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Prototype Ultra Wideband-based Wireless Body Area Network -Consideration of CAP and CFP slot allocation during human walking motion-

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Abstract— **This paper presents an experimental evaluation of communication during human walking motion, using the medium access control (MAC) evaluation system for a prototype ultra-wideband (UWB) based wireless body area network for suitable MAC parameter settings for data transmission. Its physical layer and MAC specifications are based on the draft standard in IEEE802.15.6. This paper studies the effects of the number of retransmissions and the number of commands of GTS (guaranteed time slot) request packets in the CAP (contention access period) during human walking motion by varying the number of sensor nodes or the number of CFP (contention free period) slots in the superframe. The experiments were performed in an anechoic chamber. The number of packets received is decreased by packet loss caused by human walking motion in the case where 2 slots are set for CFP, regardless of the number of nodes, and this materially decreases the total number of packets received. The number of retransmissions and the GTS request commands increase according to increases in the number of nodes, largely reflecting the effects of the number of CFP slots in the case where 4 nodes are attached. In the cases where 2 or 3 nodes are attached and 4 slots are set for CFP, the packet transmission rate is more than 95%. In the case where 4 nodes are attached and 6 slots are set for CFP, the packet transmission rate is reduced to 88% at best.**

I. Introduction

In recent years, the aging population has been an emerging issue in society in developed countries and other countries around the world. The best examples of the problem are the lack of sufficient numbers of doctors to treat the increasing numbers of elderly patients and increasing medical expenses caused by the increasing birthrate. One suggested medical information and communication technology (medical ICT) solution proposes the prevention of lifestyle-related diseases through health care and home care [1]. The communications concept of body area networks (BAN) involves short-range communications around or inside the human body (implant) or on the body surface (wearable) rather than traditional communications [2]. Various methods have been proposed for the application of BAN, with medical ICT expected to be among the most prominent applications [3]. Remote monitoring of biological information is a concrete example of the use of BAN that is of most interest. In this application, a sensor wirelessly conveys a measured physiological signal such as an electrocardiogram (ECG) or SpO2 reading to a coordinator of the wireless BAN (WBAN). The sensor should be small and lightweight, and it is therefore difficult to use a high-capacity battery in the sensor when forming a sensor network around the human body. It is also necessary to suppress the power consumption of each terminal to collect biological data continuously. A communication mechanism that allows the exchange of packet data with low-power consumption is thus crucial for WBAN. It is also desirable to use wireless sensors to avoid constraining the movement of the body. Ultra-wideband (UWB) wireless technology can potentially meet these requirements [4]. Previous studies of BAN include channel models [5] [6] and simulations of the protocols for BAN [7] [8]. However, few of these cases reported experimental studies of WBAN using UWB radio. In this study, we experimentally demonstrate the use of a prototype wireless BAN based on the IEEE802.15.6 specification [9], using UWB-impulse radio (UWB-IR) for the physical layer, with a superframe for the MAC layer configuration [10], with the aim of achieving low power consumption and reliable communication to optimize the MAC protocol. Taking into account the MAC function based on a BAN standard, we investigated the effects of human body movement on the radio transmission environment. This is based on our aim to be able to configure MAC parameters for real applications in the future. In our previous reports, we studied experimental results for typical-use scenarios [11] to investigate the differences in packet transmission between standing and walking scenarios, and performed multi node experiments [12] to investigate the packet reception status when operating at the same time as the number of nodes is being expanded from one to four. In this paper we investigate the MAC operating status, in terms of the received numbers of data packets or retransmission packets or guaranteed time slot (GTS) request commands, and the number of sensor nodes during the walking motion of the human body, by changing the number of contention access period (CAP) slots and contention free period (CFP) slots.

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II. Prototype evaluation system

A. System Overview

The evaluation system is designed to test MAC protocols. The prototype was constructed based on the IEEE802.15.6 standard draft proposed by the National Institute of Information and Communications Technology (NICT) [9]. The system is composed of the following items: a laptop personal computer to run the evaluation program, wearable wireless modules for UWB-IR, a universal serial bus (USB) hub, and USB cables. The wearable wireless UWB-IR modules are divided into a hub (coordinator terminal) and nodes (mock sensor terminals), and they use the same hardware. The prototype evaluation system forms a WBAN with a star-like topology structure and logs the transmission and reception of packet flow. Each terminal is connected to the laptop personal computer through a USB cable to send the logged data.

B. *Design of PHY layer*

Table 1 shows the physical layer specifications of the prototype wearable wireless modules. The prototype adopts UWB-IR with a signal bandwidth of 700 MHz, and its center frequency is set to 4.096 GHz. The signal bandwidth is defined as the bandwidth that contains around 99% of the peak signal power. A pulse signal has a root raised cosine waveform, and the signal duration is approximately 2 ns. The pulse repetition frequency (PRF) of a train of impulse signals is 32 MHz. Non-coherent differential binary phase-shift keying (DBPSK) with direct sequence (DS) spreading is used, and is intended to reduce the load on channel estimation. The spreading sequence length can be set to the following chip values: 124 (4×31), 60 (4×15), and 28 (4×7) chips. A bit rate of 258 kbps is achieved on the physical (PHY) layer with a spreading sequence length of 124 chips. Similarly, 1.1 Mbps is achieved with 28 chips. In this experiment, we set the length at 124 chips. No error correction is adopted to reduce the circuit scale and to save power.

Fig. 1 presents the frame format used on the PHY layer for the prototype. The frame comprises a synchronized header (SHR) including the preamble and a start frame delimiter (SFD), the PHY header (PHR) including the transfer rate (Rate) and the frame length (FLN), the PHY payload, and a cyclic redundancy check (CRC). The length of the preamble is 64 bytes, and the PHY payload is set at 47 bytes. The transmitted signal waveform generation at the transmitter uses a digital-to-analog converter (DAC) sampling rate of 32 MHz. This configuration is suitable for a transmission process at the sensor terminal (node) that requires low power operation. At the receiver, the received signal, after quadrature detection, is quantized and sampled by the analog-to-digital converter (ADC) with sampling at 32MHz. Also, decoding operations such as despreading and differential encoding are carried out using all-digital processing.

C. *Design of MAC layer*

The MAC layer in this evaluation system is narrowed down to the functions on the baseline part of the MAC specifications in the IEEE802.15.6 standard draft (referred to as the MAC-proposal) proposed by NICT. The MAC-proposal defines the superframe structure as a virtual time-division transfer concept. Fig. 2 shows the superframe construction. The superframe is divided into the active BAN and the inactive BAN. In the active BAN superframe, the hub and nodes communicate synchronously at regular intervals in each slot in the superframe, according to each transfer step. In the inactive BAN superframe, there is no communication. The nodes are effectively asleep and wait until they receive the next beacon.

Fig. 3 shows the active BAN superframe construction. A superframe consists of multiple timeslots of constant duration. One of the time slots in a superframe is assigned to send a beacon packet, which is used to control the WBAN. The other time slots are then allocated to one of the CAP, the CFP, or the priority access period (PAP). In these three periods, slotted ALOHA is adopted as the access mechanism for the CAP and PAP, and time-division multiple access (TDMA) is adopted as the access mechanism for the CFP. In the UWB-IR method, in addition to the fact that the transmission power is very low, the time rate at which pulses are sent is short. This makes implementation of the full functionality of signal detection difficult. This is why slotted ALOHA is used in the CAP.

The beacon packet delivers information on the period type for each slot. The PAP is used to send a packet in emergency scenarios. As shown in Fig. 4, a CAP slot is divided into four mini-slots. A data packet or MAC command is sent during a mini-slot, and an acknowledgement (ACK) is received in a subsequent mini-slot. Examples of MAC commands to be transmitted include a request for time slots during the CFP in the next superframe, polling from the hub device to a node device, and a request to join or disconnect the WBAN. The GTS request will be described here. The GTS request is a kind of MAC command, as described above, where the node has data to be transmitted to the hub, and the GTS request is sent to the hub from the node in the CAP. The hub receives the request by receiving the GTS request command from the node and returns an ACK to the node. Then, the hub allows the node that sent the GTS request to occupy particular slots of the CFP in a superframe, and the node then performs the data transmission. TDMA is guaranteed to work in the CFP in this way.

Table 1. Physical layer specifications of prototype.

Parameters	Value
Transmit power density (Average)	Less than -41.3 dBm/MHz
Center frequency	4.096 GHz
Signal bandwidth	700 MHz
Pulse repetition frequency (PRF)	32 MHz
Modulation	DS+DBPSK
Spreading sequence length	124
Bit rate	258 kbps

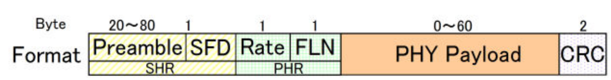

Fig. 1. Frame format on PHY layer.

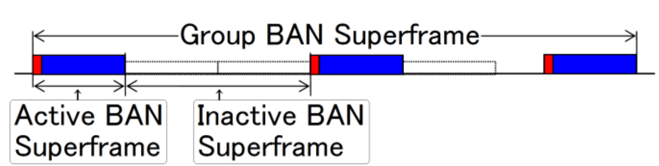

Fig. 2. Superframe construction in beacon mode.

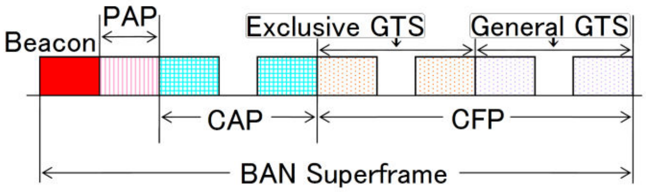

Fig. 3. Active BAN superframe construction.

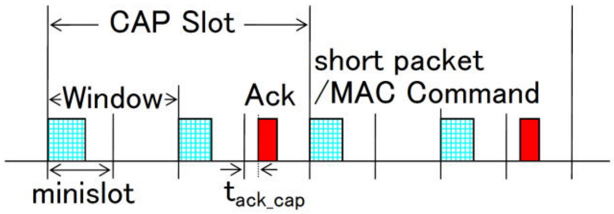

Fig. 4. Overview of operation in the CAP.

III. Experiments for Human Walking Movement

A. Experimental Overview

Experiments were performed in an anechoic chamber at Meiji University. After location of a prototype terminal on the subject body, the subject maintains a walking state (swinging arms gently, and stepping on the spot) during the measurements. By varying the number of available sensor nodes and the number of CFP slots, we investigated the effects on the total number of packets received, packet retransmission, and the number of GTS request commands. Table 2 shows the attachment locations of each of the nodes. The hub is located in the right pocket of the subject's trousers. The nodes are located, in order, on the chest, the right wrist, the right ankle and the left wrist. The data transmission from the nodes is in the direction of the hub.

Table 2. Mounting locations of prototype devices.

Device	Location
Hub	Trouser pocket on right
1st node (when 2 nodes)	Breast (Chest)
2nd node (when 2 nodes)	Right Wrist
3rd node (when 3 nodes)	Right Leg (Ankle)
4th node (when 4 nodes)	Left wrist

B. Configuration of MAC

Table 3 shows the value of the MAC parameter settings in the experiments. These default values are set based on the NICT recommendations. The total number of slots in a superframe is 16. The slots can be set to certain values because of the limitations of the MAC parameter settings. The number of CFP slots is decreased if the number of CAP slots is increased by the same amount. In this experiment, the CAP: CFP slot numbers are set to 8:6, 10:4, and 12:2. Also, the total number of transmission request packets is 300 per node. In other words, the total number of transmission request packets for the entire system is 600 packets for 2 nodes, 900 packets for 3 nodes, or 1200 packets for 4 nodes. The packet generation interval is the time interval in the buffer store when each node generates one packet, and it is not the transmission interval. The number of nodes, total number of transmission request packets and packet generation intervals are set values that do not affect the number of packets received if there is no movement of the human body.

Table 3. MAC parameter settings.

Parameter	Default	Settings
Max number of retransmissions	3 times	-
Max devices in a WBAN	4	-
Total slots in a superframe	16 slots	-
Beacon length (slots)	1 slot	-
PAP slots	1 slot	-
CAP slots	8 slots	8, 10, 12
CFP slots	6 slots	6, 4, 2
Duration of a time slot	10 ms	-
Duration of a superframe	160 ms	-
Beacon interval	320 ms	-
Number of transmission request packets	300	(per node)
Packet generation interval	1000 ms	-

C. Experimental Results

We now consider the experimental results. The graph in Fig. 5 shows the number of transmission request packets and the total received packets. In the cases of attaching 2 nodes and 3 nodes and when 10 CAP (4 CFP) slots were set, the system is seen to have successful packet transmission, with a packet loss rate of approximately 5% or less. However, when 12 CAP (2 CFP) slots were set; the packet loss rate becomes 53% for 2 attached nodes, and 58% for 3 attached nodes. The packet loss rate is 12% when attaching 4 nodes and 8 CAP (6 CFP) slots were set, 25% when 10 CAP (4 CFP) slots were set, and 80% when 12 CAP (2 CFP) slots were set, i.e. the loss rate becomes high when the number of CFP slots is reduced, and this affects the output significantly.

Fig. 6 shows the percentages of retransmission packets (data packets where retransmission occurs) as a proportion of the total received packets. The legend indicating "Retransmission" means that packet retransmission occurred, while that reading "No retransmission" means that the packet was transmitted successfully with no errors. There were maximum retransmission rates of 42% when attaching 2 nodes and 12 CAP (2 CFP) slots were set, 38% when attaching 3 nodes and 10 CAP (4 CFP) slots were set, and 46% when attaching 4 nodes and 8 CAP (6 CFP) slots were set. If we look at the numbers of total received packets in Fig. 5, if the retransmission rate is less than 30%, then this can be seen to meet the demands of the transmission request packets.

Fig. 7 shows the ratios of the number of retransmissions for the retransmission packets. The legend indicating "once" means that the packet was retransmitted once, with similar meanings for "twice" and "3 times". We can see that a gradual increase in the number of retransmissions is related to a reduction in the number of CFP slots in the 2 node case. When 3 nodes or 4 nodes were attached and 12 CAP (2 CFP) slots were set, there was a significant increase in the number of retransmissions.

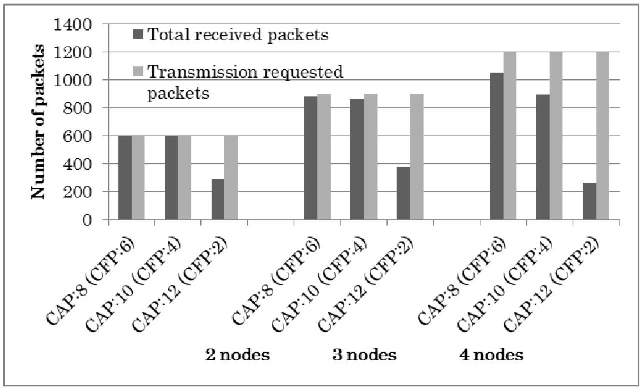

Fig. 5. Received packets and transmission requested packets.

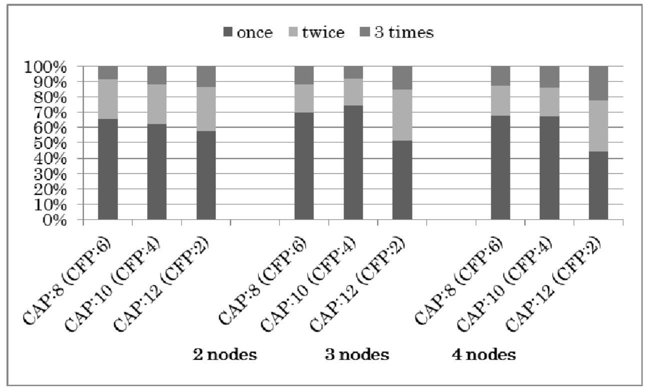

Fig. 7. Number of retransmissions in the same data packet.

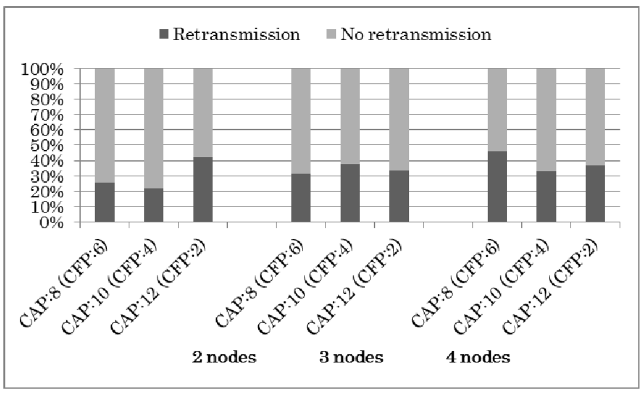

Fig. 6. Retransmission packet rate.

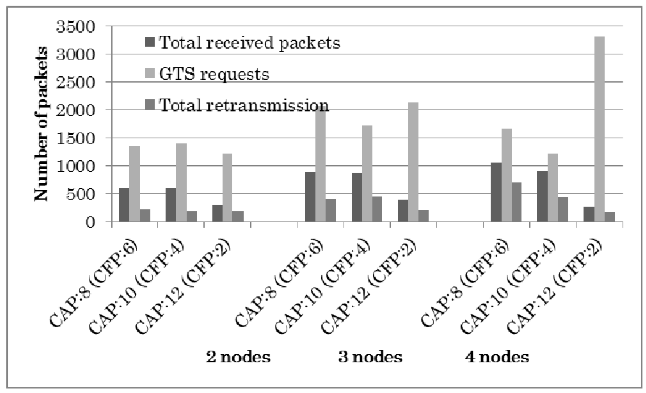

Fig. 8. Received packets, GTS requests and retransmissions (2 nodes).

Also, we can see that the retransmission ratio increases 3 times when 4 nodes are attached overall.

Fig. 8 shows the total number of received packets, the total number of GTS request commands received and the total number of retransmissions. The number of GTS requests means the total number of packets of GTS request commands which are transmitted from each node to the hub in the CAP slots, and that could be received at the hub. It is not the number of packets sent from the node. The total number of retransmissions means a count of all of the retry transfers written in the packet log. When attaching 2 nodes and setting 12 CAP (2 CFP) slots, a small decrease was observed in the number of GTS requests, along with a reduction in the number of packets received. However, little effect was observed on the number of retransmissions. When comparing the 2 node and 3 node cases, the number of GTS requests increases overall in the 3 node case. This is attributed to the effect of increasing the number of nodes. When 10 CAP (4 CFP) slots were set, the number of GTS requests decreased and the number of retransmissions increased slightly compared to the 8 CAP (4 CFP) slot case. However, no significant effect was observed on the total number of received packets.

When 12 CAP (2 CFP) slots were set, the number of retransmissions was greatly reduced and a smaller number of packets were received. If the number of nodes was increased, then a lack of CFP slots would occur, and it would not be possible to transfer all of the transmission request packets completely.

When attaching 4 nodes, except when setting 12 CAP (2 CFP) slots, the number of GTS requests is less than in the 3 node case. Also, when 10 CAP (4 CFP) slots were set, the GTS requests decreased. When 12 CAP (2 CFP) slots were set, there was a significant increase in GTS requests that reached about 3300. Although a lot of GTS request commands occurred at each node when the number of nodes increased to 4, when 8 CAP (6 CFP) slots or 10 CAP (4 CFP) slots were set, the number of CAP slots might be sufficient. However, it may also cause contention between the GTS request packets sent by each node. Meanwhile, the number of retransmissions decreased gradually, from 700 times when 8 CAP (6 CFP) slots were set, to 430 times when 10 CAP (4 CFP) slots were set, and finally to 170 times when 12 CAP (2 CFP) slots were set.

When setting 10 CAP (4 CFP) or 8 CAP (6 CFP) slots, a relationship with a similar trend is observed when attaching 3 nodes. At first glance, when 12 CAP (2 CFP) slots were set, the number of GTS requests shown seemed to have an unusually high value, but it can also be regarded as the same as the other cases for 3 nodes. After we increased the number of CAP slots (thereby reducing the number of CFP slots), the GTS requests tended to decrease, but they can be seen to have increased when setting 12 CAP (2 CFP) slots.

The significant difference between 3 nodes and 4 nodes is that more nodes lead to a sudden increase in the number of GTS requests in the 4 node case. This means that the deficiency in the number of CFP slots may be caused by a decrease in the number of packet transmissions per frame (per unit time). This suggests that with the increased number of nodes, each node would compete with attempts to reserve a slot in CFP to communicate to reduce its own buffer traffic. This might therefore cause a rapid increase in the number of GTS requests. Also, because there are only a few slots for data transmission (CFP slots), each node would accumulate transmission request packets, which wait to be sent in the buffer and cause buffer over flow. As a result, this would also reduce the number of received packets and the number of retransmissions. When 12 CAP (2 CFP) slots were set, no differences could be observed among the numbers of CFP slots in the 2 node case. However, as more nodes were added, total retransmission reached a limit of about 200 times, while the total number of received packets had a limit of between 300 and 400. For the same reasons, the total number of packets received is about 900, and the total retransmissions reached approximately 430 when 10 CAP (4 CFP) slots were set.

IV. CONSIDERATIONS

When attaching 2 nodes or 3 nodes, packet transmission is found to be successfully performed; and the transmission rate is more than 95% if there are more than 4 slots in the CFP. The retransmission rate of the data packets is 5 to 10% higher when attaching 3 nodes rather than 2 nodes, while the ratio of retransmissions in the same packets is slightly lower. However, when 2 slots were set in the CFP, the packet transmission rate was less than 50% when attaching 2 nodes or 3 nodes, and the whole retransmission situation degenerated. On the other hand, when attaching 4 nodes and when 6 slots were set in the CFP, the result was a packet transmission rate of 88% at best, which fell to 75% when 4 slots were set in the CFP, and to 20% when 2 slots were set in the CFP. Practical applications would have to use some error-correcting codes. In the case where 4 nodes were attached and 4 slots or 6 slots were set in the CFP, the packet retransmission rate increased by 5 to 10% compared to the results when attaching 2 nodes or 3 nodes. When 2 slots were set in the CFP, the number of retransmissions relative to the total number of retransmission packets produced the worst result, at less than 50% for single retransmission, and more than 20% for 3-time retransmission. The number of GTS request commands reached a significant level of approximately 3300. This was because there were many CAP slots and few CFP slots, and thus packets tended to accumulate at the buffer of each node. It can be assumed that GTS allocation requests were often made to try to resolve the accumulation on each node. As a general comment, when only 2 slots were set in the CFP, regardless of the number of nodes, it significantly reduced the total number of packets received. A possible buffer overflow would cause each node to decrease the amount of packet transmission per frame by reducing the CFP slots.

V. SUMMARY

In this report, we investigated the effects of received numbers of retransmission packets or GTS request commands using a prototype terminal using UWB-IR with a test MAC system in an anechoic chamber, by changing the number of CAP slots or CFP slots in the superframe structure, and the number of sensor nodes on the human body during walking motion. From the experimental results, when attaching 2 nodes or 3 nodes, and when 10 slots are set in the CAP (and 4 slots are set in the CFP), it was found that packet transmission rates of more than 95% could be achieved. However, when attaching 4 nodes and when 8 slots are set in the CAP (and 6 slots are set in the CFP), the optimum transmission rate value becomes 88% using these experimental parameters. Our future research must consider the effects of increasing the total number of slots. Also, we intend to conduct research on latency under various conditions and on the performance of each packet retransmission node relative to its mounting site.

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