, we have proposed a new MAC scheme, SP-MAC, based on the synchronization phenomena of coupled oscillators. However, the characteristics of SP-MAC with bidirectional flows are unclear. Thus, we have evaluated the performance of SP-MAC in a WLAN with bidirectional flows. As a result, the total throughput decreases significantly because the AP cannot send data frames efficiently. To address this problem, we have proposed a priority control method based on SP-MAC. With the proposed method, the range of back-off time in SP-MAC can be varied by using a parameter *Amp*. The proposed method was applied to an AP to send data frames preferentially compared with the wireless terminals. Furthermore, we evaluated the characteristics of the proposed method. We evaluated the relationship between the parameter *Amp* and the total throughput of all terminals. As a result, the total throughput improved significantly when the parameter *Amp* decreases even if bidirectional flows exist.

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