Rate-Adaptive MAC Protocol in High-Rate Personal Area Networks

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***Abstract*—The specification of High-Rate Wireless Personal Area Network (HR WPAN) has been standardized by the IEEE 802.15.3 Task Group for communications of consumer electronics and portable communication devices and a final draft standard has been completed. The physical layer in IEEE 802.15.3 standard is designed to achieve data rates of 11-55Mbps. However, a MAC protocol in IEEE 802.15.3 standard does not specify the method to choose an appropriate data rate. In this paper, we propose a rate-adaptive Medium Access Control (MAC) protocol for HR WPAN. The data rate for the next transmission is selected by channel prediction based on the currently received frame and informs the sender about the changed rate using a rate-adaptive acknowledgement (RA-ACK) frame. By overhearing the RA-ACK frame, a piconet controller can efficiently allocate channel times. In addition, we propose a constant physical layer frame length regardless of a data rate. In this way, the channel can be more effectively utilized by squeezing more bits into one transmission. The proposed scheme is evaluated under a time-correlated fading channel model in terms of the achieved throughput. Simulation results show that this scheme achieves a much higher throughput than a non rate-adaptive MAC protocol in HR WPAN does.**

Keywords-Wieless PAN; MAC; Rate-Adaptive Protocol

1. INTRODUCTION

Wireless Personal Area Networks (WPANs) being studied by the IEEE 802.15 Working Group (WG) enable short range wireless connectivity among consumer electronics and communication devices. The radio range of WPAN is around 10 meters. The first standard of the IEEE 802.15 WG is IEEE 802.15.1 which is a technology based on the Bluetooth system. The features of this technology are low power consumption, low data rate, low cost and small package size. The data rate of Bluetooth is up to 1 Mbps.

The next technology of WPAN is targeted to consumer electronics and portable communication devices which need higher data rates. The IEEE 802.15.3 Task Group (TG) has been chartered with creating High-Rate (HR) WPAN standard and has published a final draft standard [1] recently. The target applications of the HR WPAN can be divided two categories. The first is a multimegabyte data file transfer such as image and music files. The second is the distribution of real-time video and high-quality audio. For supporting the higher data rate and Quality of Service (QoS), the HR WPAN supports data rates up to 55Mbps and adopts a Time Division Multiple Access (TDMA)-based MAC protocol. In HR WPAN, two nodes communicate through peer-to-peer connectivity without contention during allocated channel time.

As Federal Communications Commission (FCC) approved the commercial use of Ultra Wide Band (UWB) technology [2], the IEEE 802.15.3a Study Group (SG) has been established to study about using Ultra Wide Band (UWB) technology as a physical (PHY) layer transmission technique in HR WPAN. Using UWB technology, the maximum achieved data rate can be more than 500 Mbps.

Since a typical wireless channel is time-varying and HR WPAN supports five different data rates, an efficient communication system can be achieved by selecting a data rate according to the channel condition. This process is called rate adaptation. However, the mechanism for choosing data rate is not clearly defined in the IEEE 802.15.3 standard, but two methods, which will be described in Section 2, are suggested.

We propose a rate adaptive MAC protocol for HR WPAN. In addition, a scheme using a constant physical (PHY) frame length regardless of the data rate is proposed for achieving a better performance and an efficient use of channel time. The MAC layer and the methods to support a multi-rate in IEEE 802.15.3 are described in Section 2. In Section 3, the proposed rate adaptive MAC protocol is illustrated. The simulation environment for performance evaluation of the proposed protocol is described and the performance of our proposed scheme is evaluated in Section 4. In Section 5, we provide conclusions.

2. HIGH-RATE WPAN (IEEE 802.15.3)

2.1 MAC Protocol

The MAC layer specification in IEEE 802.15.3 is designed in order to support ad-hoc networking and provide multimedia QoS provision. The nodes with HR WPAN functionality are communicating on a centralized and connection-oriented ad-hoc networking topology called piconet. One piconet consists of a Piconet controller (PNC) and Devices (DEVs). Any DEV can be a PNC. To provide support for multimedia QoS, a TDMA-beasd superframe structure is adopted in the IEEE 802.15.3 standard. Fig. 1 shows the MAC superframe structure of IEEE 802.15.3. The superframe consists of three major

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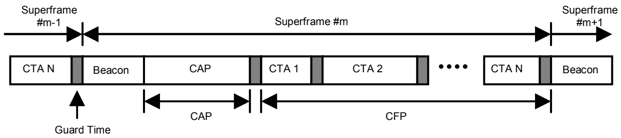


Figure 1. A superframe structure in IEEE 802.15.3 MAC

parts: a beacon, an optional Contention Access Period (CAP) and a Contention Free Period (CFP).

The beacon frame is transmitted by the PNC at the beginning of each superframe. It lets all DEVs know about the specific information for controlling a piconet. The CAP is used for short and non-QoS data frames and command frames. The medium access mechanism during the CAP is Collision Sense Multiple Access/Collision Avoidance (CSMA/CA). The remaining period in the superframe is CFP. The CFP is composed of Channel Time Allocation (CTA) periods which are assigned by the PNC through a beacon frame. During one CTA period, one DEV can transmit several frames to one target DEV without collision. Each frame transmission is followed by acknowledgement (ACK) frame and two Short Inter-Frame Spacing (SIFS) idle times as shown in Fig. 2.

The specification for the MAC protocol defines three acknowledgement types; no-acknowledgement (No-ACK), immediate-acknowledgement (Imm-ACK) and delayed-acknowledgement (Dly-ACK). An Imm-ACK will be transmitted from the destination DEV when a transmitted frame is received correctly, while in the No-ACK case, any ACK will not be transmitted to the source DEV. A Dly-ACK is used only for directed stream data frame, i.e. isochronous connections.

2.2. *Multi-Rate Support*

The IEEE 802.15.3 PHY layer is operating in the unlicensed frequency band between 2.4 GHz and 2.4835 GHz. The symbol rate is 11 Mbaud. The raw PHY layer data rates are 11Mbps for uncoded QPSK modulation, and 22, 33, 44, and 55 Mbps for trellis-coded QPSK, 16/32/64-QAM, respectively. The specification in IEEE 802.15.3 MAC suggests two methods to obtain channel condition information and to select a data rate for transmission. The first method is to periodically transmit the channel request command to a target DEV. When receiving that command, the target DEV sends a channel status response command back to the transmitting DEV. The channel status response command includes the number of successfully received frames, the number of erroneous frames and the number of measured frames. The source DEV decides a data rate based on this information. In the second method, the channel condition is evaluated by the presence or absence of ACKs for the transmitted frames. This information is used to decide the data rate for the next frame transmissions. If the Dly-ACK mechanism is used, all frames in a burst are transmitted with the same data rate.

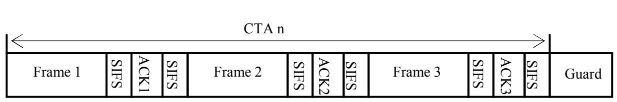


Figure 2. Multi-frame transmission within a CTA

3. PROPOSED MAC PROTOCOL

3.1. Motivation

As mentioned in Section 2.2, the channel condition in IEEE 802.15.3 is estimated based on the results of attempted transfers of data frames between two DEVs that are actively participating in a data transfer. The other method to estimate the channel condition is to use a PHY layer parameter indicating the channel condition, i.e. Signal-to-Noise Ratio (SNR). In [4], these two methods for the channel condition estimation are evaluated over WLAN environment. The evaluation in [4] shows that the method using the PHY layer parameter achieves the higher performance gain than that using the result of attempted transfers of data frames.

In wireless cellular networks, many rate-adaptation schemes have been proposed using centralized TDMA-based MAC protocols [5][6]. All these schemes are developed at the Base Station (BS) in a centralized fashion. Since all communication links are established between a BS and Mobile Terminals, the BS can collect the channel information of all communication links so that a data rate for each communication link is easily selected by the BS. On the other hand, in IEEE 802.15.3 standard, a source DEV communicates directly with a target DEV, not with a PNC. Thus, the channel estimation and the rate selection have to be done by a pair of DEVs participating in a communication. However, the PNC needs to know the selected data rate in order to allocate an optimal channel time for the communication of the pair of DEVs.

In addition, contrary to the cellular networks transmitting one frame in a timeslot, a source DEV can transmit multiple frames to one target DEV during allocated channel time as mentioned in Section 2.1. In this situation, the frames within a CTA may experience different channel quality that leads to a rate change. Thus, a mechanism needs to monitor the channel change.

In order to solve such problems mentioned above and to enhance the throughput performance, we propose a rate-adaptive MAC protocol for IEEE 802.15.3. The main application for our proposed protocol is file transfer of asynchronous bursty data such as Music files (average 3Mbytes) and image file (average 500 Kbytes) defined in [3]. In addition, this application uses Imm-ACKs as acknowledgements.

3.2. Rate-Adaptive MAC protocol for IEEE 802.15.3

In our protocol, the data rate is selected at the receiver based on the channel condition estimated in the PHY layer as mentioned above. Instead of using a command frame for a rate adaptation, data and acknowledgement frames are used in the proposed protocol. When a target DEV receives a data frame, it estimates the channel condition and selects the data rate. If the selected rate is not the same as the rate of the received frame, the target DEV sends an Rate-Adaptive Acknowledgement (RA-ACK) frame including the selected rate back to the source DEV. The RA-ACK frame is slightly

Bits : 5	1	1	1	2	1	3	2
Reserved	More Data	Retry	Delayed ACK request	ACK policy	SEC	Frame type	Protocol version

Figure 3. Frame control field in the MAC header of IEEE 802.15.3

changed from an ACK frame in the specification of IEEE 802.15.3 standard, but no additional bits are needed. As Fig. 3 shows, the *Reserved* subfield in the *Frame control* field in the MAC header is used as the *Rate* subfield, witch indicates the selected rate for the next transmission and the *frame type* subfield is set to the value 101.

In the IEEE 802.15.3 standard, when the transmission of a data frame fails, no ACK frame is sent back to the source DEV. However, the transmission failure can be caused by a channel quality change. Thus, when the rate needs to be changed even in the case of the transmission failure, the target DEV sends the RA-ACK to the source DEV.

As mentioned in Section 3.1, the PNC also needs to know the rate of each communication link for the better channel time allocation. Whenever the PNC hears a RA-ACK frame, it updates a data rate of the communication link to one obtained from the RA-ACK frame. Then, the PNC modifies the currently allocated channel time for the communication link with the updated data rate and the modified information is broadcasted through a beacon frame in the beginning of the next superframe. If a power control mechanism is applied to the communication of the pair of DEVs, the RA-ACK frame is transmitted with the highest possible power so that the PNC can reliably hear it. Since a source DEV has no information of a rate and a channel condition before the first frame transmission, it requests a CTA to the PNC with an initial data rate, which may be the lowest rate and the PNC allocates a channel time with the initial data rate. When the data rate needs to be changed, the source DEV and the PNC will hear the first RA-ACK frame from the target DEV. In addition, the lastly changed data rate in a CTA is used for the first transmission of a data frame in the CTA of the next superframe. An example of allocating a channel time in a certain scenario will be illustrated in Section 4.1.

3.3. Constant PHY frame length

Using rate adaptation with a fixed MAC frame length, the length of a PHY frame varies according to the data rate [7][8]. The higher the data rate is, the shorter the length of the PHY frame is. In general, it is assumed that a channel is static during one frame transmission [3][7][8]. This means that the channel is constant even during the transmission of a PHY frame at the lowest data rate, which is the longest PHY frame among all frames at the supported rates. Thus, more information bits can be transmitted at the higher data rates during the same period as that of a PHY frame transmission at the lowest data rate. For this purpose, the PHY frame length needs to be kept constant regardless of the data rate, while the MAC frame length needs to vary according to the data rate. In our previous study, we demonstrated the advantage of this scheme for a distributed wireless LAN [8]. To better understand the mechanism, sample protocol time lines for the

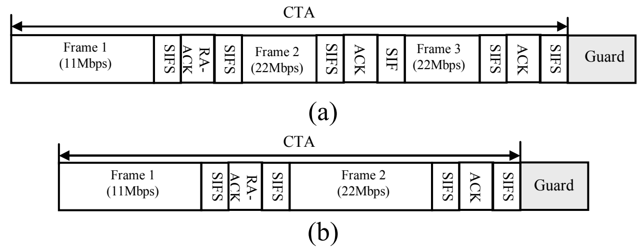


Figure 4. Time lines for the cases with (a) constant MAC frame length and (b) constant PHY frame length

cases with constant MAC frame length and constant PHY frame length under the proposed rate-adaptive protocol are shown in Fig. 4. In Fig. 4(a), the length of Frame 3 at 55Mbps is shorter than that of Frame 1 at 33Mbps. On the other hand, the lengths of all frames using the proposed scheme are the same in Fig. 4(b). In IEEE 802.15.3, the MAC frame payload and Frame Check Sequence (FCS) are modulated at the desired rate. Thus, to maintain a constant PHY frame length, the MAC frame payload size at the desired rate R needs to be

$$N_R = \frac{N_L \cdot R}{SR} - N_{FCS} \quad , \qquad (1)$$

where N_L is the MAC frame payload size with the FCS at the lowest rate, N_{FCS} is a number of bits in the FCS, and *SR* is the symbol rate. Using the scheme of uniform PHY frame length reduces the number of PHY frames required for transmitting a certain amount of information comparing to the same MAC frame length. Therefore, the overheads caused by the preamble, PHY/MAC headers, two SIFSs, and ACK frame produced by one data frame transmission are reduced. With UWB technology employed in the physical layer for the future HR WPAN, this scheme is more efficient since the communication system using UWB needs a long preamble to synchronize a received PHY frame [9].

3.4. Interaction between MAC and LLC layers

In IEEE 802.15.3, an MAC Service Data Unit (MSDU) comes down from the Logical Link Control (LLC) layer. If the MSDU length is larger than that of a required frame, it is fragmented into smaller frames. The length of a MSDU is set to 2048 bytes in the IEEE 802.15.3 standard. However, a larger MSDU is required in order to keep all PHY frame lengths be the same. For instance, according to (1), if a MAC frame length at 11 Mbps is 1024bytes, the length at 55Mbps is around 5120bytes, which is larger than the maximum MSDU length. Therefore, we propose an interaction mechanism between the MAC and LLC layers. For a multimegabytes file transfer, it is assumed that the LLC layer has enough information to transmit. When the rate is selected and the required MAC frame length is larger than 2048bytes, the LLC layer sends more MSDUs down to the MAC layer by the request of MAC layer and these MSDUs are combined into one large frame. Finally, one MAC frame is generated from these MSDUs. When the length of the large frame is larger than a required length, the remaining part of the frame after the required MAC frame is generated is combined with MSDUs coming from the LLC layer for the next MAC frame.

This process continues until the transmission of all information in the LLC layer is completed.

4. PERFORMANCE EVALUATION

4.1. Simulation Setting

Our proposed scheme is evaluated over the application of bulk file transfer such as music or image files. Thus, we assume that all DEVs in a piconet have large files to be transferred and the size of the file is uniformly distributed over the range from 500K bytes to 3M bytes at each node. For simplicity, we assume that the size of the file is same as the total information that MAC layer have to transmit. In our simulation, the channel time for each CTA are evenly divided for all DEVs in a superframe since traffic types of all DEVs have the same priority. The channel time of a CTA in a superframe is

$$T'_{CTA} = \frac{T_{CFP}}{N_{DEV}} \quad , \tag{2}$$

where T_{CFP} is a duration of the CFP in the superframe and N_{DEV} is a number of DEVs in a piconet. When a DEV requests a CTA to the PNC, the data rate for the frame transmission is informed to the PNC. Therefore, PNC can estimate the time duration for one frame transmission. With this estimated duration, the channel time of a CTA with (2) is then

$$T_{CTA} = \left\lfloor \frac{T'_{CTA}}{\left(T_{frame} + 2 \cdot T_{SIFS} + T_{ACK}\right)} \right\rfloor \cdot \left(T_{frame} + 2 \cdot T_{SIFS} + T_{ACK}\right), \tag{3}$$

where T_{frame}, T_{SIFS}, and T_{ACK} are the data frame transmission time, SIFS idle time and the ACK frame transmission time, respectively.

We assume that all nodes are uniformly distributed in the coverage area of a piconet, which is 10 meter radius in [14], and within the radio range of each other. For simplicity, we assume that the headers of all types of packets are always reliably received. Since the control and command frames are much shorter than data frames, no transmission failure of these frames are considered for simplicity. The parameters used in this simulation study are chosen based on the IEEE 802.15.3 standards [1].

We compare the throughput achieved by the following three different configurations:

Case 1: protocol with RA-ACK and constant PHY frame length (RA-ACK-CPF);

Case 2: protocol with RA-ACK and constant MAC frame length (RA-ACK-CMF); and

Case 3: protocol with fixed data rate (FDR).

In Case 3, once the initial data rate is chosen, a rate change is not allowed until a communication between two DEVs finishes.

To succinctly demonstrate the ability of the proposed protocol of adapting to the changing channel condition, we assume that the system adapts the data rate by properly choosing one from a set of modulation schemes according to the channel condition. The set of modulation schemes used in this simulation study are BPSK, QPSK, 8PSK, 16QAM, and 32QAM. For simplicity, we ignore other common physical layer components such as error correcting coding. The symbol rate is 11 Mbaud based on IEEE 802.15.3 so that data rates using above modulation set are, respectively, 11, 22, 33, 44, and 55 Mbps, which are the same as IEEE 802.15.3. A modulation scheme from the above set is chosen so that a target Frame Error Rate (FER) can be achieved at the current channel SNR level. Assuming that the symbol errors within a PHY frame are independent, the FER is related to the SER by

$$FER = 1 - (1 - SER)^N \quad , \tag{4}$$

where N is the number of symbols in the frame. We set the target FER to 8% according to the IEEE 802.15.3 standard [1]. We study the performance of our scheme with the frame sizes, 1024bytes and 2048bytes, which include the MAC frame payload and FCS, at the lowest data rate (11Mbps), that is N_L in (1) is 1024bytes or 2048bytes. The MAC payload length is set from (1). With these choices of parameters, the target SERs are obtained from (3). By consulting the theoretical SER performance of each modulation scheme in [10], the SNR ranges for corresponding modulation schemes that the target SER is satisfied are chosen.

The SNR ranges for case2 are different from those of case 1 because the PHY frame lengths for the two cases are different so that different SNR ranges need to be applied to meet the same target FER requirement. The SNR ranges for case 3 are same as that for case 2.

We evaluate the performance of the proposed scheme in a time-correlated fading channel with 8Hz Doppler frequency, which corresponds to a pedestrian speed (1m/s). The fading gain is generated according to the modified Clarke and Gans fading model [11]. We set the path loss exponent to 2 in the log-distance path loss model, which is obtained from measurements in an office environment at 2.4 GHz in [12]. For the channel condition estimation and prediction process in our simulations, we use the SNR measured at the end of the reception of data frames for the next frame transmission. In practice, more practical prediction and tracking algorithms are needed, e.g., the adaptive long-range prediction scheme in [13]. The transmit power is 0dBm that complies with FCC rules [14]. All simulations were performed for the duration of 60 seconds simulation time.

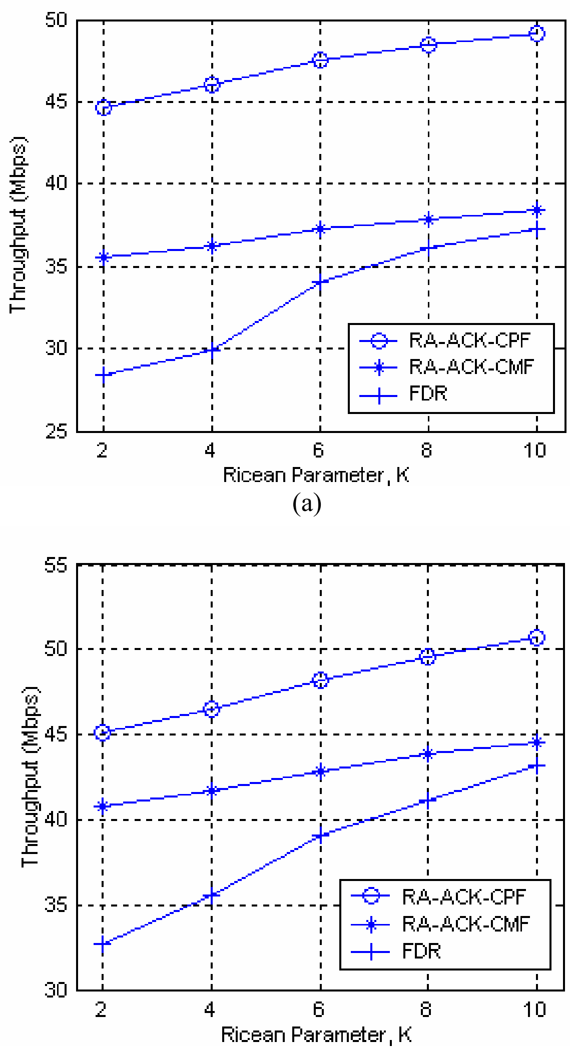
4.2. Performance Evaluation

We vary the Ricean parameter, K, from 2 to 10. The number of DEVs is 10. The Ricean parameter, K, represents the strength of the line of the sight component of the received signal. As K increases, the strength of the LOS component increases. Therefore, the performances of the three configurations improve with increasing K. Fig. 5 shows the throughput performance under different Ricean parameters. Form Fig. 5(a), the throughput of RA-ACK-CPF is up to 28%

higher than that of RA-ACK-CMF and 58% higher than that of FDR. From Fig. 5(b), we observe that the throughput of RA-ACK-CPF is up to 13% higher than that of RA-ACK-CMF and 38% higher than that of FDR.

The performance difference between RA-ACK-CMF and FDR reduces with the higher K. Fig. 6(a) and (c) explains this. Fig. 6(a) shows the rate of the number of CTAs experiencing the data rate change among total number of CTAs. RA-ACK-CMF can cope with the channel quality change by the rate adaptation employing RA-ACK frame while FDR cannot. The FER performances of theses two cases in Fig. 6(c) reflect the effect of the rate adaptation. Thus, RA-ACK-CMF achieves the performance gain comparing to FDR. However, as K increases, the probability that the data rate changes during a file transfer reduces and the effect of the rate adaptation reduces as shown in Fig. 6(c). Therefore, the gain of RA-ACK-CMF reduces with the higher K.

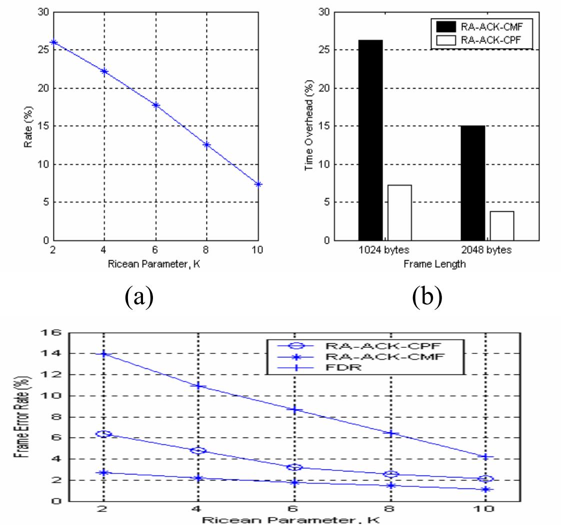
The performance gain of RA-ACK-CPF comparing to that of RA-ACK-CMF is mainly achieved by the difference of the



(a)

(b)

Figure 5. The throughput as a function of Ricean Parameter with different frame sizes at 11 Mbps, (a) 1024bytes and (b) 2048bytes



(a) (b)

(c)

Figure 6. The performance evaluation for (a) the rate of CTAs with a data rate change and (b) time overhead and (c) Frame Error Rate

overhead required to transmit a certain amount of data. In Fig. 6(b) shows the portion of the time overhead during simulation time. The time overhead includes the time durations of the preamble, PHY/MAC headers, Header Check Sequence (HCS), FCS, SIFS idle time, and ACK/RA-ACK frames. The time overhead in RA-ACK-CPF drops up to 26% of that in RA-ACK-CMF as Fig. 6(b) shows. On the other hand, because the length of PHY frames in RA-ACK-CPF is always equal or larger than that in RA-ACK-CMF, the FER of RA-ACK-CPF is higher than that of RA-ACK-CMF as shown in Fig 6(b). However, the FER difference between theses two cases reduces with the higher K. This explains that the performance gain of RA-ACK-CPF comparing to RA-ACK-CMF increases with the increase of K as shown in Fig. 5.

5. CONCLUSION

In this paper, we propose a rate-adaptive MAC protocol with a constant PHY frame length for HR WPAN. The data rate is selected based on the channel condition estimated from the received data frame in PHY layer. The selected rate information is delivered by the RA-ACK frame. When the PNC hears the transmission of RA-ACK frame, it updates the data rate of the communication link. Using this rate adaptation scheme, the HR WPAN system efficiently copes with the time-varying channel. To obtain better performance, a constant PHY frame length mechanism is proposed so that the channel efficiency is increased due to reduced overheads. Simulation results show that the proposed rate-adaptive MAC protocol gives a 58% throughput gain over the non rate-adaptive MAC protocol in IEEE 802.15.3.

REFERENCES

[1] Draft Standard for Part 15.3: Wireless Medium Access Control and Physical Layer Specifications for High Rate Wireless Personal Area Networks (WPAN), Draft P802.15.3/D17, 2003.

[2] Federal Communications Commission (FCC 02-48), "Revision of Part 15 Regarding Ultra-Wideband Transmission," ET Docket 98-153, First Report and Order, April 2002.

[3] "IEEE 802.15.3 (TG3) Criteria Definitions," IEEE 802.15-00/110r13, September 2000.

[4] G. Holland, N. Vaidya, and P. Bahl, "A rate-adaptive MAC Protocol for wireless networks," Proc. ACM MOBICOM'01, pp. 236-251, July 2001.

[5] V. K. Lau, and Y.-K. Kwok, "On the synergy between adaptive physical layer and multiple-access control for intergrated voice and data service in a cellular wireless network," IEEE Transactions on Vehicular Technology, vol. 51, pp.1338-1351, November 2002.

[6] T. Ikeda, S. Sampei, and N. Morinaga, "TDMA-based adaptive modulation with dynamic channel assignment for high-capacity communication systems," IEEE Transactions on Vehicular Technology, vol. 49, pp. 404-412, March 2000.

[7] Sadeghi, V. Kanodia, A. Sabharwal, and E. Knightly, "Opportunistic media access for multirate ad hoc networks, Proc. ACM MOBICOM' 02, September 2002.

[8] B-S. Kim, Y. Fang, T. F. Wong, and Y. Kwon, "Dynamic Fragmentation Scheme for Rate-Adaptive Wireless LANs," Proc. IEEE PIMRC'03, September 2003.

[9] S. S. Kolenchery, J. K. Townsend, and J. A. Freebersyser, "A Novel Impulse Radio Network for Tactical Military Wireless Communications," Proc. IEEE MILCOM'98, vol. 1, pp. 59-65, October 1998.

[10] J. G. Proakis, "Digital communications," 3rd ed. New York:McGraw-Hill, pp. 257-282, 1995.

[11] R. J. Punnoose, P. V. Nikitin, and D. D. Stancil, "Efficient simulation of ricean fading within a packet simulator," Proc. IEEE VTC'00, pp.764-767, 2000.

[12] G. G. M. Janssen and R. Prasad, "Propagation measurements in indoor radio environments at 2.4 GHz, 4.75 GHz and 11.5 GHz," Proc. IEEE VTC'92, pp. 617-620, May 1992.

[13] A. Duel-Hallen, S. Hu, and H. Hallen, " Long-range prediction of fading signals," IEEE Signal Processing Magazine, pp. 62-75, May 2000.

[14] J. Karaoguz, "High-Rate Wireless Personal Area Networks," IEEE Communication Magazine, pp. 96-102, December 2001.