Fundamental Investigation of Backoff Control Method for Fair Communication Opportunity of mmW WBAN in Overcrowded Environment

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***Abstract*—Wireless Body Area Network (WBAN) is a communication system between wearable devices in the human body area. WBAN using millimeter-wave (mmW) is expected to solve the inter-WBAN interference problem. The human body attenuation is important to reduce the interference, especially in user-dense conditions. In the mmW, due to its straightness and attenuation characteristics, the number of interferers varies depending on the location of the WBAN user. However, conventional interference avoidance protocols such as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) do not consider variations in the number of inter-WBAN collisions. Thus, the fairness of communication opportunities in an overcrowded environment is degraded. In this paper, we propose an inter-WBAN interference avoidance method that selects the optimal Contention Window (CW) size to ensure the communication time of WBAN users. The fairness and total communication time of the proposed method are evaluated by computer simulation. The results show that the proposed method can achieve high fairness even when the interference increases.**

I. Introduction

With the recent proliferation of Internet of Things (IoT) devices, Wireless Body Area Network (WBAN), which deploys wireless terminals around the body surface, has attracted attention. WBAN is the system that supports a wide range of medical and non-medical applications with communication in the human body area [1]. For example, medical applications are expected to communicate biological data such as pulse rate, blood oxygenation level, and blood pressure between wearable sensor nodes and information collection nodes such as smartphones. In non-medical applications are expected to communicate audio and video data between wireless earphones or Head-Mounted Display (HMD) and smartphones.

Figure 1 shows the interference problem in a WBAN. As shown in Fig. 1(a), in a single WBAN, intra-WBAN communication is generally performed around the coordinator node, and interference between WBAN nodes is avoided by scheduling in the WBAN. On the other hand, interference occurs between WBANs when other WBAN users are in the vicinity, as shown in Fig. 1(b). WBAN using microwave such as 2.4 GHz, inter-WBAN interference is seriously in an overcrowded environment with multiple WBAN users. A WBAN in the millimeter-wave (mmW) such as 60-GHz band

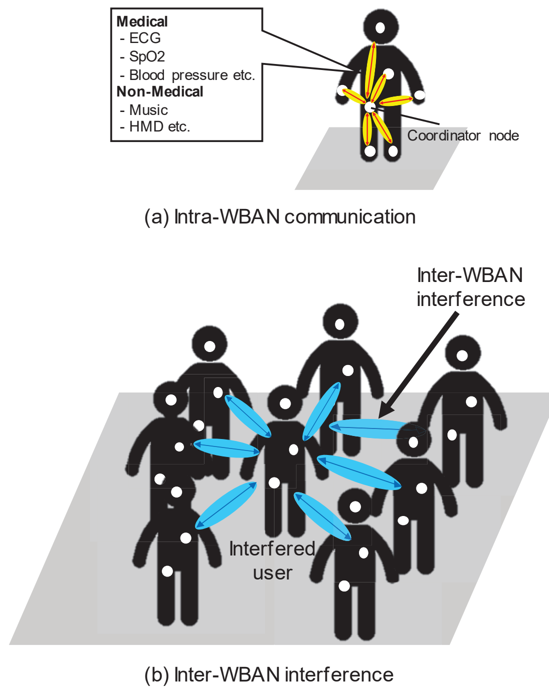

Fig. 1. (a) Intra-WBAN communication in WBAN and (b) inter-WBAN interference problem in an overcrowded environment.

that utilizes the interference power attenuation effect of human body blocking solves this problem.

For mmW WBAN, the attenuation caused by the human body in the communication within a 60-GHz-band WBAN has been studied in [2]–[6], and the interference propagation characteristics between two nearby users in a 60-GHz-band WBAN in a line-of-sight environment has been studied in [7]. However, the above studies did not consider the interference between multiple WBANs in an overcrowded environment with human body blocking. We have investigated the intra-WBAN propagation characteristics [8] and inter-WBAN interference [9]–[12] of 60-GHz-band WBANs considering human

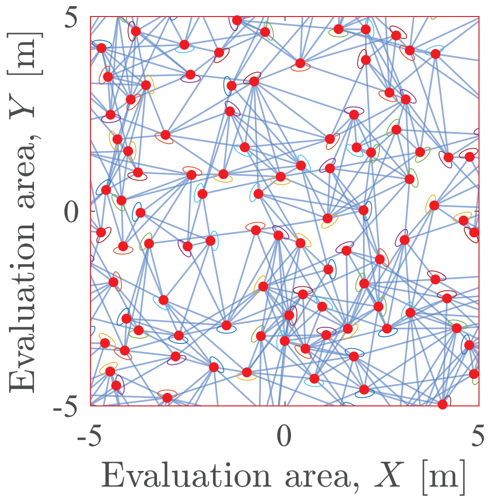

Fig. 2. Interference map for 100 users.

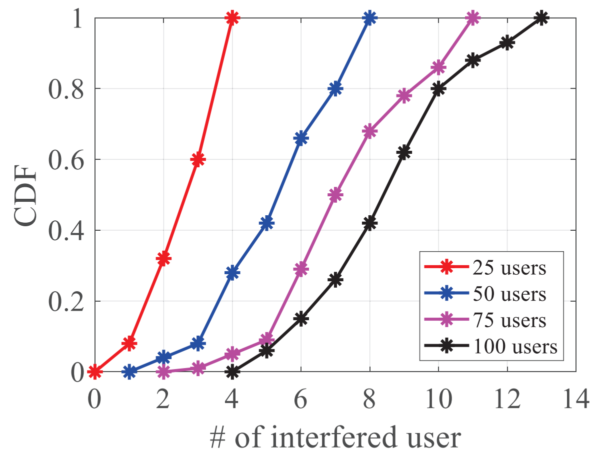

Fig. 3. CDF of number of interfered user.

body blocking. In the previous study [9], the environment of inter-WBAN interference with human body blocking in a dense user environment was investigated by computer simulation. Reference [12] considered the direction of the human body blocking, and the capacity of the communication channel within a WBAN was calculated by computer simulation. However, these studies do not consider the effect of inter-WBAN interference from other users on communication opportunities. WBAN user's interferences in mmW vary due to their human body blocking effect and attenuation characteristics. Conventional interference avoidance protocols, such as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), do not consider the variation in the number of interferences among WBAN users, which reduces the fairness of communication opportunities in an overcrowded environment. In this paper, we propose a method for avoiding the effects of inter-WBAN interference in an environment with variations in the number of interferences and evaluate the fairness of communication opportunities by computer simulation.

II. Interference Problems Caused by mmW WBAN

Figure 2 shows the interference graph when 100 WBAN users are placed in the space of 10 m $\times$ 10 m. The ellipses and red dots indicate top view of the human body of WBAN user and WBAN nodes, respectively. The orientation of the human body is assumed to be random. The nodes connected by the blue line show that they are interference nodes each other. As mentioned earlier, the straightness and attenuation effects in the mmW are more considerable than in the microwave. Despite the close distance, it can confirm that the interference varies with the WBAN user's body angle.

Figure 3 shows the Cumulative Distribution Function (CDF) of number of interfered user when 25, 50, 75, and 100 WBAN users are deployed. When the CDF is 1, the interferences increase linearly to 4 for 25 users and 8 for 50 users. On the other hand, when the number of users is 100, the interference is only 13. Therefore, when the number of users is large, the number of interferences is saturated by mmW, and the interference suppression effect is observed. However, the slope of the CDF graph decreases as the number of users increases, confirming the existence of variations in the number of interferences in overcrowded environments.

Suppose conventional CSMA/CA is used in this situation. In that case, the difference in communication opportunities due to the presence or absence of interference becomes more pronounced, which raises the issue of degrading the fairness of communication opportunities in wireless communication systems. Therefore, there is a need for fair wireless communication in the mmW WBAN.

III. mmW WBAN Communication System Model with Fairness Consideration

A. Proposal of interference avoidance method

We propose an inter-WBAN interference avoidance method that performs carrier sense and selects the optimal Contention Window (CW) size to ensure equal communication time for all users in each WBAN. As mentioned earlier, in mmW, the fairness of communication is reduced due to the variation of interference. In our proposal, it is necessary to determine the CW size according to the number of interferences. In this study, before sending data packets in the WBAN, a node informs the existence of itself to surrounding nodes. This allows other users to understand the interference situation. By the above actions, it is assumed in this system that each WBAN can decide the CW size. In this system, we assume that each WBAN operates as an interference avoidance method between WBANs by the above actions.

From the interference graph in Fig. 2, we see many situations where many users interfere with one user, so we assume a situation where there is a difference in the number of interferences. Figure 4 shows the inter-WBAN interference environment assumed for the evaluation in Sect. IV. There

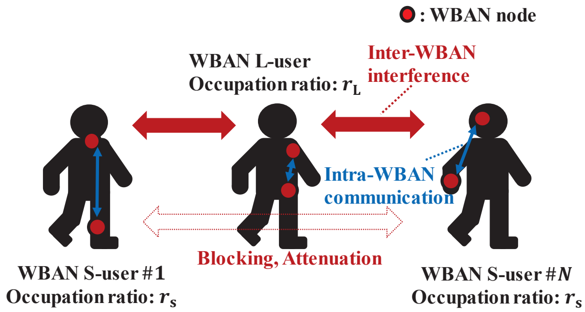

Fig. 4. Assumed interference environment between WBANs.

are a total of N S-users and one L-user. Here, L-user and S-user are defined as users with high and little interference in this model, respectively. The L-user is assumed to receive interference from all the S-users, and each S-user receives interference only from the L-user. It is also assumed that the interference that L-user receives from all S-users is equal, and the interference that each S-user receives from L-user is also equal.

B. Determining the optimal CW for S-user

As shown in Fig. 4, let r_{L} be the occupation ratio of the communication time that an L-user can secure, and r_{S} be the average occupation ratio of the communication time that an S-user can secure. Here, the occupation ratio is the ratio of data frames per analysis time. The optimal CW in this investigation is defined as the value when $r_{\mathrm{L}} - r_{\mathrm{S}}$ is close to 0. Figure 5 shows the $r_{\mathrm{L}} - r_{\mathrm{S}}$ when the CW of the L-user is set to 7. The analysis time was set to 10 s. The numbers in parentheses indicate the number of L-user and S-user, respectively. From this figure, we obtained the CW for each S-user such that $r_{\mathrm{L}} - r_{\mathrm{S}} = 0$.

Figure 6 shows the approximate curve of the optimal CW. In the figure, the mark $\circ$ indicates the optimal CW of the S-user that minimizes the difference in occupancy in Fig. 5. In this study model, since the optimal CW of S-user exists in a specific interval, the optimal CW was determined by performing a quadratic approximation and rounding the resulting value to an integer. As a comparison, we determined the optimal CW of the S-user when the CW of the L-user was set to 3 and 15 using the same method.

IV. Evaluating Fairness through Simulation

A. Simulation environment

In this section, we examine the fairness of the communication time for each CW value of L-user. For simplicity, the frame structure consists only of a CW section for backoff control and a data frame section for sending packets, with 20 μs per slot, 1 ms per frame, and 10 s for analysis time. The CW of the L-user was set to 3, 7, and 15.

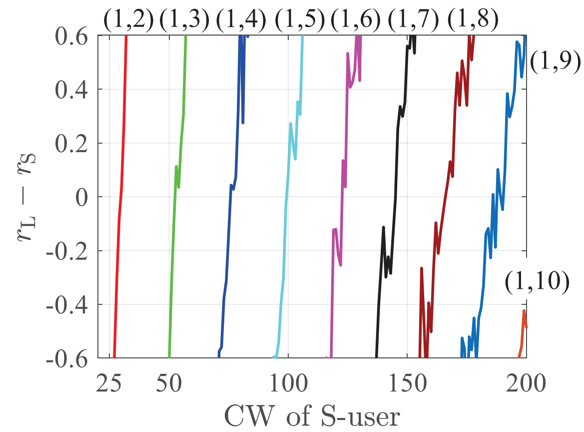

Fig. 5. $r_{\mathrm{L}} - r_{\mathrm{S}}$ versus CW of S-user in the case of CW of L-user of 7.

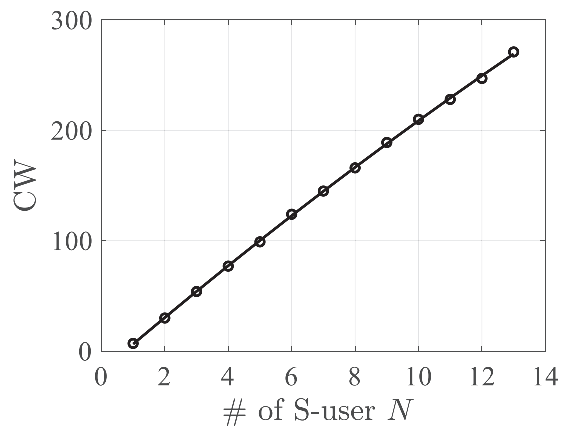

Fig. 6. Approximation curve of optimal CW of S-user in the case of CW of L-user of 7.

B. Simulation result

Figures 7 to 9 show the simulation results of the occupancy ratio against the number of S-user when the CW of L-users is set to 3, 7, and 15, respectively. The figures show that the red lines are the L-user, the blue lines are the S-user, the dashed lines are the conventional CSMA/CA, and the solid lines are the proposed method using the optimal CW. In the conventional method, there was a considerable difference in the occupation ratio between L-user and S-user. For example, the occupation ratio of L-user became less than 0.01 when the number of S-user exceeded 6. These results indicate that the fairness of wireless communication using mmW WBAN by the conventional method is much reduced in an overcrowded environment. On the other hand, in the proposed method, equal communication opportunities are provided for most case of numbers of S-user when the CW of L-user is 7 or 15. Communication opportunities are ensured even when the number of S-user increases. The CW of L user 3 deviated from the other two. Furthermore, a common point among the three types of CWs in the proposed method is that there is

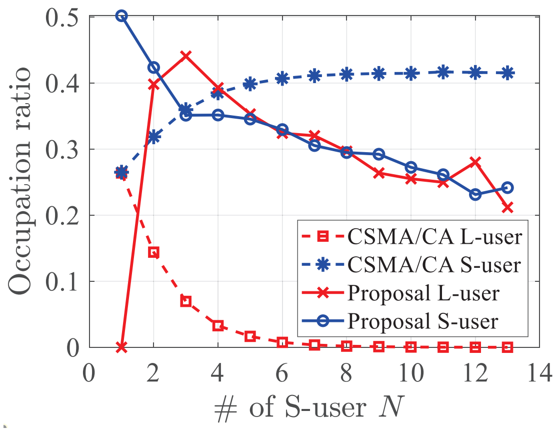

Fig. 7. Occupation ratio when CW of L-user is 3.

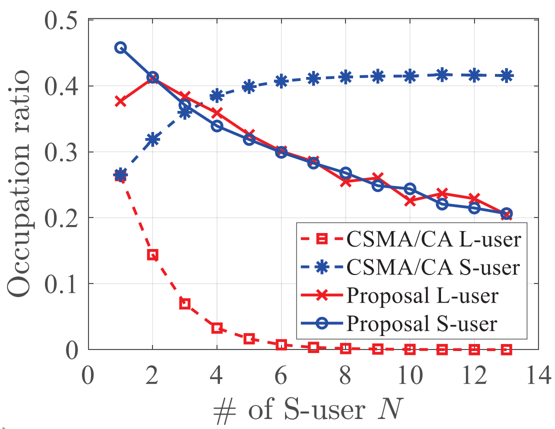

Fig. 8. Occupation ratio when CW of L-user is 7.

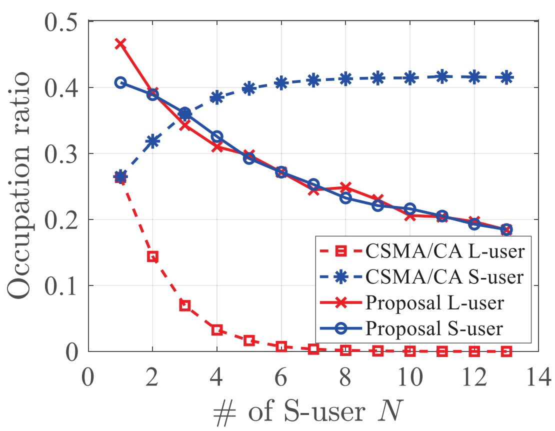

Fig. 9. Occupation ratio when CW of L-user is 15.

a large difference in the occupation ratio when the number of S-user is 1. Those problems due to the influence of the error caused by the second-order approximation, and this effect is more pronounced in Fig. 7, where the CW of the L-user

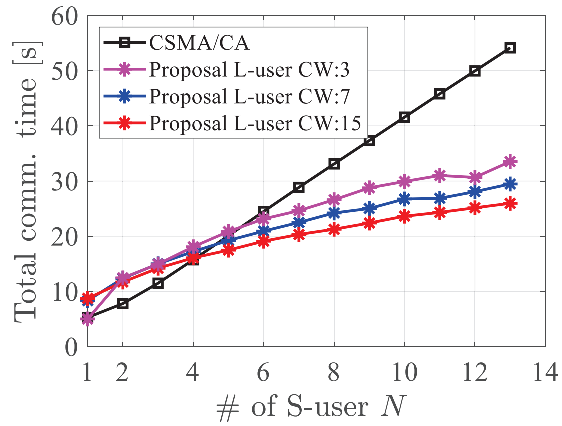

Fig. 10. Total communication time for each user.

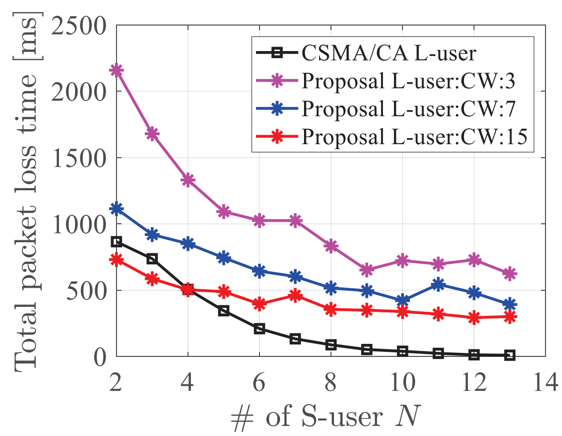

Fig. 11. Sum of packet loss time due to collision for each user.

is small. However, when the CW of the L-user is 7 or 15, the fairness of the proposed method is higher than that of conventional CSMA/CA. It is confirmed that the fairness can be improved by optimizing the communication opportunity of each user by backoff control in the overcrowded mmW WBAN environment.

In Fig. 10, the total communication time is compared between the proposed method with CW of 3, 7, and 15 for L-user and the conventional CSMA/CA. The vertical axis shows the sum of the communication time acquired by each user during the analysis time. It can be seen that the total communication time can be secured in the following orders: 3, 7, and 15 for the CW of the L-user. The total communication time on the vertical axis exceeds 10 s, i.e. simulation time, because each S-user is assumed to receive interference only from the L-user as a condition of the model under consideration. Therefore, when the L-user is not communicating, all S users can communicate at the same time. In addition, we can confirm that the total communication time of the proposed method is higher than the conventional method while maintaining fairness when the number of S-users is up to 4. Furthermore, when the number of S-users is 7, the communication time is 80.4 %, 73.2 %, and 64.3 % of that of CSMA/CA when the CW of L-user is 3, 7, and 15, respectively. The total communication time of the conventional CSMA/CA exceeds that of the CSMA/CA as the number of S-user increases is that the communication opportunity of S-user increases because L-user becomes impossible to communicate.

In Fig. 11, the packet loss time caused by collisions is compared between the proposed method and the conventional CSMA/CA. The vertical axis shows the sum of the packet loss times of each user during the analysis time. It can be seen that the smaller the CW of the L-user is, the more packet loss time due to collision there is in the proposed method. The simulation results confirm that the fairness of the proposed method is improved compared to the conventional CSMA/CA. In addition, when the CW of the L-user is 7, the total communication time is 8.9 points higher than when the CW of the L-user is 15. These results show that the proposed model improves fairness and ensures the total communication time when the CW of the L-user is 7 in the crowded mmW WBAN.

V. Conclusions

In a millimeter-wave (mmW) Wireless Body Area Network (WBAN) in an overcrowded environment, a situation occurs where many users interfere with one user. As a result, the fairness of communication opportunities is greatly reduced. In this study, we propose an inter-WBAN interference avoidance method that performs carrier sense and selects the optimal Contention Window (CW) size to ensure equal communication time for all users in each WBAN. The simulation results show that the optimal CW for S-user is determined when the CW of L-user is 7, which greatly improves the fairness of communication opportunities. Although the total communication time was degraded by 26.8 %, but the impact was minimized. These results show that the proposed model enables intra-WBAN communication without loss of fairness when the CW of L-user is 7 in an overcrowded mmW WBAN.

Acknowledgment

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