Characterization of Priority Control based on Media Access Control Method SP-MAC over WLAN

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***Abstract*—In wireless local area networks (WLAN) based on IEEE 802.11, when the number of wireless terminals connecting to the same access point (AP) increases, data frame collisions cause the decreasing of total throughput for all wireless terminals. To address this problem, we have proposed a new media access control (MAC) method, Synchronized Phase MAC (SP-MAC), based on the synchronization phenomena of coupled oscillators. We have obtained evaluation results that SP-MAC can improve the total throughput of terminals significantly by its mechanism that can avoid data frame collisions among terminals. However, previous studies have addressed the network environment in which only uplink flows from the wireless terminal to an AP exist, but it is necessary to take into consideration the more real network environment in which uplink and downlink flows are generated simultaneously. If many bidirectional data flows exist in the WLAN, the AP receives a large number of frames from both uplink and downlink by collision avoidance of SP-MAC and the buffer overflow occurs frequently in the AP. Especially, when TCP is used as the transport protocol in the bidirectional environment, TCP-ACK segments as well as TCP-Data segments are received by the AP. In this case, strong impact due to the loss of TCP-ACK segments causes the degradation of the total throughput drastically. In this paper, we propose a priority control method based on SP-MAC for avoiding extreme loss of segments in the AP under the bidirectional environment. Next, we show that the proposed method has an effect for improving communication quality by the simulation.**

Keywords*—*Wireless LAN, Media access control, Synchronization phenomena of coupled oscillators, Kuramoto-model, Priority

I. Introduction

In recent years, locations in which users can access public Wireless Local Area Networks (WLANs) are increasing according to users' request for using freely the Internet access services anywhere, anytime. Moreover, not only network devises (smartphones, laptops, tablets, etc.) but also the Internet access services used by these devises are becoming diverse extremely due to rapid development of Information and Communications Technology (Fig.1). When the Internet access services via WLANs began to be used, its communication system 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 and downlink flows) network services, such as cloud services (Dropbox [1], Microsoft OneDrive [2], etc.) and IP telephones based on Voice over Internet Protocol (VoIP).

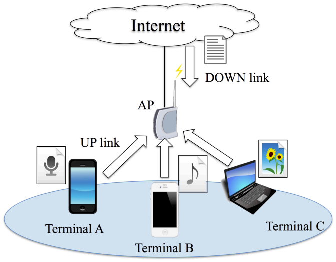
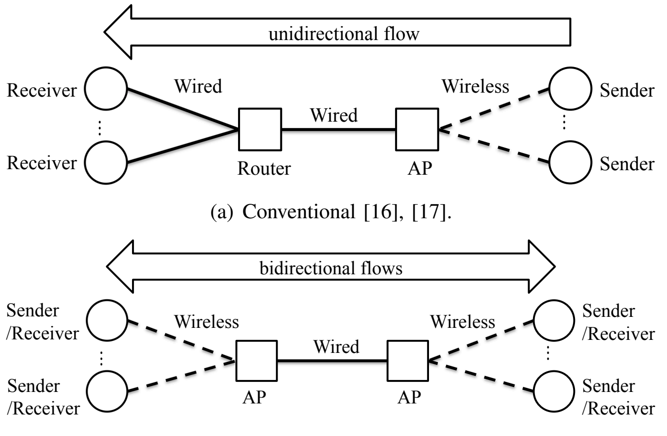


Fig. 1. Bidirectional (uplink and downlink) flows in a WLAN.

Many researchers have worked in order to improve the utilization efficiency for bidirectional network services in WLANs: [3] proposed a new bidirectional data transfer approach to improve the network performance of multi-rate WLANs environment, and [4] presented an analytic model to understand the performance of the bidirectional MAC frame aggregation. [5] proposed the bidirectional MAC protocol for cognitive radio network and showed its protocol increased the network goodput in simulation results. In [6], network performance (throughput, congestion level) was investigated in multi-channel MAC protocol with bidirectional flow control. Moreover, the unfairness of the transmission opportunity between uplink and downlink flow has been pointed out for the network environment with the bidirectional flows in the WLAN [7]: uplink flows can obtain significantly greater throughput than the competing downlink flows. Some studies [8]–[13] proposed and evaluated the method to solve the unfairness between uplink and downlink flow.

One of WLAN-related standards decided by IEEE is IEEE 802.11 [14], which refers to the existing Medium Access Control (MAC) and PHYsical layer (PHY) functions for WLAN computer communication. IEEE 802.11 uses ordinarily Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) for a MAC mechanism. However, in CSMA/CA, when the number of wireless terminals connecting to the same access point (AP) increases, data frame collisions often occur among the wireless terminals [15]. To improve the total throughput of wireless terminals by avoiding data frame collisions in WLANs, we proposed a new MAC scheme, Synchronized Phase MAC (SP-MAC) [16], [17], based on the synchronization phenomena of coupled oscillators [18]. In [16], [17], we showed that SP-MAC can improve the total throughput of all



(a) Conventional [16], [17].

(b) This study.

Fig. 2. Network topology.

wireless terminals by reducing data frame collisions extremely. Note that previous studies [16], [17] used the network model that receivers are connected to the router via wired LAN.

However, the characteristics of SP-MAC are unclear when multiple bidirectional flows exist, because [16], [17] considered the network environment in which only uplink flows exist (Fig.2(a)). If many bidirectional data flows exist in the WLAN (Fig.2(b)), we expect that the AP receives a very large number of frames due to a great effect of collision avoidance mechanism by SP-MAC, but its advantage causes adversely the frequent occurrence of buffer overflow in the AP. Especially, when TCP is used as the transport protocol in the bidirectional environment, TCP-ACK segments as well as TCP-Data segments are received by the AP. In this case, strong impact due to the loss of TCP-ACK segments causes the degradation of the total throughput drastically by comparison with the loss of TCP-Data segments.

In this paper, we propose a priority control method based on SP-MAC for avoiding extreme loss of segments in the AP under the bidirectional environment. Here, this paper assumes that receivers in the network are connected to the AP as Fig.2(b). Next, we show that the proposed method has an effect for improving communication quality, while comparing the performance of SP-MAC with that of CSMA/CA by the simulation. Note that the aim of this paper is to propose a priority control mechanism based on SP-MAC and to evaluate its characteristics. Future works include the comparison of the performance of proposal and some existing methods.

The remainder of this paper is organized as follows: Sec. II introduces the IEEE 802.11 WLAN standard and the synchronization phenomena of coupled oscillators which is a strong guiding principle for our proposed method. In Sec. III, we describe SP-MAC and show the problem with SP-MAC when bidirectional flows exist. Sec. IV explains the proposed mechanism, and Sec. V discusses an evaluation of the proposal. Finally, we summarize this paper in Sec. VI.

II. RELATED WORKS

In this section, we present an overview of the IEEE802.11 wireless LAN and the synchronization phenomena of coupled oscillators by which our proposed method is inspired.

A. IEEE 802.11 wireless LAN

The IEEE 802.11 WLAN standard is one of the most popular standards [19]–[22] for wireless Internet access. In IEEE 802.11 WLANs, a wireless terminal uses CSMA/CA as the MAC and autonomously sends data frames. Thus, each wireless terminal individually determines the timing of data transmission. In CSMA/CA, 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 downlink flows. It leads to unfairness between uplink and downlink flows. For example, let assume an AP aggregates μ downlink 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 uplink flow is μ times as large as that of a downlink flow [7].

B. Synchronization phenomena of coupled oscillators

In the mid-17th century, the great Dutch scientist Huygens noticed that two pendulum clocks always end up swinging in same rhythm, regardless of their initial individual motion. This phenomenon is called *synchronization*, which we can observe often in our natural environment, such as the synchronous flashing of fireflies [23] and the synchronization of metronomes [24]. Synchronization is a phenomenon caused when multiple oscillators with different periods transform incoherent rhythms into synchronized rhythms with each interaction. These synchronized oscillators are called coupled oscillators. During synchronization, the phase differences and frequencies of all coupled oscillators converge at certain values. The *Kuramoto model* [18] is the most popular mathematical model representing the behavior of a large set of coupled oscillators. This model has been used in various fields of study, such as chemistry, biology and engineering. Several studies [25]–[27] have discussed the synchronization phenomena and proposed mathematical models to explain the phenomena based on *Kuramoto model*. The Kuramoto model

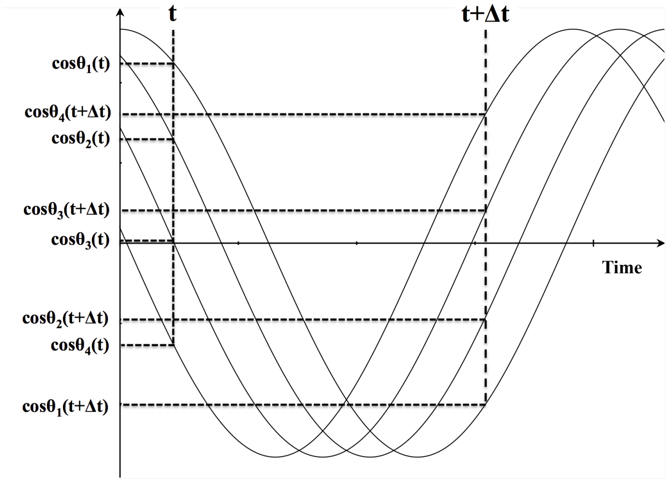


Fig. 3. Example: cosine curves of synchronized oscillators with phase shifting.

for synchronization phenomena is also the basis for modeling of the behavior of our proposed SP-MAC.

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).

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

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.

Next, in the Kuramoto model, Eq.(2), K has to satisfy Eq.(3) for collective synchronization.

$$\begin{aligned} K &> K_c\,, \\ K_c &= \frac{2}{\pi g(\omega_0)}. \end{aligned} \tag{3}$$

In Eq.(3), K_c and $g(\omega_0)$ are the critical coupling strength and density function of a natural frequency (i.e., the symmetric function with ω_0 as the center of all ω), respectively. For example, if the natural frequency ω has a uniform distribution in $[\alpha,\beta]$, the density function is derived using $g(\omega_0) = (\beta - \alpha)^{-1}$. In this case, the critical coupling strength is determined using Eq.(4).

$$K_c = \frac{2(\beta - \alpha)}{\pi}. \tag{4}$$

Note that this is a theoretical threshold when there are infinitely several oscillators. Therefore, we have to carefully calculate K_c.

III. 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.

A. 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 3 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. 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.
- SP-MAC is implemented in the AP and all wireless terminals.

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 a 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 $\theta_i(0)$ 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.(5) and phase $\theta_i(t)$ for each ID i. Then, the wireless terminal sends the data frame in the same manner as CSMA/CA. If the wireless terminal detects data frame collisions, it calculates a new back-off time using Eq.(5) and the phase when the collision is detected again.

$$\text{Backoff} = ((|\cos\theta_i(t)| \times \alpha) \bmod N_c) \times \text{SlotTime}. \tag{5}$$

In Eq.(5), 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 [16] because of setting the time scale of the back-off time equal to the one used with the CSMA/CA. SP-MAC only sends the control parameters for calculating the phase at the beginning of transmission when the number of wireless terminals does not change. Hence, each wireless terminal works autonomously based on the model for the synchronization phenomena of coupled oscillators. Furthermore, 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 [17].

Next, we discuss the problem of SP-MAC in a WLAN environment with bidirectional flows. [16], [17] showed that SP-MAC can avoid the data frame collision drastically under the network environment with only uplink flows. If bidirectional flows exist in the WLANs, the AP receives a larger number of data frames from both uplink senders and downlink senders. As mentioned above, SP-MAC is implemented in only wireless terminals but also the AP. If the transmission opportunity of the AP is the same as that of terminals for SP-MAC, we expect the buffer overflow occurs more significantly. In case that TCP is used as the transport protocol, the loss of TCP-ACK segments is a serious problem that 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.

IV. Priority control for AP based on SP-MAC

This section proposes a priority control method for the AP based on SP-MAC for the problem (Sec. III) of the original SP-MAC that considers the network environment in which only uplink flows exist. 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

$$\text{Backoff} = ((|\cos\theta_i(t)| \times \alpha) \bmod N) \times Amp \times \text{SlotTime}. \quad (6)$$

From Eq. (5) and (6), 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.

Note that this study assumes that *Amp* is some constant values in the evaluations (Sec. V) in order to learn the characteristics and the trend of priority control of SP-MAC. Thus, considering a dynamic setting method for *Amp* according to network condition is future work.

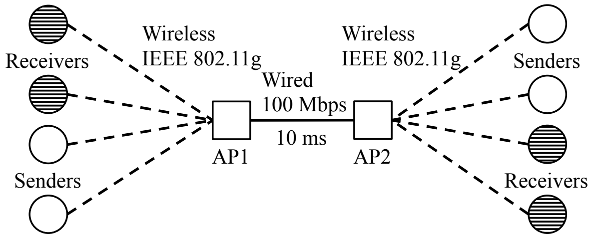


Fig. 4. Network model for the evaluation.

TABLE I. The propagation model and Antenna parameters.

Propagation model	Two-ray ground reflection
Antenna gain	1.0
Antenna height	1.5 [m]
System loss	1.0

TABLE II. The protocol for each layer.

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

V. Evaluation

In this section, we evaluate characteristics of our proposed priority control for the AP, compared with the original SP-MAC and CSMA/CA by using network simulator NS2 [28]. Moreover, we discuss the effectiveness and the availability of our priority control method for network performance from simulation results.

A. Simulation environment

Firstly, we explain the simulation environments. Figure 4 shows the simulation model: this network used IEEE802.11g (PHY) for the wireless LAN environment, and SP-MAC is implemented in all wireless terminals and APs. We assumed that none of the terminals were moved. To avoid the exposed node problem, the distance between AP1 and AP2 in Fig.4 is 600 m. 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. Table I shows the radio propagation model and the antenna parameters. Table II shows the protocol for each others layer.

Note that we consider UDP [29] and TCP [30] 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 [31], 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. Then, we set the coupling strength K to $4\pi^{-1} + 1$ by considering Eq.(3) and Eq.(4), such that it is larger than the critical coupling strength $K_c = 4\pi^{-1}$. The control interval Δt is set to 10 ms. Furthermore, the simulation

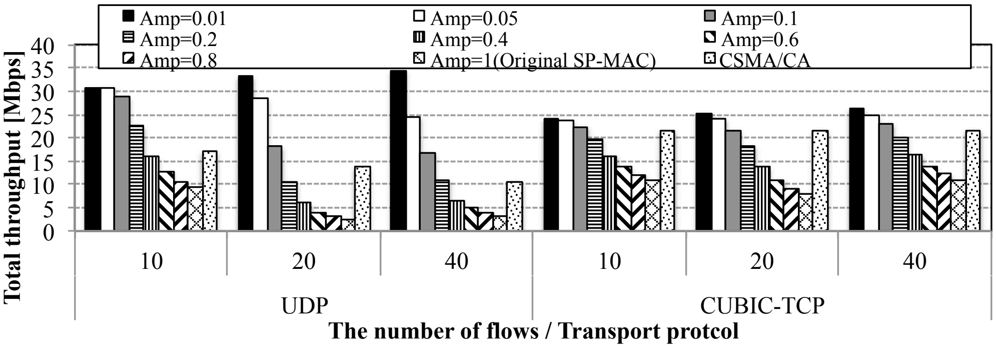


Fig. 5. Total throughput for each *Amp* value and number of flows.

TABLE III. 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 IV. 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

results show the average results obtained through 10 trials. Here, AP1 and AP2 have the same parameter *Amp* from 1 to 0.01 and all terminals are set with *Amp* = 1 in Eq. (6).

We set the parameter of Eq.(5) 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.

B. Evaluation results

This section shows the performance of our priority control method for total throughput, the number of data frame collisions and the number of dropped packets by buffer overflow. Moreover, we discuss the fairness among flows for SP-MAC in the presence of the bidirectional flows.

1) Total throughput of terminals for parameter Amp: Figure 5 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.

As can be seen in Fig. 5, 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.

2) Number of data frame collisions for parameter Amp: Table III and Table IV 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 out proposal when *Amp* is equal to 0.01. Here, the data frame collisions include the collisions of TCP-ACK as well as 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 III that the number of collisions has a nearly same value for various values of *Amp* in the case of UDP. From Table IV, 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. 5. 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.

3) Number of dropped packets by buffer overflow in APs: Next, we show the relationship between each value of pa-

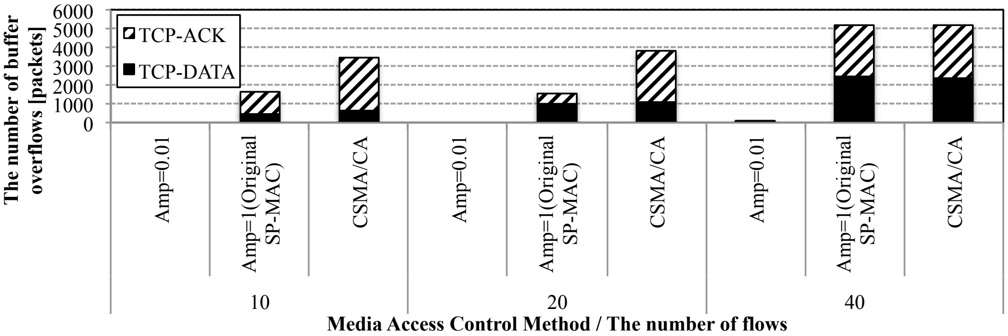


Fig. 6. The number of TCP-ACK and TCP-Data segments which overflowed the buffer of APs.

TABLE V. 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 VI. 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

rameter *Amp* and the number of dropped packets by buffer overflow in both APs. Table V and Table VI denote results for UDP and CUBIC-TCP, respectively. Firstly, when comparing original SP-MAC with CSMA/CA using UDP for the transport protocol, we can see from results of Table V 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 VI, on the other hand, when CUBIC-TCP is used for the transport protocol, 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. 5, the total throughput of all terminal can be maximized when *Amp* is 0.01. When UDP is used for the transport protocol, 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.

4) The fairness among flows from the point of view of segment types: In this section, we crarify 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.

Figure 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 figure 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.

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 can not 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 uplink and the downlink. The difference of the amount of transmission data per a unit time between the uplink and the downlink 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

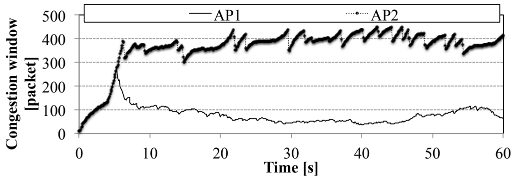


Fig. 7. The total congestion window size of all wireless terminals of connected each APs (CSMA/CA).

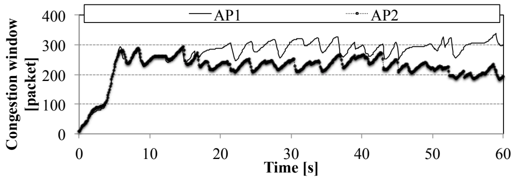


Fig. 8. The total congestion window size of all wireless terminals of connected each APs (Amp=1 : Original SP-MAC).

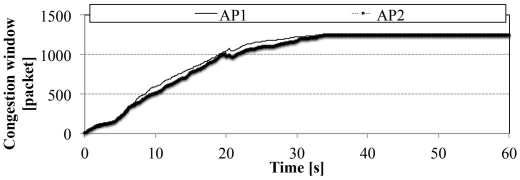


Fig. 9. The total congestion window size of all wireless terminals of connected each APs (Amp=0.01).

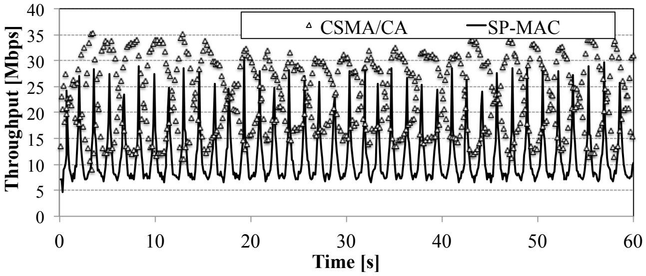


Fig. 10. Time evolution of the total throughput for both AP's when CUBIC-TCP is used for the transport protocol (CSMA/CA, original SP-MAC).

uplink flow and the downlink flow occurs. The reason why the difference in case of original SP-MAC occurs is because the transmission opportunity is assigned between each terminal and the AP. 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 7, 8 and 9 are the time evolution of the total congestion window size of wireless terminals for CSMA/CA, original SP-MAC (Amp = 1) and SP-MAC (Amp = 0.01), respectively. From these figures, we can confirm the unfairness of the total congestion window size for for CSMA/CA and original SP-MAC (Amp = 1), but the time evolution of the total congestion window size for the proposal (Fig. 9) is almost the same between AP1 and AP2. We can see from Fig. 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 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) Total throughput of all APs for the parameter Amp: Finally, to clarify the reason for 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 10 shows the time evolution of total throughput for all APs. Note that Fig. 10 shows the results when the number of flows is 40 and CUBIC-TCP is used. The horizontal and vertical axes show the time and total throughput of both APs, respectively. From Fig. 10, the total throughput has large variation when CSMA/CA is used for the MAC protocol. 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.(5)). 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 11 shows the time evolution of the total throughput for all APs when the number of flows is 40 and CUBIC-TCP is used as the transport protocol. From Fig. 11, 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 UDP is used, the average throughput of Amp = 0.01 and Amp = 1 is 34.3 Mbps and 3.1 Mbps, respectively. In contrast, when CUBIC-TCP is used, 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

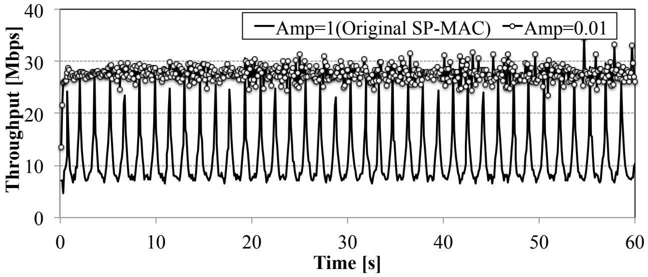


Fig. 11. Time evolution of total throughput for all APs for each *Amp* value when CUBIC-TCP is used for the transport protocol.

exist.

VI. SUMMARY

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. In future, we plan to evaluate SP-MAC in ad hoc networks and to tune parameter dynamically according to network environment.

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