

Frame-Size Adaptive MAC Protocol in High-Rate Wireless Personal Area Networks

Eun-Chang Choi, Jae-Doo Huh, Kwang-Sik Kim, and Moo-Ho Cho

ABSTRACT—In this letter, we propose a frame-size adaptive MAC protocol for high rate wireless personal area networks (WPANs). In the proposed scheme, during communication, frame error rate is periodically reported to a transmitting device and the frame size is changed according to the measured results. Thus, the channel can be more effectively utilized by adapting to variable radio conditions. Analytical results show that this scheme achieves a much higher throughput than a non-frame-size adaptive media access control protocol in high-rate WPANs.

Keywords—Wireless PAN, MAC, frame-size adaptive.

I. Introduction

The quality of wireless personal area network (WPAN) links suffers from time varying channel degradations such as interference, flat-fading, and frequency-selective fading. The channel variations are inherently uncontrollable, and their dynamic range is so large (fades can be as deep as 20-30 dB) that it is not energy efficient to design the radio for the worst case [1]. To adapt the channel variations, the IEEE 802.15.3 standard for high-rate (HR) WPANs supports five different data rates and an efficient communication system can be achieved by adapting the data rate according to the channel conditions [2]. Rate adaptation schemes have been proposed in some papers [1], [3]. In a time-correlated fading channel communication environment, as frame size increases, frame error rate (FER) also increases [1]; thus, an efficient communication system also can be achieved by selecting

media access control (MAC) frame size according to the channel conditions. Recent results based on simulations and measurements have shown that optimizing frame size can significantly improve throughput as well as energy efficiency [1], but there is little research on an analytical model of MAC frame-size adaptation in wireless communication. Therefore, an analytical model is presented here to show the advantage of MAC frame-size adaptation in WPAN environments. In this letter, we focus on the analysis of a frame-size adaptation protocol in HR WPANs for achieving better performance and efficient use of channel time.

II. The Proposed MAC Protocol

1. Channel Access in IEEE 802.15.3

In the IEEE 802.15.3 standard, a source device (DEV) communicates directly with a target DEV [2]. Thus, the channel estimation has to be done by a pair of DEVs that are actively participating in a data transfer. To support multimedia QoS, a time division multiple access (TDMA)-based superframe structure is adopted [2]. In the superframe, channel time allocations (CTAs) are used for commands, isochronous streams, and asynchronous data connections. During one CTA period, one DEV can transmit several frames to one target DEV without collision. Thus, even within a CTA, the frames may experience different channel quality. A mechanism needs to monitor the channel change and to adapt the channel variation to enhance performance. We propose a frame-size adaptive MAC protocol for IEEE 802.15.3. The main application for our proposed protocol is the file transfer of asynchronous bursty data such as music files (average 3 MB) and image files (average 500 kB) defined in [4]. In addition, this application uses immediate acknowledgments (Imm-ACKs).

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2. Frame-Size Adaptive MAC Protocol

Once the initial data rate is chosen using the mean signal to noise ratio (SNR), the data rate is not changed until a communication between two DEVs finishes. Initially, fixed sized training frames are transmitted with known data, and the FER is calculated with burst and gap size from received data. Then, the allowable MAC frame size L is obtained from the equation derived in the next section considering the mean burst size (MBS) and mean gap size (MGS), while the initial FER with the frame size must be lower than the required FER of 8% [2], [3]. Periodically, the FER is measured after two DEVs start communication. Measured FERs are obtained with the window size of multiple received frames, where the window size means the number of frames used for FER measurement.

The frame size can be calibrated against changing channel conditions. The measured results are reported to the sender using a modified acknowledgement (ACK) frame. The modified ACK frame is changed from the specification of IEEE 802.15.3 standard and uses the reserved subfield in the frame control field in the MAC header as the size adaptation subfield [2], [3]. If the measured FER is lower than the required FER, the frame size is increased to $L+\Delta$, where Δ is a group of bits (64 bits or 128 bits) and depends on the channel conditions. Otherwise, if the calculated FER is higher than the required FER, the frame size is decreased to $L-\Delta$. Upper and lower boundaries for FER are used to prevent L fluctuating around the optimal frame-size value. Therefore, when the MBS and MGS are stable, this adaptive scheme may not fluctuate around the optimal value.

3. MAC Frame Error Modeling

The HR WPAN system uses four different modulation schemes to achieve 22, 33, 44, and 55 Mbps transfer rates while keeping the symbol rate fixed at 11 Mbaud. To sustain the higher rates, an eight state variable rate Ungerboeck trellis coded modulation or TCM is used [2]. Most approaches assume that an error occurs independently between bit streams in a frame [3]. However, an error event happens as a bursty type in real communication systems that use Viterbi decoding as a channel coding scheme [5].

Recently, a computer simulation was performed to show agreement between the geometric distribution proposed by Miller [6] and the result of a simulation about probability density function (PDF) of burst size used in terrestrial digital audio broadcasting (DAB) mobile communication [7], [8]. The channel model in an HR WPAN can be different from the COST-207 model used in DAB [8]. However, two systems will present similar FERs in the same MBS and MGS because the same convolutional coding scheme is used for both systems.

Therefore, in this letter, the FER is derived based on the probability distribution of a burst as follows.

The bit stream of “ $exxx \cdots xe$ ” is defined as a “burst” of the length B . The bit stream of c 's between two consecutive bursts is defined as a “gap” with the length G , which is larger than $K-1$, where character c means the decoded bit without error, e means the bit with error, and x means c or e , and K is the constraint length of convolution coder [7].

Miller [6] used geometric distribution for modeling the probability distribution of bursts and gaps. Model parameters are the MGS, MBS, and mean bit error rate within a burst. The probability distribution of burst size is given by

$$P(B=l) = p(1-p)^{l-1}, \quad l > 0, \quad (1)$$

where $p = 1/\bar{B}$, \bar{B} means MBS.

The FER is mainly affected by the probability distribution of a gap which is defined as $P(G=g)$. $P(G=g)$ means g consecutive bits without error in the output of a Viterbi decoded bit stream. The probability distribution of gap size is given by [6]

$$P(G=g) = q(1-q)^{g-K+1}, \quad \forall g \geq K-1, \quad (2)$$

where $q = 1/(\bar{G} - K + 2)$, \bar{G} means MGS, and K is the constraint length of the convolution coder.

Define $FER(L)$ as the frame error rate in a MAC frame with the size L . Then, $FER(L)$ can be approximated by

$$FER(L) = \frac{\bar{B} + L - 1}{\bar{B} + \bar{G}} (1-q)^{L/2 - K + 1 - \bar{B}/2}, \quad (3)$$

where the range of L is $(4K - 4 + \bar{B}) \leq L \leq (\bar{G} + 1)$.

4. Throughput of the Proposed MAC

In our proposed scheme, the channel time for each CTA is evenly divided for all DEVs in a superframe, if traffic types of all DEVs assume the same priority. The channel time T_{CTA} of a CTA in a superframe is obtained by

$$T_{CTA} = T_{CFP} / N_{DEV}, \quad (4)$$

where T_{CFP} is a duration of the contention free period (CFP) in the superframe and N_{DEV} is a number of DEVs in a piconet.

When a DEV requests a CTA to the piconet coordinator (PNC), the data rate for the frame transmission is informed to the PNC. Therefore, the PNC can estimate the time duration for one frame transmission [3]. The throughput TP_{CTA} of the proposed MAC is given by

$$TP_{CTA}(L) = (R \cdot T_{CTA} / T_{STT}) (1 - FER(L)) / (1 + \alpha), \quad (5)$$

where R is the data rate, T_{STT} is the superframe transmission time, L is the MAC frame payload size with the frame check sequence and α is the ratio of overhead time to frame time consisting of the preamble, the PHY/MAC headers, two short interframe spaces, and the ACK frame produced by one data frame transmission.

III. Performance Analysis

1. Assumptions

We assume that all nodes are uniformly distributed in the coverage area of a piconet, which has a 10 meter radius [9], and are within 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 the data frames, no transmission failure of these frames is considered for simplicity. The parameters used in this simulation and analytical study are chosen based on the IEEE 802.15.3 standards [2]. We compare the throughputs achieved by the following two different configurations. The first is a protocol with variable MAC frame size (VMFS), and the second is a protocol with constant MAC frame size (CMFS). VMFS and CMFS are evaluated under various channel conditions in terms of the achieved throughput. For performance analysis, probability distributions of burst and gap are used instead of the fading channel model [7], [10]. Assuming that burst events are generated with (1) and gap events are generated with (2), these events are generated in turn, and frames are generated with a Poisson process with the mean value of overhead ratio $\alpha = 0.02$ of 8,192 bits (maximum frame size). The data rate is 11 Mbps and constraint length K of the Viterbi decoder is 3 [2], [3].

2. Simulations and Analytical Results

The computer simulation is performed with the window size of 300 frames, $MBS = 9.972$, $MGS = 9,606.66$ [5], [7] and a MAC frame size equal to 1024 bits. As the window size increases, the variation of measured FER is lower. The window size of 300 frames (1024 bits/frame) means 30 ms under the data rate of 11 Mbps, which is reasonable to cope with changeable radio channel conditions or under a slow fading condition such as 10 Hz.

Figure 1 shows the throughput and optimal frame size which is changed by the measured FER. Upper and lower boundaries for FER such as 15% of the target FER (8%) are used to prevent L fluctuating around the optimal frame-size value. As shown in Fig. 1, the throughput is maintained, as optimal frame size is changed quickly to satisfy the target FER.

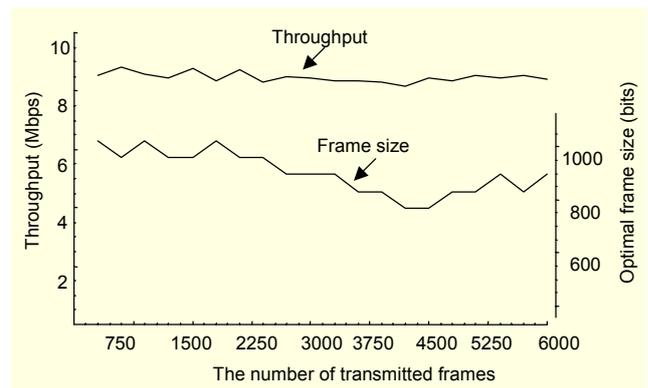


Fig. 1. Throughput and optimal frame size (window size = 300).

From Fig. 2, we can see that the simulation results agree well with our numerical calculations. In Fig. 2, MAC frame sizes that make maximum throughput are shown according to the MBS and MGS values used. With an MBS equal to 9.972 and an MGS equal to 9,606.66, maximum throughput is obtained in a MAC frame size near 1,500 bits rather than 8,192 bits which is the MAC frame size proposed in [3]. As frame size increases, the throughput decreases quickly. That is because the measured FER increases quickly as the frame size increases.

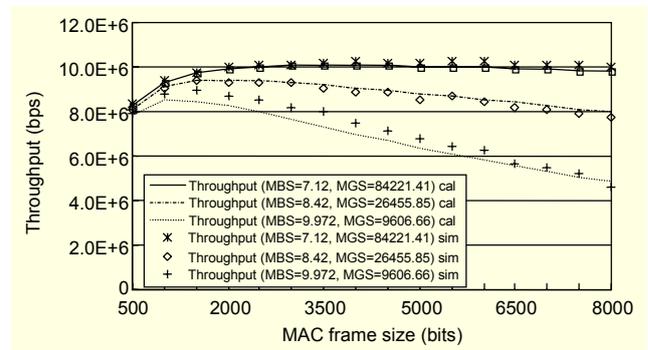


Fig. 2. Throughput according to MAC frame size L without considering required FER.

With better channel conditions such as an MBS equal to 7.12 and an MGS equal to 84,221.41, maximum throughput is obtained in a MAC frame size of more than 3,500 bits. As frame size increases, the throughput decreases slowly. Even though Fig. 2 obtains the throughput in the required FER instead of the bit error rate (BER) used in [1], the trend of throughput according to MAC frame size in Fig. 2 is similar to the simulation results of Fig. 5(a) in [1]. That is because BER is related to FER.

Figure 3 shows the throughput according to variable MGS. FER is mainly affected by the size of the gap. This is because we assume that burst size is smaller than frame size so that a

burst affects no more than two frames broken, but gap size is larger than frame size so that a gap affects many more than two frames. We assume that the MBS is 8.27; the data rate is 11 Mbps; and frame sizes are 1,024, 2,048, 4,096, and 8,192 bits. The frame size of the highest throughput depends on radio channel conditions. With a low MGS (under 10,000 bits) which means poor radio channel conditions, a MAC frame size of 1,024 bits results in a better throughput than others. With a high MGS (over 220,000 bits) which means good radio channel conditions, a MAC frame size of 8,192 bits results in better throughput than others.

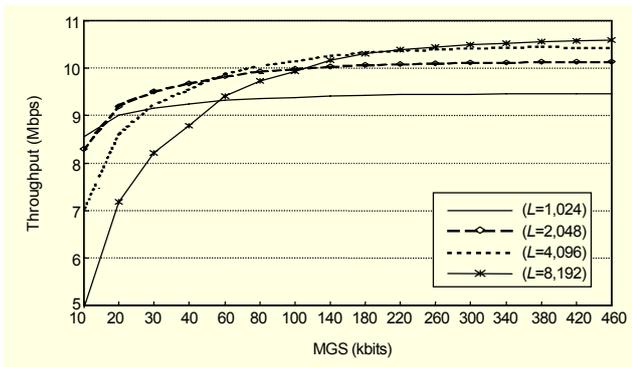


Fig. 3. Throughput according to variable MGS.

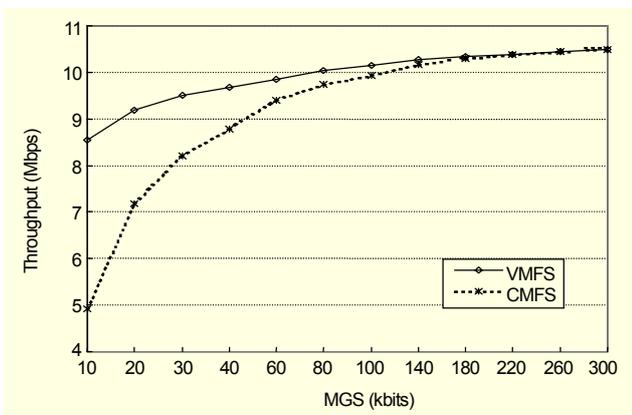


Fig. 4. Throughput of VMFS and CMFS schemes according to variable MGS.

Figure 4 shows the throughput of the VMFS and CMFS schemes according to MGS. We assume that the MBS is 8.27 and the data rate is 11 Mbps. In the VMFS scheme, frame sizes are changed according to radio channel conditions, but in the CMFS scheme, the frame size is fixed as 8,192 bits. Less than 220,000 bits, the VMFS scheme results in better throughput than the conventional CMFS scheme. With a high MGS (over 220,000 bits), the two schemes present the same throughput. Therefore, the proposed VMFS scheme is better than the CMFS scheme for all data rates.

IV. Conclusions

In this letter we proposed a frame-size adaptive MAC protocol for high rate WPANs to support QoS requirements for various applications. In the proposed scheme, FER is periodically reported to the transmitting DEV, and the MAC frame size is adjusted according to the measured results. In this way, channel resources can be more effectively utilized by sending optimal bits into one transmission frame according to the wireless channel conditions. Analytical results show that the proposed VMFS scheme achieves a much higher throughput than the legacy non-frame-size adaptive MAC protocol in high rate WPANs. As a further study, the frame-size adaptation scheme and rate adaptation scheme will be jointly studied as MAC protocols, because better throughput may be possible.

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