2015 International Symposium on Nonlinear Theory and its Applications
NOLTA2015, Kowloon, Hong Kong, China, December 1-4, 2015

Performance Evaluation of Media Access Control Method based on Synchronization Phenomena of Coupled Oscillators over Multi-rate WLAN

Ryo Hamamoto, Hiroyasu Obata, Yuuki Yamamoto, Ryoma Ando, Chisa Takano, and Kenji Ishida

Graduate School of Information Sciences, Hiroshima City University
3-4-1 Ozuka-Higashi, Asa-Minami-Ku, Hiroshima, 731-3194 Japan
Email: {ryo@net.info., obata@, yamamoto@net.info., ando@net.info., takano@, ishida@}hiroshima-cu.ac.jp

Abstract—In Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) of IEEE802.11 Wireless Local Area Network (WLAN), it is known that data frame collisions often occur if the number of wireless terminals increases. To solve this problem, a novel media access control method based on synchronization phenomena of coupled oscillators (SP-MAC) has been proposed. SP-MAC can obtain higher total throughput compared to CSMA/CA in a single-rate environment where all terminals use same transmission rate. However, the performance of SP-MAC over a multi-rate WLAN environment has not been evaluated. In this paper, we evaluate the performance of SP-MAC over the multi-rate WLAN environment and clarify that SP-MAC can get higher total throughput compared to CSMA/CA.

1. Introduction

A lot of mobile terminals such as smartphones can use Wireless Local Area Network (WLAN) based on IEEE802.11 [1]. In order to avoid data frame collisions among these mobile terminals, Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) is used for a Media Access Control (MAC) in IEEE802.11 WLAN. In CSMA/CA, however, it is known that data frame collisions often occur if the number of wireless terminals connecting an access point (AP) increases. Then, the collisions cause the degradation of the total throughput.

To solve the problem, the authors have already proposed a novel MAC method based on the synchronization phenomena of coupled oscillators (SP-MAC) [2, 3]. SP-MAC uses the synchronized phase obtained by *Kuramoto model* [4] in order to calculate the back-off time instead of the random integer in CSMA/CA. Furthermore, [2, 3] evaluated that SP-MAC can dramatically decrease the data frame collisions and improve the total throughput of all wireless terminals compared to CSMA/CA in a single-rate environment where all terminals use same transmission rate. Here, the wireless terminals usually use a rate adaptation (RA) control for effective communication over the environment where each terminal has the different communication environments. RA control supports multiple transmission rates (multi-rates) and dynamically adjusts the data rate so that the terminals in better (worse) radio wave environments communicate using a higher (lower) transmission rate. If RA control is used in CSMA/CA environment, it is known that the low rate terminal decreases the total throughput of WLAN system. However, because the performance of SP-MAC over the multi-rate WLAN environment has not been evaluated, it is not clear that SP-MAC can obtain higher performance than CSMA/CA when the terminal uses different transmission rate. Thus, this paper evaluates the performance of SP-MAC over the multi-rate WLAN environment and clarifies whether SP-MAC can get higher total throughput compared to CSMA/CA.

The rest of the paper is organized as follows. Section 2 describes the overview of IEEE802.11 WLAN, multi-rate transmission, and the synchronization phenomena of coupled oscillators. Next, we explain SP-MAC and evaluates the performance of SP-MAC over the multi-rate WLAN environment by simulation in Section 3 and Section 4, respectively. Finally, Section 5 concludes this paper.

2. Related works

2.1. IEEE 802.11 wireless LAN

2.1.1. CSMA/CA

In CSMA/CA, if the channel becomes idle when a data frame arrives in the transmission queue, it defers to DCF 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 calculated independently 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 IEEE802.11, 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 sets the back-off time using Eq.(1) again. In this case, the CW becomes twice as large as the previous value, and the upper bound is CW_{max}. If the retransmission exceeds the maximum retry limits (usually 7), the terminal discards the data frame.

2.1.2. Multi-rate transmission in IEEE802.11 WLAN

Most IEEE 802.11b/a/g WLANs [1] employ multi-rate transmission. For example, the transmission rates in IEEE802.11a/g are 54, 48, 36, 24, 18, 12, 9, and 6 Mbps. In the multi-rate environment, efficient communication is provided for dynamic environment conditions by RA control [5], which can utilize higher (lower) transmission rates for better (worse) radio wave environments. Here, it is known that AP throughput (the total throughput of all wireless terminals) Th can be estimated by using Eq.(2) [6] in the multi-rate environment.

$$Th = N\left(\sum_{i=1}^{N}(b_i)^{-1}\right)^{-1} \tag{2}$$

In Eq.(2), N and b_i denote the number of wireless terminals connected to the AP and the transmission rate of the i-th terminal connected to the AP, respectively. Note that Th is equal to the harmonic average value of the transmission rate of terminals connected to the same AP in the multi-rate environment. Moreover, the Performance Anomaly problem [7] causes the throughput degradation for all terminals connected to the same AP in the multi-rate environment. That is, terminals with high transmission rates are forced to accept the lower rate wireless terminals in poor environments. As a result, Th is greatly decreased.

2.2. Synchronization phenomena of coupled oscillators

Synchronization indicates that the phenomena caused by multiple oscillators with different periods transform incoherent rhythms into synchronized ones with each interaction. This phenomena is also observed in nature such as the synchronous flashing of fireflies and the synchronization of metronomes. These synchronized oscillators are called coupled oscillators. One of the typical synchronization models is the *Kuramoto model* [4,8]. In the Kuramoto model (synchronization of N coupled oscillators), the i-th oscillator runs independently at its own natural frequency ω_i and interacts with all the others. Then, the i-th oscillator's phase θ_i $(0 < \theta \leq 2\pi)$ is calculated using Eq.(3).

$$\frac{\mathrm{d}\theta_i}{\mathrm{d}t} = \omega_i + \frac{K}{N}\sum_{j=1}^{N}\sin(\theta_j - \theta_i) \quad (i = 1, 2, \cdots, N) \tag{3}$$

In Eq.(3), $K(> 0)$ indicates coupling strength and the second term is an interaction term. Note that the interaction term is standardized by K/N to be independent from system size N.

3. SP-MAC : Media access control method based on the synchronization phenomena of coupled oscillators

SP-MAC uses the synchronized phase with phase shifting based on Eq.(3) for setting the back-off time instead of using a random integer in CSMA/CA; thereby avoiding the overlap of the back-off time among terminals. SP-MAC sets the following preconditions; (1) the number of wireless terminals does not change after data transmission has started, (2) the AP and all wireless terminals do not move, and (3) the AP and all wireless terminals stop using the RTS/CTS function.

In SP-MAC, AP determines the natural frequency ω_i (i means a node ID) and coupling strength K, which satisfy the synchronizing condition according to the number of wireless terminals N prior to starting transmission. 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, AP sets an ID i $(1 \leq i \leq N)$ 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, AP sends the control parameters, which include i, $\theta_i(0)$, ω_i, K, a control interval Δt, and N for all wireless terminals.

After receiving the beacon, each wireless terminal immediately starts the calculation of the phase using the control parameters. Next, the wireless terminal calculates the phase $\theta_i(t)$ for all ID i using Eq.(3) for every Δt. The calculation of the phase continues while the terminal connects to the AP, even if no data exists for transmission. When the wireless terminal wants to send data frame at time t, it calculates the back-off time (Backoff) using Eq.(4) and phase $\theta_i(t)$ for each ID i. Then, the wireless terminal sends the data frame, identical to the behavior of CSMA/CA.

$$\text{Backoff} = ((|\cos\theta_i(t)| \times \alpha) \bmod N) \times \text{SlotTime} \tag{4}$$

In Eq.(4), SlotTime and α show the slot time interval specified in IEEE802.11 and a coefficient for obtaining the normalized phase, respectively. α is set equal to 100 [2]. Because SP-MAC uses cosine for calculation, the access interval changes like the original CSMA/CA (random value). If the wireless terminal detects the data frame collisions, it calculates the new back-off time using Eq.(4) and the phase when the collision is detected again. That is, SP-MAC does not use a binary increase of back-off time. SP-MAC only sends the control parameters for calculating the phase at the beginning of transmission. 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, it can be used for an environment where both the SP-MAC terminals and the original CSMA/CA terminals exist [3].

4. Evaluation

In this section, we evaluate the performance of SP-MAC using the network simulator ns2 [9].

4.1. Simulation environment

Table 1 and Fig. 1 show simulation parameters and the simulation model. This network used IEEE802.11g (PHY) for the wireless LAN environment, and SP-MAC was implemented in all wireless terminals. We assumed that the number of terminals N is stable and none of

Table 1: Simulation parameters.

Simulator	ns2 (ver.2.34)
Wireless LAN	IEEE802.11g
AP's buffer size	250 packet
Transport protocol	UDP
Segment size	1000 byte
Simulation time	60 second

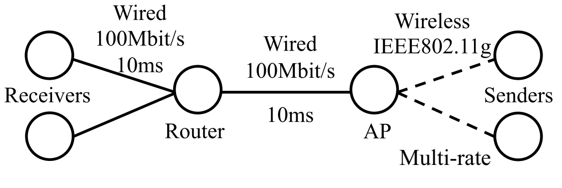

Figure 1: Simulation model.

the terminals were moved. In this model, we considered the case in which wireless terminals were the senders and generated 60 seconds of traffic (each wireless terminal generated one flow). Next, all wireless terminals generate UDP traffic (30 Mbps). The simulation results showed averages of 10 trials. This study evaluated the total throughput determined by receipt data at the receiver terminal, the number of data frame collisions, and the improvement ratio of the SP-MAC's average throughput compared to CSMA/CA. In SP-MAC, we set the control parameters [2] as follows. First, the initial phase $\theta_i(0)$ and natural frequency ω_i were set to non-overlapped values in the range of $(0, 1.0)$ and $[0, 2.0]$, respectively. Then, we set the coupling strength K to 5. The control interval Δt was set to 10 ms.

In this evaluation, we consider following two multi-rate scenarios; (Case1) $N-1$ terminals send data with 54 Mbps and one terminal sends data with 6 Mbps, (Case2) $N-1$ terminals send data with 6 Mbps and one terminal sends data with 54 Mbps. Note that Case1 and Case2 show the impact of performance anomaly is small or large, respectively. Table 2 indicates the estimated total throughput using Eq.(2) in case of CSMA/CA.

4.2. Simulation results

Fig. 2 and Fig. 3 show the total throughput of all wireless terminals when the number of flows changes from 5 to 20. Fig. 2 and Fig. 3 indicate the result of Case1 and Case2, respectively. From Fig. 2 and Fig. 3, SP-MAC can get higher total throughput compared to CSMA/CA in both cases. For example, in Case1, when the number of flows is 5, 10, and 20, the differences between CSMA/CA and SP-MAC are 5.8 Mbps, 10.1 Mbps and 13.3 Mbps, respectively. From the above results, SP-MAC improves the total throughput drastically over the multi-rate WLAN environment compared to CSMA/CA. Furthermore, the total throughput of SP-MAC is close to the estimated value shown in Table 2. From these results, we confirmed that SP-MAC can use the bandwidth effectively in the multi-rate environment than CSMA/CA. Here, Table 3 and Table 4 show the number of data frame collisions. Note that each number in parenthesis indicates collision probability. Table 3 and Table 4 indicate the results of Case1 and Case2, respectively. From Tables 3 and 4, the number of data frame collisions (collision probability) increases with the number of flows in each MAC protocol. However, SP-MAC can dramatically reduce the number of data frame collisions (collision probability) compared to CSMA/CA in both cases. It is because the data transmission timing of SP-MAC is specified by the synchronized phase with phase shifting. That is, each terminal can send data like TDMA. Therefore, SP-MAC can obtain higher total throughput than CSMA/CA. Note that, the data frame collisions only occur at the beginning of data transmission in SP-MAC. This is because each phase θ_i does not synchronize at the beginning of data transmission.

Table 2: Estimated total throughput of all terminals when CSMA/CA is used for MAC protocol.

Number of flows	5	10	20
Case 1	20.8 Mbps	30.0 Mbps	38.6 Mbps
Case 2	7.3 Mbps	6.6 Mbps	6.3 Mbps

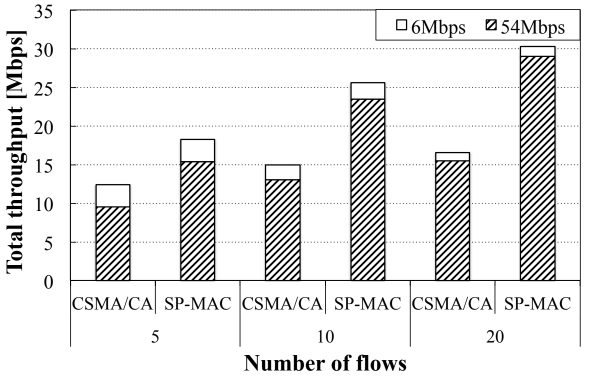

Figure 2: The total throughput for each flow (Case1).

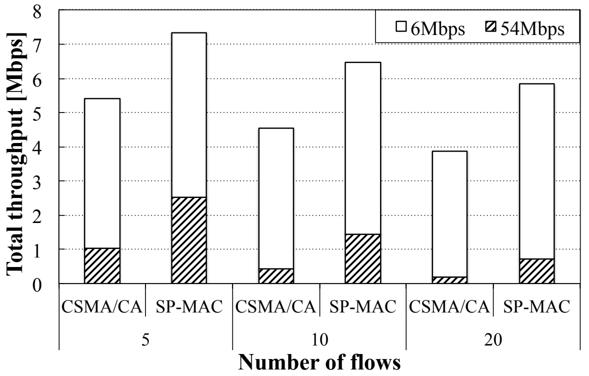

Figure 3: The total throughput for each flow (Case2).

Next, Fig. 4 and Fig. 5 plot the throughput improvement ratio of SP-MAC compared to CSMA/CA in Case1 and Case2, respectively. From Figs. 4 and 5, SP-MAC increases the throughput improvement ratio as the number of flows increases in both cases. In Case1, when the number of flows is 20, the improvement ratio of SP-MAC terminals with 54 Mbps rate are 1.9 times greater than the one of CSMA/CA terminals. Moreover, the SP-MAC terminal with 6 Mbps is 1.2 times greater than the one of CSMA/CA terminal. This is because SP-MAC can use the bandwidth effectively by avoiding data frame collisions compared with CSMA/CA even if the number of flows increases. Furthermore, the throughput of 54 Mbps terminal in Case2 drastically improves compar-

Table 3: The number of collisions for each flow (Case1, each number in parenthesis indicates collision probability).

Number of flows	CSMA/CA	SP-MAC
5	24129.8 (19.6%)	0.5 (0.4×10^{-3}%)
10	53868.2 (31.3%)	2.2 (1.2×10^{-3}%)
20	95943.2 (42.4%)	9.2 (4.4×10^{-3}%)

Table 4: The number of collisions for each flow (Case2, each number in parenthesis indicates collision probability).

Number of flows	CSMA/CA	SP-MAC
5	10557.6 (19.7%)	0.8 (1.9×10^{-3}%)
10	16561.8 (30.9%)	3.2 (7.7×10^{-3}%)
20	22928.7 (43.6%)	12.2 (29.2×10^{-3}%)

ing with the one in Case1. Especially, if the number of flows is 20, the terminal with 54 Mbps can improve about 3.5 times larger than CSMA/CA. That is, the effect of SP-MAC for the high rate terminal becomes larger in the environment where the impact of performance anomaly is large. On the other hand, the improvement ratio of the terminal with 6 Mbps rate in Case2 is almost same as the one in Case1. This is because the throughput of 6 Mbps terminals is mainly affected by the transmission delay rather than the number of collisions.

From these simulation results, we confirmed that SP-MAC can obtain higher total throughput than CSMA/CA in two multi-rate environments.

5. Conclusion

The IEEE802.11 wireless LAN usually uses CSMA/CA for the media access control. However, in CSMA/CA, data frame collisions often occur with the increase of the number of wireless terminals. To solve this problem, the media access control method based on synchronization phenomena of the coupled oscillators (SP-MAC) has been proposed and evaluated in the single-rate environment. In order to clear the applicability of SP-MAC, this paper evaluated the performance of SP-MAC in the multi-rate environment. From simulation results, we confirmed that SP-MAC can get higher total throughput compared to CSMA/CA by avoiding data frame collisions dramatically in the multi-rate wireless LAN environment. Future work includes the evaluation of SP-MAC in the ad-hoc networks and dynamic environments where the number of wireless terminals changes.

Acknowledgements

This work was partly supported by JSPS KAKENHI Grant Numbers 26420367, 15H02688, 15K00431, 26280032, and Project Research Grants of the Graduate School of Information Sciences, Hiroshima City University.

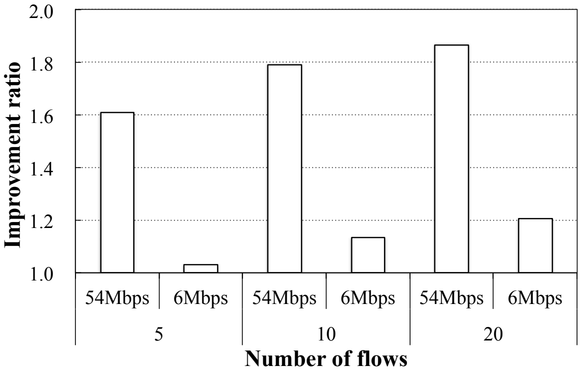

Figure 4: Improvement ratio of the SP-MAC's average throughput compared to CSMA/CA (Case1).

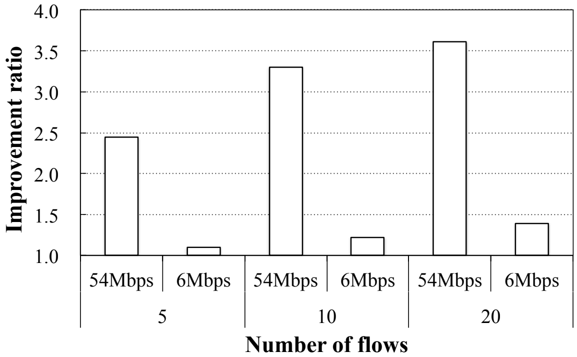

Figure 5: Improvement ratio of the SP-MAC's average throughput compared to CSMA/CA (Case2).

References

[1] IEEE Standard, "Wireless LAN medium access control (MAC) and physical layer (PHY) specifications," *ANSI/IEEE Std 802.11*, 2012.

[2] R. Hamamoto, H. Obata, C. Takano, K. Ishida, and K. Yamada, "Media access control mechanism based on synchronization of coupled oscillators over wireless LAN," *IEICE Technical Report*, IN2013-157, 2014. (in Japanese)

[3] H. Obata, R. Hamamoto, C. Takano, and K. Ishida, "Throughput characteristics evaluation of media access control method based on synchronization phenomena of coupled oscillators over WLAN coexisting of CSMA/CA terminals," *Proc. the 7th International Workshop on ASON 2014*, pp.254–259, 2014.

[4] Y. Kuramoto, *Chemical oscillations, waves, and turbulence*, Springer, 1984.

[5] A. Kamerman and L. Monteban, "WaveLAN-ii: A high-performance wireless LAN for the unlicensed band," *Bell Labs Technical Journal*, 2, 3, pp.118–133, 1997.

[6] K. Medepalli and F.A. Tobagi, "Throughput analysis of IEEE 802.11 wireless LANs using a average cycle time approach" *Proc. IEEE GLOBECOM 2005*, pp.3007–3011, 2005.

[7] M. Heusse, F. Rousseau, G. Berger-Sabbatel, and A. Duda, "Performance anomaly of 802.11b," *Proc. IEEE INFOCOM 2003*, pp.836–843, 2003.

[8] J.A. Acebrón, L.L. Bonilla, C.J.P. Vicente, F. Ritort, and R. Spigler, "The Kuramoto model: A simple paradigm for synchronization phenomena," *Rev. Mod. Phys.* 77, pp.137–185, 2005.

[9] Network Simulator ns (version 2), available from `http://www.isi.edu/nsnam/ns/`, 2015.