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# Throughput Efficiency of Hybrid ARQ Error-Controlling Scheme for UWB Body Area Network

Haruka Suzuki and Ryuji Kohno

*Division of Physics, Electrical & Computer Engineering  
Graduate School of Engineering, Yokohama National University  
Japan*

## 1. Introduction

Recently, semiconductor and circuits have been developed to make many high technologies of processing be easier to be introduced. By using this technology, there has been considerable amount of research effort directed towards applied information and communications technology (ICT) to medical services [1, 2]. Body area networks (BANs) have emerged as an important subject in personal wireless communications. The standardization task group IEEE 802.15.6 determines the standardization of PHY and MAC layers for BANs. WBAN are networks composed of in vivo and in vitro wireless communication. Communication between devices located outside of a human body is named wearable WBAN, and similarly, Communication between devices located inside of a human body is called implanted WBAN.

Wearable WBAN is expected to have numerous applications [3]. For example, each sensor device, which consists of wearable WBAN, can continuously measure and transmit vital parameters data via wearable WBAN. Based on the information sent by a wearable WBAN worn by a particular patient, the hypo-thetical Healthcare Central System of the hospital can be continuously aware of the patient vital functions and is able to take the appropriate countermeasures in case of medical alert. And wearable WBAN is also taken non-medical use (entertainment: video game, music, etc) into consideration. The potential mass market includes medical and non-medical applications. In wearable WBAN, devices treat vital signs of a human body and, therefore, more secure communications are needed. Furthermore, medical ICT has needed data rates of about 10 kbps. Considering practical purposes and non-medical use, however, it is necessary to achieve higher data rates [4, 5]. Most cases of non-medical applications do not require strong error controlling but less complexity and power consumption, and in the special case of video transmission a large throughput and low latency are needed to keep their battery life longer. On the contrary, medical applications require high reliability and relative low data rate transmission as well high data rate transmission. Hence, strong error controlling is expected while relatively larger complexity is allowed. As they require different quality of service (QoS) in terms of reliability and performance, a fixed error controlling mechanism like forward error correction (FEC) is not appropriate.

In order to reconcile medical and non-medical applications requirements, we propose an adaptive error controlling mechanism in the form of hybrid ARQ (H-ARQ). Such error-controlling system adapts to the channel conditions which can optimize the throughput, latency and reliability according to the application specification and channel conditions.

The proposed scheme can be used for both narrowband and wideband PHYs. Although, in the current status of the task group IEEE 802.15.6, non-medical applications are envisioned for the wideband PHY proposal only, i.e., UWB-PHY. On the other hand, medical applications use the narrowband and wideband PHYs. Therefore, we focus on the UWB-PHY for designing and showing the coexistence of medical and non-medical applications for BANs through the proposed H-ARQ.

UWB systems have emerged as a potential candidate for on-body communications in BANs. Indeed, UWB radios allow [1]:

- Low implementation complexity, which is critical for low power consumption.
- The signal power levels are in the order of those used in the MICS band. That is, UWB provides safe power levels for the human body, besides low interference to other devices.
- Finally, impulse radio based UWB systems allows bit rate scalability.

In this section, we propose a simple and practical binary pulse position modulation (2PPM) scheme with energy detection at the receiver. This makes it feasible to implement an analogue front-end at the receiver (with low power consumption) in the high band of UWB, where UWB-BANs are proposed to operate, globally.

In this research, it is assumed that there are interference among coexisting piconets BANs, because a coordinator in each piconet BAN of IEEE802.15.6 can control the whole device access within its coordinating piconet so as to avoid contention among accesses of all the devices although interference among coexisting piconet BANs due to asynchronous access among the coexisting piconets. Since high band of UWB regulation such as 7.25-10.25GHz has suppressed interference enough low for coexistence with other radio communication systems. However, non-coherent transceivers have poorer performance than coherent architectures. Therefore, it is necessary to introduce an error controlling mechanism that can guarantee QoS and performance depending on the application and channel condition, while relying on a simple UWB-PHY.

We show that the good performance in UWB-BAN channels can be achieved. Therefore, a robust scheme is possible for the medical applications of BANs. The advantage of this scheme is its less complex and consequently less power consumption plus it achieves higher throughput compared to using the FEC alone, which are important for BAN applications. Furthermore, from comparing the performance of without our proposed scheme, the proposed schemes obtain up to 2dB of gain at the uncorrected erroneous packet rate and its throughput efficiency improves at a maximum 40 percent while the bit rate for non-medical communications is not changed. Moreover, this error-controlling scheme is proposed at IEEE 802.15.6 committee and that standardization makes agreement to oblige employing this scheme for UWB based medical applications.

## 2. System model and the definition of WBAN

In this section, we briefly describe the definition of wireless body area network (WBAN) [1, 2], and the description of ultra wideband (UWB) signal and transmission system [4, 5].

## 2.1 Aim of WBAN

WBAN is for short range, wireless communication in the vicinity of, or inside, a human body (but not limited to humans). It uses existing ISM bands as well as frequency bands approved by national medical and/or regulatory authorities such as UWB(Ultra Wide Band). Quality of service (QoS), extremely low power, and data rates up to 10 Mbps are required while satisfying a strict non-interference guideline. IEEE 802.15.6 standardization considers effects on portable antennas due to the presence of a person (varying with male, female, skinny, heavy, etc.), radiation pattern shaping to minimize Specific Absorption Rate(SAR) into the body, and changes in characteristics as a result of the user motions.

The purpose of WBAN is to provide an international standard for a short range (ie about human body range), low power and highly reliable wireless communication for use in close proximity to, or inside, a human body. Data rates can be offered to satisfy an evolutionary set of entertainment and healthcare services. Current Personal area networks (PANs) do not meet the medical (proximity to human tissue) and relevant communication regulations for some application environments. They also do not support the combination of reliability, QoS, low power, data rate and non-interference required to broadly address the breadth of body area network applications.

## 2.2 General framework elements

This section provides the basic framework required for all nodes and hubs. It covers the following fundamental aspects: the network topology used for medium access, the reference model used for functional partitioning, the time base used for access scheduling, the state diagram used for frame exchange, and the security paradigm used for message protection.

### 2.1.1 Network topology

All nodes and hubs will be organized into logical sets, referred to BANs in this specification, and coordinated by their respective hubs for medium access and power management as illustrated in figure 1. There should be one and only one hub in a BAN. In a one-hop star BAN, frame exchanges may occur directly only between nodes and the hub of the BAN. In a two-hop extended star BAN, the hub and a node may optionally exchange frames via a relay capable node.

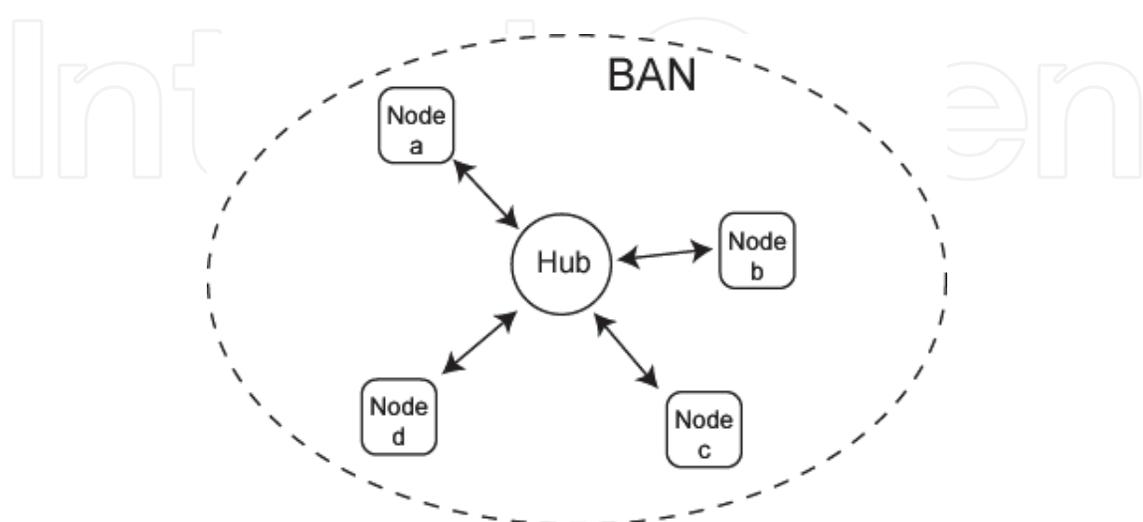


Fig. 1. Network topology

### 2.1.2 MAC frame formats

All nodes and hubs should establish a time reference base, if their medium access must be scheduled in time, where the time axis is divided into beacon periods (superframes) of equal length and each beacon period is composed of allocation slots of equal length and numbered from 0, 1, .... An allocation interval may be referenced in terms of the numbered allocation slots comprising it, and a point of time may be referenced in terms of the numbered allocation slot preceding or following it as well.

If time reference is needed for access scheduling in its BAN, the hub will choose the boundaries of beacon periods (superframes) and hence the allocation slots therein. In beacon mode operation for which beacons are transmitted, the hub shall communicate such boundaries by transmitting beacons at the start or other specified locations of beacon periods (superframes), and optionally time frames (T-Poll frames) containing their transmit time relative to the start time of current beacon period (superframe). In non-beacon mode operation for which beacons are not transmitted but time reference is needed, the hub will communicate such boundaries by transmitting time frames (T-Poll frames) also containing their transmitted time relative to the start time of current superframe.

A node requiring a time reference in the BAN will derive and recalibrate the boundaries of beacon periods (superframes) and allocation slots from reception of beacons or/and time frames (T-Poll frames). A frame transmission may span more than one allocation slot, starting or ending not necessarily on an allocation slot boundary.

### 2.3 UWB PHY description

The UWB PHY specification is designed to provide robust performance for BANs. UWB transceivers allow low implementation complexity (critical for low power consumption). Moreover, the signal power levels are in the order of those used in the MICS (Medical Implant Communication Services) band, for example, safety power levels for the human body and low interference to other devices.

#### 2.3.1 Signal model

The paper assumes UWB impulse radio and non-coherent modulation in the form of 2PPM, energy detection. This is the most promising candidate as mandatory mode for the wideband PHY of the IEEE 802.15.6 TG on BANs.

$$x(t) = \sum_m w(t - g_m T_{BPM} - m T_{sym}) \quad (1)$$

$$w(t) = \sum_{n=0}^{N_{cpb}-1} d_{m,n} p(t - n T_c) \quad (2)$$

where  $g_m \in \{0,1\}$  is the  $m$ th component of a given codeword,  $T_{BPM}$  is the slot time for 2PPM, and  $T_{sym}$  is the symbol time. The basis function  $w(t)$  is a burst of short pulses  $p(t)$ , where  $d_{m,n}$  is a scrambling sequence and  $N_{cpb}$  is a sequence length. This is only to control data rate and legacy to IEEE 802.15.4a systems.

For the sake of illustration and without loss of generality, it is assumed that  $N_{cpb}=1$  and  $d_{m,0}=1$ , for all  $m$ . Moreover,  $p(t)$  is a modulated square root raised cosine pulse waveform with duration  $T_p=2\text{nsec}$ , roll-off factor of 0.5 and truncated to 8 pulse times. The central frequency

$f_c$  is 7.9872 GHz (corresponding to the 9th band of the IEEE 802.15.4a band plan) and the bandwidth is 499.2 MHz.

### 3. Proposed error-controlling scheme for WBAN

This section explains our proposed error controlling scheme for WBAN. First, proposed scheme and system model description are described. Next, we derive the theoretical performance of our proposed scheme.

#### 3.1 Error-controlling scheme necessity

Medical and non-medical applications need to coexist in BANs. In particular, the communication link for medical applications requires higher reliability or QoS in contrast to non-medical applications. Most cases of non-medical applications do not require strong error controlling but less complexity and power consumption, and in the special case of video transmission a large throughput and low latency are needed. On the contrary, medical applications require high reliability and relative low data rate transmission. Hence, strong error controlling is expected while relatively larger complexity is allowed. Consequently, the higher QoS BAN needs, the more complexity and higher power consumption are required.

##### 3.1.1 Our idea for error-controlling scheme

As they require different QoS in terms of reliability and performance, a fixed error controlling mechanism like FEC is not appropriate. Thus, in order to reconcile between medical and non-medical applications requirements, we propose an adaptive error controlling mechanism in the form of H-ARQ. Such error system adapts to the channel conditions which can optimize the throughput, latency and reliability according to the application specification and channel conditions.

As H-ARQ combines FEC and retransmission, the main purpose is to design the FEC such that it corrects the error patterns that appear frequently in the channel. The FEC is maintained with low complexity as much as possible. On the other hand, when error patterns appear less frequently like time-varying behaviour and/or deep fades, a retransmission is requested. Hence, a fine balance between throughput and error correction is achieved, which makes the system much more reliable.

##### 3.1.2 H-ARQ scheme of our proposed system

The compliant UWB PHY in cases of medical and non-medical should support a mandatory FEC [1] : (63, 51) BCH codes. Since it is not our research, we refer the draft of IEEE 802.15.6 WBAN standard. In order to harmonize medical a non-medical applications, the first transmission packet should be encoded by (63, 51) BCH code. H-ARQ is only required for high QoS medical applications. Thus, we propose that non-medical devices employ only (63, 51) BCH code and medical devices are H-ARQ enabled.

As WBAN devices should be as less complex as possible, when the retransmitted packet is received, it would be better to minimize the buffering size of the receiver.

In general, the two main types of H-ARQ are Chase combining (CC) and incremental redundancy (IR) [6, 7, 8]. With CC schemes, the same encoded packet is sent for transmission and retransmission. On retransmission, the packets are combined based on

either the weighted SNR's (signal to noise ratio) of individual bits or soft energy values. Thus, the receiver must utilize soft decision, and buffer soft output. Its buffering size is three times higher than without using H-ARQ; i.e., '111' represents '1'.

With IR schemes, transmission and retransmission differ. However, if a half-rate code is used in this scheme, the buffering size is same or double than without using H-ARQ. In this scheme, retransmission packets consist only of parity bits. The receiver combines additional parity bits from retransmission, and decodes in an efficient manner. The retransmissions are alternate repetitions of the parity bits and first transmission bits.

Thus, we employ the notion of IR scheme. At the first transmission of both medical and non-medical, the transmission packets consist only of (63, 51) BCH codewords. For a retransmission, the transmitter encodes the first transmission packets based on a half-rate systematic codes and obtains retransmission packets of parity bits only. Therefore, the buffering size of our proposed scheme is same or double than without using H-ARQ. Additionally, decoding (63, 51) BCH codes and a half-rate systematic codes makes its performance more effective than the basic IR scheme since double coding and decoding.

This error-controlling scheme is proposed at IEEE 802.15.6 committee by Prof.Kohno in March and May 2009. That standardization makes agreement to oblige employing this scheme for UWB based medical applications.

### 3.2 Proposed system description

As mentioned above, the proposed system is H-ARQ with IR scheme. In such scheme, only parity bits are sent with some retransmissions. Erroneous packets are not discarded and the decoder can employ the previous received packets. The main requirement for the error controlling scheme are low coding overhead and are suitable for bursty (time-varying) channels.

Figures 2 and 3 show the flowchart and our proposed system model, respectively. Where,  $\hat{u}$  and  $u'$  represent demodulated and decoding bits

In our proposed system, both of the medical and non-medical applications use the same modulation and demodulation schemes. But only the medical application has a H-ARQ function. Hence, when the lack of the reliability has detected, the medical devices can request a retransmission.

First transmissions packet (we call data packet) shown in figure 3(a) consists of  $(n=63, k=51)$  BCH codewords  $\mathbf{c}_0=(\mathbf{m}, \mathbf{p}_0)$  where

$$\mathbf{m} = \{m_1, m_2, \dots, m_i, \dots, m_k\}, m_i \in \{0, 1\}, (1 \leq i \leq k) \quad (3)$$

$$\mathbf{p}_0 = \{p_{01}, p_{02}, \dots, p_{0j_0}, \dots, p_{0(n-k)}\}, p_{0j_0} \in \{0, 1\}, (1 \leq j_0 \leq n - k) \quad (4)$$

denote information and parity bits respectively.

Date packets occur in both case of medical and non-medical and decoding based on (63, 51) BCH codes is processed. If medical receiver detects erroneous bits by computing its syndrome, the packet consists only of half-rate systematic parity bits  $\mathbf{c}_1$  (we call parity packet) is required by sending *NAK*. Figure 3(b) shows the parity packet transmission. Upon receiving the second *NAK*, the transmitter re-sends the data packet or the parity packet alternately. The parity bits  $\mathbf{c}_1=(\mathbf{p}_1)$

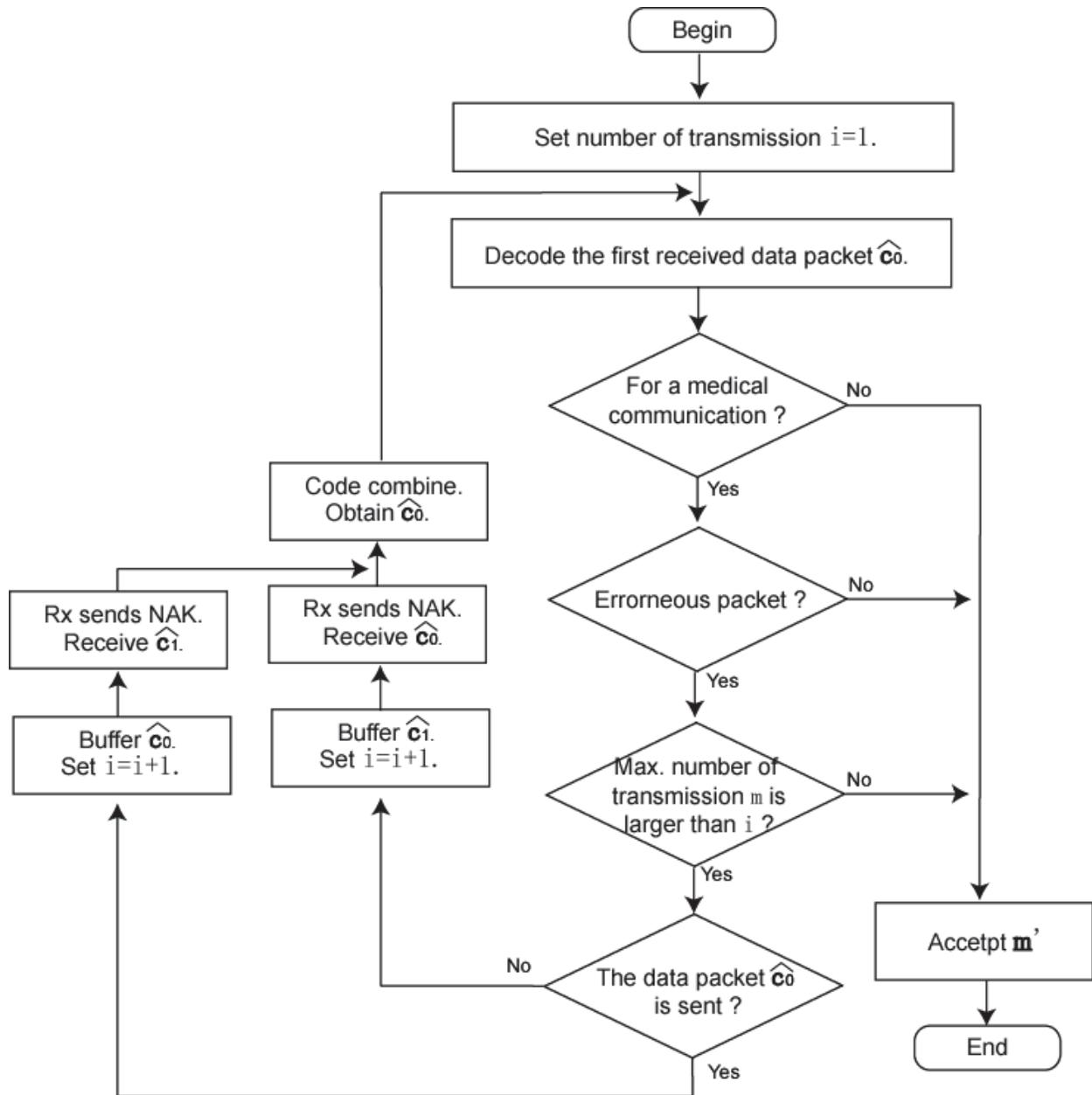


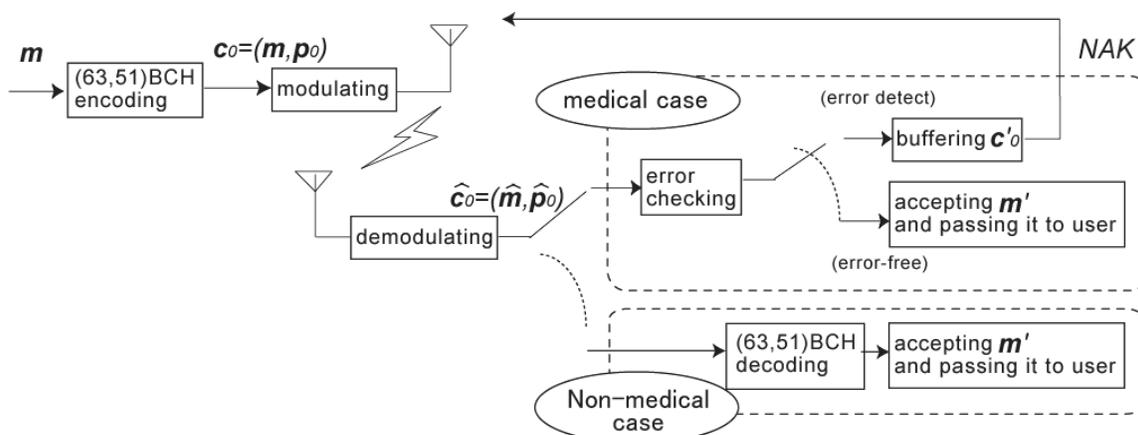
Fig. 2. The flowchart of the proposed system

$$\mathbf{p}_1 = \{p_{11}, p_{12}, \dots, p_{1j_1}, \dots, p_{1(n_1-k_1)}\}, p_{1j_1} \in \{0, 1\}, (1 \leq j_1 \leq n_1 - k_1) \quad (5)$$

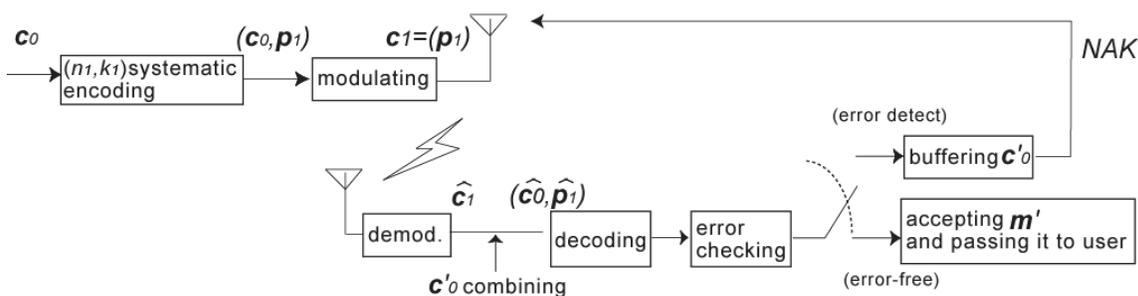
are obtained from encoding the data packet  $\mathbf{c}_0$ .

After receiving the data (or parity) packet or parity packet, previous data (or parity) packet is discarded and combined with previous parity (or data) packet. And the receivers decode based on (63, 51) BCH codes and a half-rate systematic codes. Thus, the data and parity packet are buffered at the receiver.

The retransmissions continue until the error bits are not detected in information bits  $\mathbf{m}'$  or the number of retransmission reaches the limited number.



(a) transmitter and receiver (Data packet transmission)



(b) transmitter and receiver (Parity packet transmission)

Fig. 3. The proposed system model

### 3.2.1 Packet construction of our proposed system

From above mentioned, figure 4 shows packet construction of our proposed system.

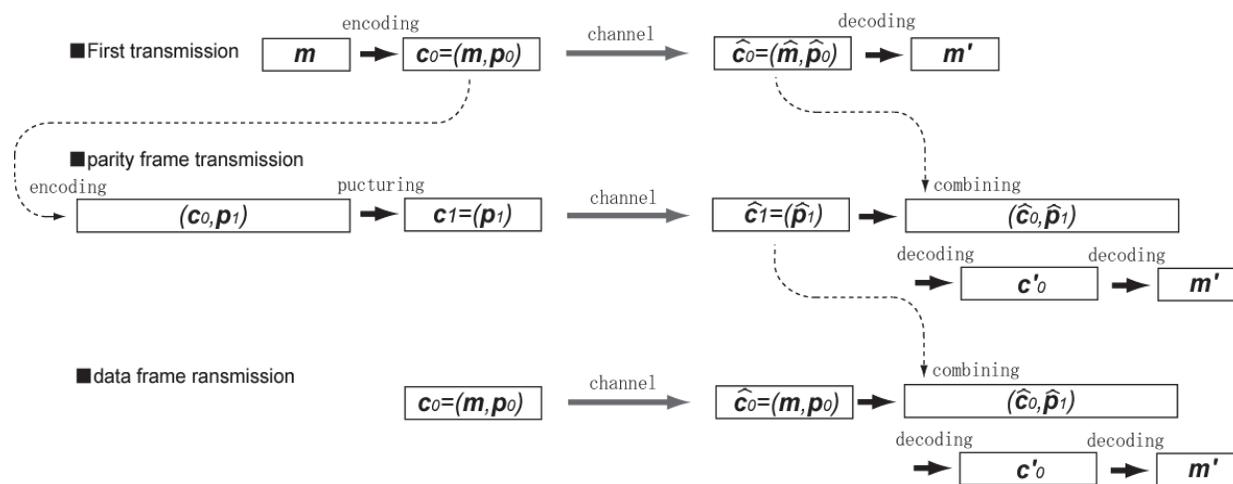


Fig. 4. Packet construction of our proposed system

The data packets  $c_0=(m, p_0)$  comprise of  $(n=63, k=51)$  BCH codewords. And the parity packets  $c_1=(p_1)$  consist of only parity bits of a half-rate systematic  $(n_1, k_1)$  codewords.

After receiving the parity packets, the receivers combine the data packets  $c_0$  and the parity packets  $c_1$  and obtain a half-rate systematic  $(n_1, k_1)$  codewords. First, the receivers decode based on a half-rate systematic  $(n_1, k_1)$  codes, and then decode based on  $(n=63, k=51)$  BCH codes.

### 3.3 Derived theoretical performance

In this section, we derive the theoretical performance of our proposed scheme. For comparison, we also consider the case of ARQ system. In this case, the retransmission is occurred by collision.

#### 3.3.1 Assumed MAC layer configuration

Figure 5 shows the diagram of transmission protocol. The message is divided into the packets and then transmitted. The length of the packet is less the length of the slot. If the number of retransmission is limited, there is a possibility of accepting the erroneous packet. The quality of the message is deteriorated by accepting the erroneous packet. We evaluate this performance after. Considering the message of other devices, it is necessary to think about not only PHY but also MAC. Hence, the network coordinator defines the start and end of a superframe by transmitting a periodic beacon. The superframe may consist of both an active and inactive period. The active portion of the superframe is composed of three parts: a beacon, a contention access period (CAP), and a contention free period (CFP). In this research, only CAP or CFP case is assumed. Therefore, we evaluated the proposed scheme in each network algorithm of Slotted ALOHA or Polling.

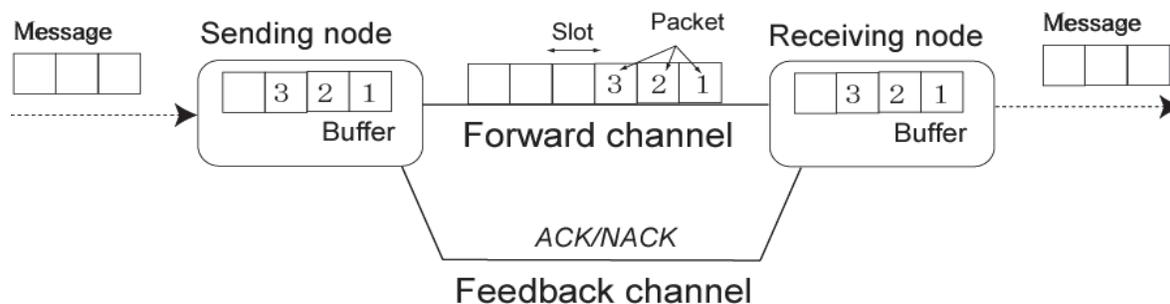


Fig. 5. Transmission protocol

The message transmission delay  $D$  is assumed to be a passing number of slots between the message  $A$  arrive at sending node and all  $N$  packets that belong to  $A$  are accepted at receiving node. Then we can calculate the throughput efficiency  $\eta$ .

$$\eta = L_m(1 - \epsilon) / D \tag{6}$$

where  $L_m$  and  $\epsilon$  represent message length and message error rate respectively.

#### 3.3.2 ARQ system

- We determine the following variables.
- $q$  : The collision probability.
- $m$  : The number of transmission per one packet.
- $N$  : The total packets belonging to one message.

$p_b$  : Channel bit error rate.

$R_c$  : Passing number of slots until the following transmission (or retransmission) when collision occurred.

We must note that ACK/NAK is sent until the end of slot.

The probability of transmission success  $P_s$  and failure  $P_f$  with each number of retransmission are followed.

- $m=1, P_s=1-q, P_f=q.$
- $m=2, P_s=q(1-q), P_f=q^2, P_s$  (when  $m=1$ ) $=1-q.$
- $m=i, P_s=q^{(i-1)}(1-q), P_f=q^i, P_s$  (when  $m=1,2,\dots,i-1$ ) $=1-q^{(i-1)}.$

Thus, when the maximum number of transmission equals  $M$ , received bit error rate  $p_{ARQ}$  and the message transmission delay  $D_{ARQ}$  are calculated by these equations.

$$p_{ARQ} = (1 + q^M)p_b + q^M \quad (7)$$

$$D_{ARQ} = R_c \left\{ \sum_{m=1}^{M-1} (m-1)q^{m-1}(1-q) + (M-1)q^{M-1} \right\} + N \quad (8)$$

### 3.3.3 Our proposed system

Additionally, we use the following variables.

$p_{b1}, p_{b2}, \dots, p_{bi}, \dots$  : Channel bit error rate for each number of transmission ( $i=1,2,\dots$ )

$p_{f1}, p_{f2}, \dots, p_{fi}, \dots$  : Channel packet error rate for each number of transmission ( $i=1,2,\dots$ )

$R_e$  : Passing number of slots until the following transmission (or retransmission) when erroneous packet is detected.

- $m=1, P_s=(1-q)(1-p_{f1}), P_f=q+(1-q)p_{f1}.$
- $m=2, P_s=(1-q)(1-p_{f1}) + (1-q)^2p_{f1}(1-p_{f2}), P_f=q^2+2q(1-q)p_{f1}+(1-q)^2p_{f1}p_{f2}.$
- $m=i,$

$P_s$  : sum of the following matrix  $\mathbf{X}_i \mathbf{Y}_i$ 's row.

$P_f$  : sum of the following matrix  $\mathbf{X}'_i \mathbf{Y}'_i$ 's row

$$\mathbf{X}_i \mathbf{Y}_i = \mathbf{X}_i \begin{bmatrix} q^{i-1}(1-q)^1(1-p_{f1}) \prod_{j=0}^{1-1} p_{fj} \\ \vdots \\ q^{i-k}(1-q)^k(1-p_{fk}) \prod_{j=0}^{k-1} p_{fj} \\ \vdots \\ q^0(1-q)^m(1-p_{fi}) \prod_{j=0}^{i-1} p_{fj} \end{bmatrix}^T \quad (9)$$

$$\mathbf{X}'_i \mathbf{Y}'_i = \mathbf{X}'_i \begin{bmatrix} q^i(1-q)^{1-1} \prod_{j=0}^{1-1} p_{fj} \\ \vdots \\ q^{i-k+1}(1-q)^{k-1} \prod_{j=0}^{k-1} p_{fj} \\ \vdots \\ q^0(1-q)^i(1-p_{fi}) \prod_{j=0}^{i-1} p_{fj} \end{bmatrix}^T \quad (10)$$

where,

$$\mathbf{X}_i = \begin{bmatrix} \mathbf{X}_{i-1} \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ \mathbf{X}_{i-1} \end{bmatrix}, \mathbf{X}_1 = 1 \quad (11)$$

$$\mathbf{X}'_i = \begin{bmatrix} \mathbf{X}'_{i-1} \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ \mathbf{X}'_{i-1} \end{bmatrix}, \mathbf{X}'_1 = \begin{bmatrix} 1 \\ 1 \end{bmatrix} \quad (12)$$

Thus, when the maximum number of transmission equals  $M$ , received bit error rate  $p_{prop}$  and the message transmission delay  $D_{prop}$  are described by the equations below.

$$p_{prop} = \sum_{m=1}^M p_{sm} + p_{eM} \quad (13)$$

$$D_{prop} = \sum_{m=1}^M d_{sm} + d_{eM} \quad (14)$$

Where,

$p_{sm}$ : sum of the following matrix  $\mathbf{X}_m \mathbf{Y}_m \mathbf{P}_m$ 's row.

$p_{fm}$ : sum of the following matrix  $\mathbf{X}'_m \mathbf{Y}'_m \mathbf{P}'_m$ 's row

$d_{sm}$ : sum of the following matrix  $\mathbf{X}_m \mathbf{Y}_m \mathbf{R}_m$ 's row.

$d_{fm}$ : sum of the following matrix  $\mathbf{X}'_m \mathbf{Y}'_m \mathbf{R}'_m$ 's row

$$\mathbf{X}_m \mathbf{Y}_m \mathbf{P}_m = \mathbf{X}_m \mathbf{Y}_m \begin{bmatrix} p_{b1} \\ \vdots \\ p_{bk} \\ \vdots \\ p_{bm} \end{bmatrix}^T, \mathbf{X}'_m \mathbf{Y}'_m \mathbf{P}'_m = \mathbf{X}'_m \mathbf{Y}'_m \begin{bmatrix} p_{b0} = 1 \\ \vdots \\ p_{b(k-1)} \\ \vdots \\ p_{bm} \end{bmatrix}^T \quad (15)$$

$$\mathbf{X}_m \mathbf{Y}_m \mathbf{R}_m = \mathbf{X}_m \mathbf{Y}_m \begin{bmatrix} (m-1)R_c + R_e \\ \vdots \\ (m-k)R_c + kR_e \\ \vdots \\ mR_e \end{bmatrix}^T \quad (16)$$

$$\mathbf{X}'_m \mathbf{Y}'_m \mathbf{R}'_m = \mathbf{X}'_m \mathbf{Y}'_m \begin{bmatrix} (m-1)R_c + R_e \\ (m-1)R_c + R_e \\ \vdots \\ (m-(k-1))R_c + (k-1)R_e \\ \vdots \\ mR_e \end{bmatrix}^T \quad (17)$$

#### 4. Code selection for proposed error-controlling scheme

First, we explain the description of a mandatory FEC for WBAN. And the bit error rate performance of our proposed scheme in cases of using other codes is showed. Moreover, we derive the effect of FEC of Hybrid ARQ on the bit error rate performance at each number of retransmission.

Finally, we determine which code employed for proposed scheme. Moreover, since our proposed scheme is employed the IEEE802.15.6 standardization, code selection is important research.

##### 4.1 Requirements for codes of our proposed H-ARQ scheme

In order to ensure interoperability, a mandatory mode is required. A compliant FEC for UWB PHY should support systematic (63, 51) BCH code [1].

From the construction of packet for our proposed system in section 3, candidate codes must have the following features:

- The code is a half-rate and systematic. For decreasing the buffer usage as far as possible, it is desired that the length of candidate codeword is double as long as first transmission codeword.
- The information length of the code is 63 or it is a divisor of 63. Since a compliant FEC for UWB PHY should support systematic (63, 51) BCH code.

If a compliant FEC for UWB PHY is different, requirement of the code is a half-rate and systematic is same.

##### 4.2 Candidate codes for proposed error-controlling scheme

The above mentioned are qualified as a candidate FEC for H-ARQ of our proposed system. Since it is satisfied the above mentioned requirements for codes of our proposed H-ARQ scheme, we use shortened BCH codes and systematic convolutional codes to make the code rate 1/2. The decoding methods are the bounded distance decoding and the viterbi decoding. For employment viterbi decoding, constraint length must be less of 10 [8].

Parameters and its generator polynomial are noted in table 1 and 2.

Although, (30, 15) BCH code is not satisfied for our proposed H-ARQ scheme, we consider to compare.

$(n, k)$ code	$d_{\min}$
(6, 3) BCH code (shortened (7,4) BCH code)	3
(30, 15) BCH code (shortened (31,16) BCH code)	7
(126, 63) BCH code (shortened (127,64) BCH code)	21

Table 1. Parameters of systematic BCH code with code rate 1/2.

Constraint length $K$	$d_{\min}$
3	4
7	6
9 (,10)	8

Table 2. Parameters of systematic convolutional code with code rate 1/2.

### 4.3 Performance evaluation for code selection

In this section, the performances of the above-mentioned candidate codes are evaluated for code selection.

#### 4.3.1 Decoded bit error performance of candidate codes

The decoded bit error performances of the above-mentioned candidate codes are evaluated by the Monte-Carlo simulations.

The simulation parameters are summarized in the table 3 [1, 5, 8].

Channel	IEEE802.15.6 CM3
Pulse shape	Modulated RRC
Bandwidth	500MHz
Bit rate	2Mbps
Coding	Data packet : (63,51) BCH codes Parity packet : above-mentioned
ARQ protocol	Selective Repeat ARQ

Table 3. Simulation Parameters for code selection

In the case of using the candidate BCH codes, the improvement of the data packet retransmission is larger than the parity packet retransmission. This performance declares the block code is affected by erroneous data bits. On the other hand, using convolutional codes, the improvement of each retransmission is same. It denotes that the encoding and decoding processes are influenced previous bits.

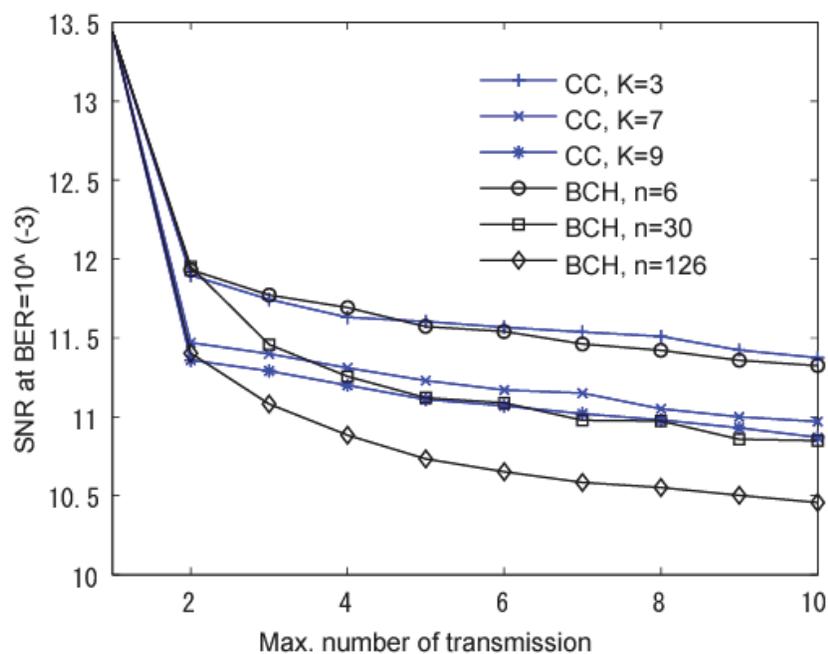


Fig. 6. SNR (signal to ratio) at BER (bit error rate)= $10^{-3}$  with each codes

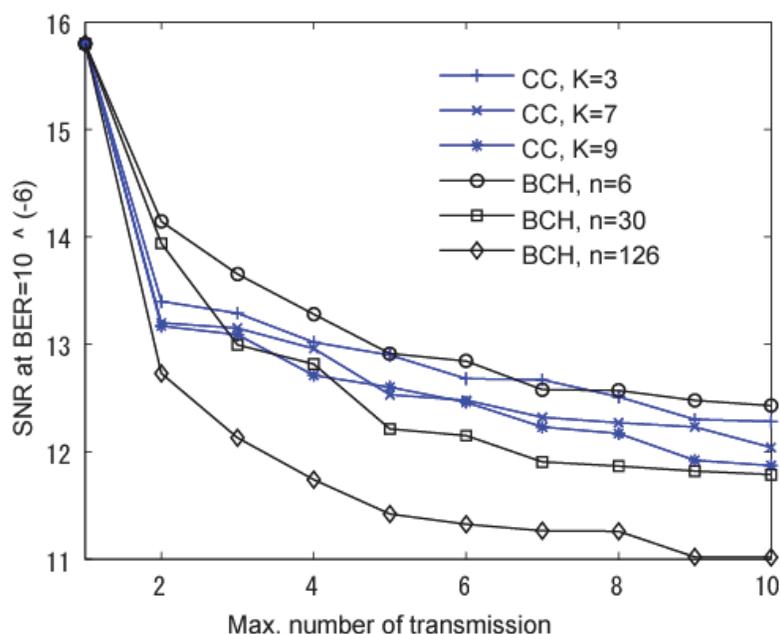


Fig. 7. SNR (signal to ratio) at BER (bit error rate)= $10^{-6}$  with each codes

#### 4.3.2 Decoding complexity of candidate codes

In bounded distance decoding with euclid algorithm, the decoding complexity is  $O(t^2)$ , where  $t$  represents error correcting capability and it is calculated by this equation.

$$t = \left\lfloor \frac{d_{\min} - 1}{2} \right\rfloor \quad (18)$$

$(n, k)$	(6, 3)	(30, 15)	(126, 63)
$O(t^2)$	$O(1)$	$O(9)$	$O(100)$

Table 4. The decoding complexity  $O(t^2)$  of bounded distance decoding

Meanwhile, the complexity of viterbi decoding increases as  $O(2^K)$ , with the constraint length  $K$ .

$K$	3	7	9
$O(2^K)$	$O(8)$	$O(128)$	$O(512)$

Table 5. The decoding complexity  $O(2^K)$  of viterbi decoding

Table 5.4 and 5.5 show  $O(t^2)$  and  $O(2^K)$  of the candidate codes, respectively.

The complexity of (126, 63) BCH code is smaller than  $K=7$  convolutional code. Also, (126, 63) BCH code has good bit error rate performance. Moreover, lower code rate of block codes makes low undetected erroneous bit. It is good for retransmission to determine.

From these performances, we select (126, 63) BCH code.

## 5. Performance evaluation

In this section, the above-mentioned proposed system considering PHY and MAC is evaluated by the Monte-Carlo simulations. Then, we evaluate the performance of our

proposed scheme, and we show that our proposed scheme makes low erroneous frame rate. Moreover, message throughput efficiency becomes more efficient than using FEC only.

### 5.1 Simulation parameters and definitions

The simulation parameters are summarized in the table 6. We refer the standardization of IEEE 802.15.6 [1, 5, 8].

Channel	IEEE802.15.6 CM3
Pulse shape	Modulated RRC
Bandwidth	500MHz
Bit rate	2Mbps
Coding	Data packet : (63,51) BCH codes Parity packet : (126,63) BCH codes
Decoding	Bounded distance decoding
ARQ protocol	Selective Repeat ARQ
$R_c$	1~5 slot (uniform pseudorandom number)
$R_e$	1 slot
$N$	5 [packets]
$L_m$	1020 [bits]

Table 6. Simulation Parameters

Using Slotted ALOHA algorithm, if the average probability of frame arrival is equal to  $\lambda$ , the probability  $P(K)$  that the  $K$  frames arrive at the sending node in the interval time  $\tau$  is

$$P(K) = \frac{(\lambda\tau)^K \exp(-\lambda\tau)}{K!} \quad (19)$$

Then, offered traffic  $G = \lambda \tau$  is fixed; 0.01, 0.5, 1.00 and the probability of occurring collision are calculated [22]. Besides, using Polling algorithm, the number of users  $U$  is fixed; 2, 4, and the performance are derived.

For comparing, we also derive the performance of without using H-ARQ scheme. In this case, the receiver can detect erroneous bits by calculating the syndrome of (63,51) BCH codes. However, an only data packet is retransmitted.

### 5.2 Numerical results and theoretical value

The maximum number of transmissions  $M$  is bounded 1~10.

We show our proposed scheme effectively from evaluating the performances of uncorrected erroneous packet rate and throughput efficiency. And, since the drawback is increasing of buffer usage, also we derive this performance.

#### 5.2.1 Uncorrected erroneous packet rate

Erroneous packet is received when the number of transmission is reached the maximum number of transmission  $M$ . Figures 7 shows the performances of uncorrected erroneous packet rate of simulation and theoretical results using S-ALOHA algorithm when  $G=0.01$ .

In case of polling algorithm, the performance is not influenced from the number of other users  $U$ . We show only the performance of uncorrected erroneous packet rate of simulation and theoretical results using polling algorithm when  $U=2$  at figures 8.

For deriving the performance by Monte-Carlo simulations, the large number of trials requires a lot of time. Thus, at low value of uncorrected erroneous packet rate cannot be shown these figures.

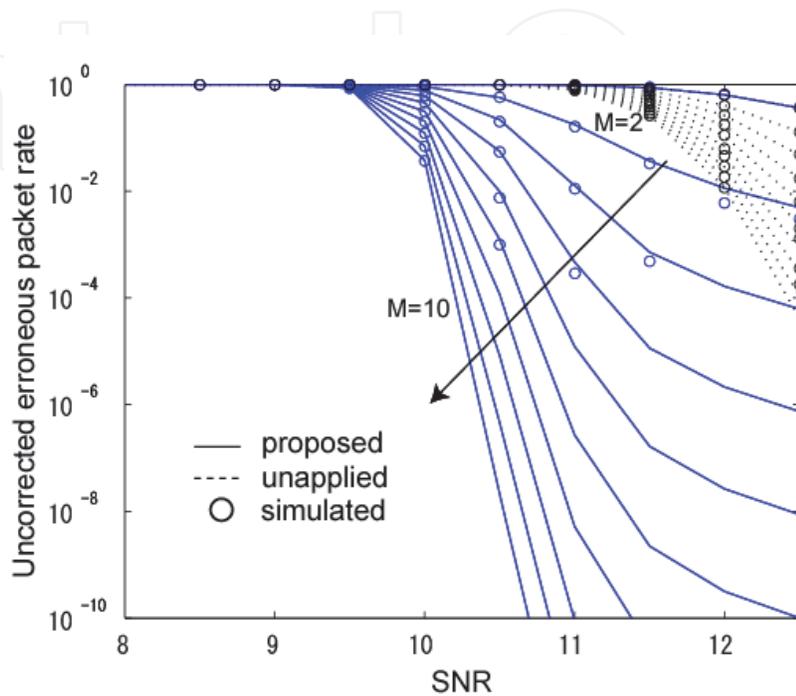


Fig. 8. Uncorrected erroneous packet rate using S-ALOHA algorithm ( $G=0.01$ )

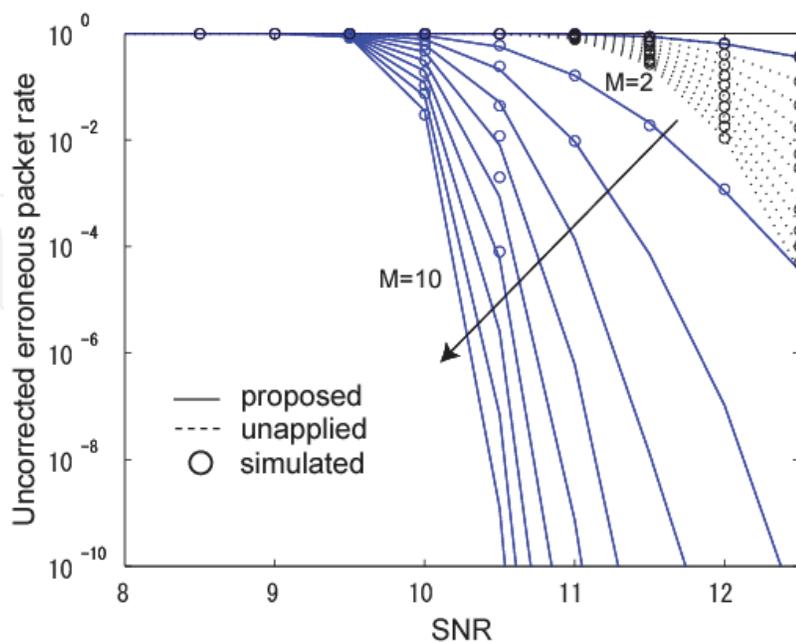


Fig. 9. Uncorrected erroneous packet rate using polling algorithm ( $U=2$ )

### 5.2.2 Buffer usage

Figure 10 shows the average buffering usage [packets] per one message with S-ALOHA and polling algorithms. When the  $N$  packets are accepted, they are sent to the user and deleted in buffer.

To compare without using proposed scheme, figure 11 and 12 show the performance of  $G=1.0$  and  $U=2$  respectively.

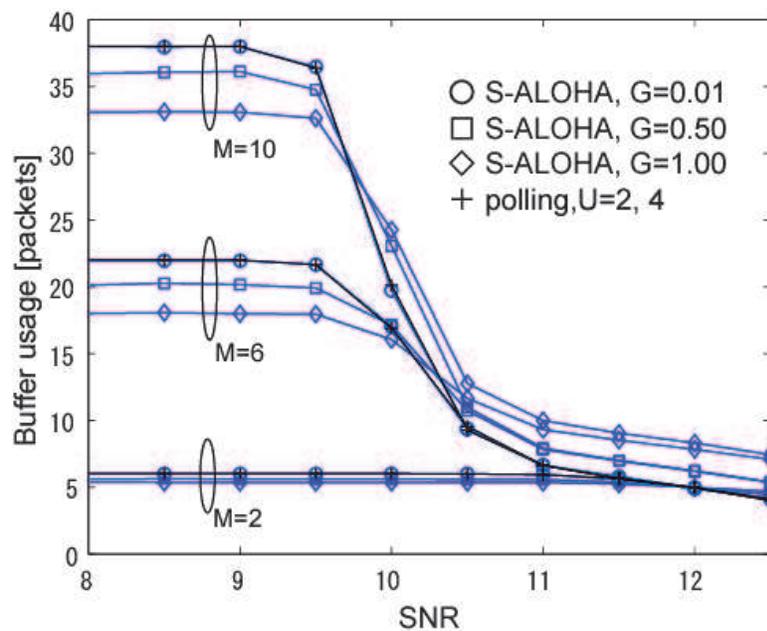


Fig. 10. The average number of buffering packets per one message

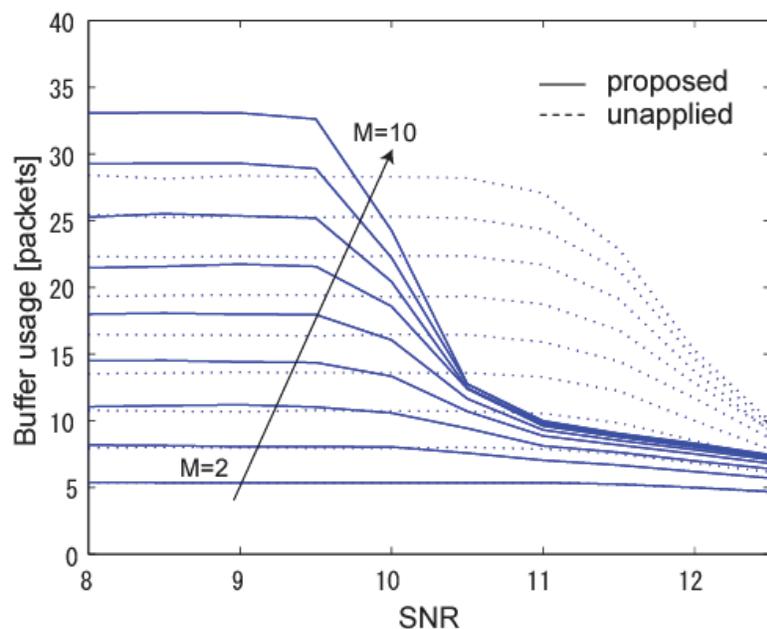


Fig. 11. The average number of buffering packets per one message using S-ALOHA algorithm ( $G=1.0$ )

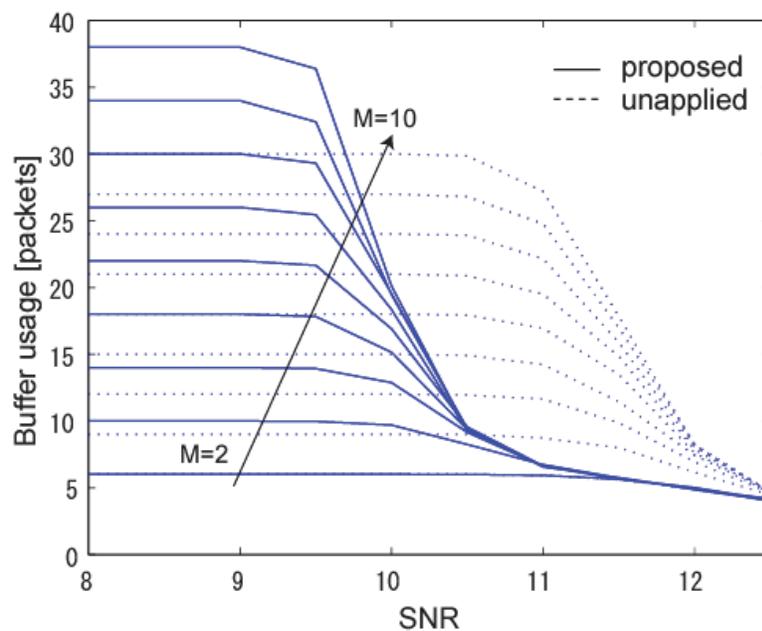


Fig. 12. The average number of buffering packets per one message using Polling algorithm ( $U=2$ )

### 5.2.3 Throughput efficiency

The message throughput efficiency  $\eta$  with S-ALOHA and polling algorithm shows in figures 13 and 14. We want to make the performance more visible, these figures show at SNR=11.5 and 12.5dB respectively (each marker denotes:  $\circ$ :S-ALOHA,  $G=0.01$ .,  $\square$ :S-ALOHA,  $G=0.5$ .,  $\diamond$ :S-ALOHA,  $G=1$ .,  $+$ :polling,  $U=2$ .,  $\times$ :polling,  $U=4$ .)

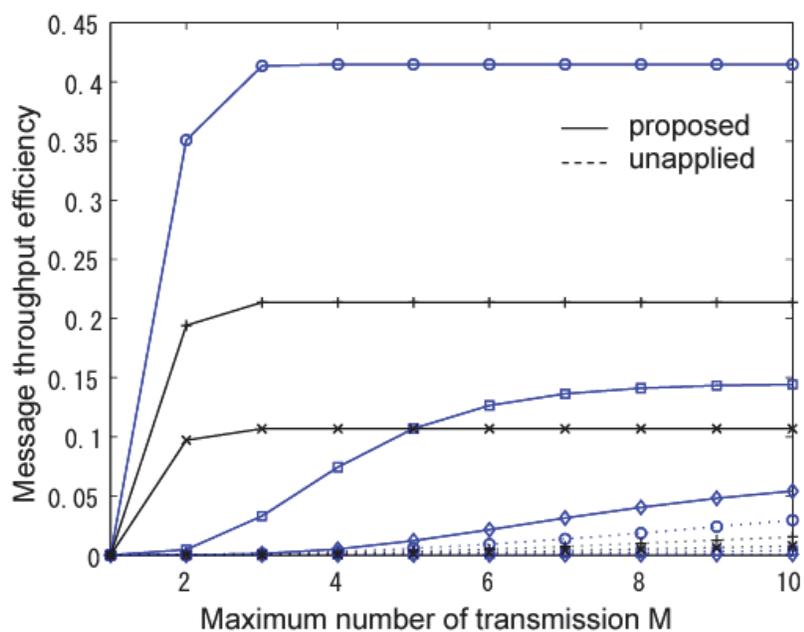


Fig. 13. Message throughput efficiency using S-ALOHA and polling algorithms at SNR=11.5 dB (medical case)

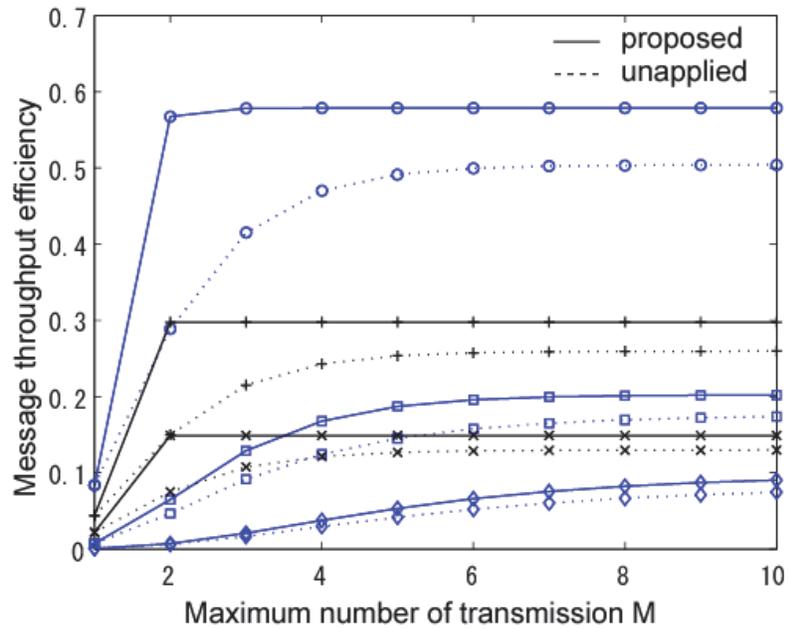


Fig. 14. Message throughput efficiency using S-ALOHA and polling algorithms at SNR=12.5 dB (medical case)

In figure 14, the message throughput efficiency  $\eta$  of without or using our proposed scheme with S-ALOHA algorithm ( $G=0.01$ ).

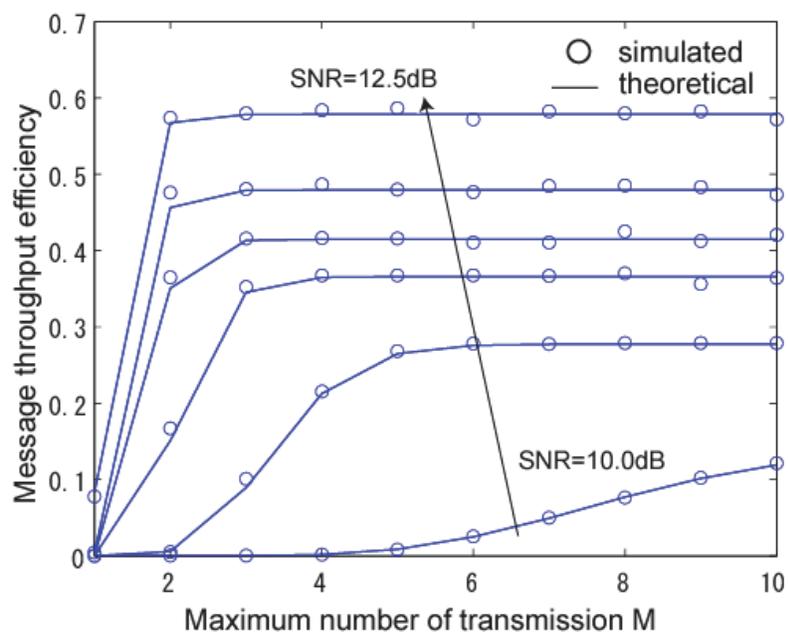


Fig. 15. Message throughput efficiency using S-ALOHA algorithms (medical case)

Furthermore, figures 15 and 16 shows the throughput efficiency of medical and non-medical communication cases. For comparing medical and non-medical usage, the throughput efficiency is redefined the following equations.

$$\eta = L_m(1 - \varepsilon') / D \quad (20)$$

Medical cases:  $\varepsilon'$  denotes received erroneous packet rate.

Non-medical cases:  $\varepsilon'$  denotes received bit error rate.

In the case of non-medical communications, the receiver does not check the erroneous packet and accepts any packet. On the other hand, in medical cases, the receiver checks. Furthermore, the erroneous packet is discarding.

Since the performances of first transmission of proposed scheme overlap the unapplied one, the first transmission performance of proposed scheme is not shown in figures 15 and 16.

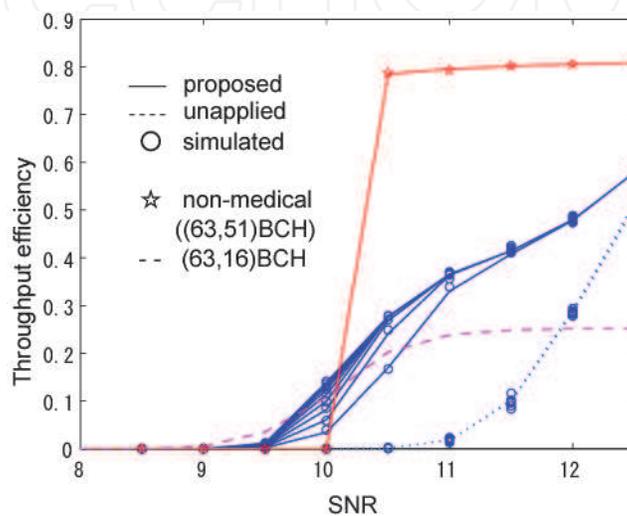


Fig. 16. Throughput efficiency of simulation and theoretical results using S-ALOHA algorithm (medical and non-medical)

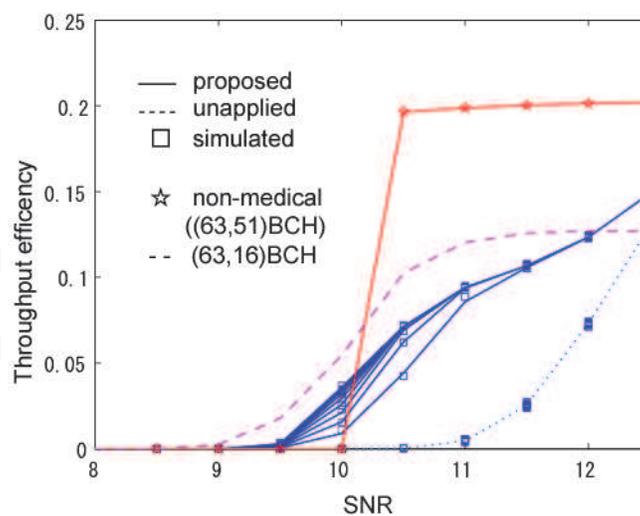


Fig. 17. Throughput efficiency of simulation and theoretical results using polling algorithm (medical and non-medical)

### 5.3 Performance evaluation

From figure 7, since the collision is a lot of occurred and the same data or parity packet are retransmitted, the improvement by H-ARQ is limited. On the other hand, using polling

algorithm, there is no collision. Thus, our proposed scheme performances of each number of transmissions improve as shown figure 8. Both of S-ALOHA and polling algorithm, our proposed schemes achieve up to 2dB of gain from comparing the unapplied proposed scheme. So the proposed scheme provides the high reliability of the medical communications.

Figure 9 shows the average number of buffering packets per one message. If SNR is low, they are not accepted easily. Therefore the buffering usage increases. However, when a lot of the collision makes the number of the transmission reaches  $M$ , the receiver accepts the packet and deletes in buffer. So the buffering usage is decreases. Therefore, at SNR < 9.5-11 dB, as  $G$  is larger, the buffer usage is lower. Meanwhile, since  $N$  packets are accepted successfully by improvement of receiving both of data and parity packets, a lot of deleted packet is arisen. Hence, the buffering usage decreases.

For comparing the unapplied proposed scheme, figures 10 and 11 bring out our proposed scheme drawback. When SNR is low, a lot of data and parity packets are transmitted. Therefore, the proposed scheme is less inferior to the unapplied. However, if the channel condition becomes good, packets are accepted successfully by improvement of H-ARQ and a lot of deleted packet is arisen.

In figures 12 and 13, the performance of our proposed scheme has large efficient at SNR=11.5dB. It shows the effectiveness of H-ARQ on the poor channel conditions. And, the performance of using S-ALOHA algorithm  $G=0.50$  at SNR=11.5dB is larger than using polling  $U=4$  at  $M > 6$ . This reason is that the using polling algorithm makes a lot of message delay when the maximum number of retransmission is large. Furthermore, figure 14 shows the adequate number of transmission is determine at each SNR (i.e. at SNR=12.5dB, the adequate number of transmission is 3).

From figures 15 and 16, the throughput performance of non-medical case exceed medical cases at SNR < 10dB. The reason of performance is receivers of non-medical applications do not check erroneous packets. It makes high bit rate for non-medical communications. Also figures show throughput efficiency of proposed scheme improves at a maximum 40 percent. Therefore, the medical communications can satisfy its QoS by using proposed scheme while the bit rate for non-medical communications is not changed. Our proposed scheme achieves to reconcile medical and non-medical applications requirements.

To summarize, using polling algorithm achieves good performance of received erroneous packet rate and buffering usage. However, it is not same for the throughput efficiency. When there are many other communication devices, the performance using polling algorithm is low efficiency as shown figures 12 and 13. Thus, we are going to propose the system which can decide retransmission by consideration of both PHY and MAC.

## 6. Conclusion

We show using our proposed error-controlling scheme can be achieved robustness for medical applications without ruining efficiency of data rate for non-medical applications in UWB-BAN channels.

This research work explored H-ARQ techniques for BANs. The signalling scheme was IR-UWB in the high band of UWB with 2PPM and energy detection. The investigated H-ARQs were based on IR scheme combined with two linear codes. We employed (126, 63) BCH codes based H-ARQ to achieve both of high data rate of the non-medical application and low bit error rate of the medical one. This error-controlling scheme is proposed at IEEE

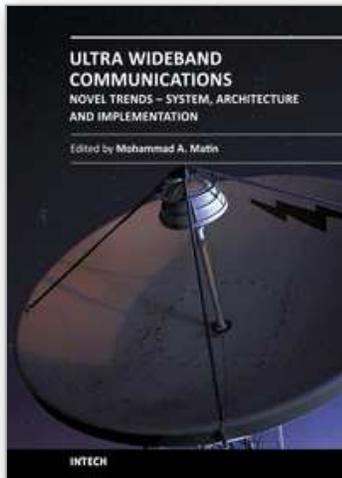
802.15.6 committee and that standardization makes agreement to oblige employing this scheme for UWB based medical applications.

Simulation results show that good performance in UWB-BAN channels can be achieved. Hence, a robust scheme is possible for the medical applications of BANs. The advantage of this scheme is less complex and consequently less power consumption plus it achieves higher throughput than when only the FEC was used, which are important for BAN applications. Furthermore, from comparing the performance of without our proposed scheme, the proposed schemes obtain up to 2dB of gain at the uncorrected erroneous packet rate and its throughput efficiency improves at a maximum 40 percent while the bit rate for non-medical communications is not changed. Finally, the proposed schemes showed a practical form of coexistence between the medical and the non-medical applications in BANs.

According to the performance evaluation, it is obvious not only channel condition but also the probability of collision effect the performance. It is considered that if the waiting time for packet transmission exceeds the tolerable quantity or transmission delay  $D$  much increases, using more complexity decoding at the receiver makes the number of waiting packets decrease. However, the drawback is the improvement of the error rate cannot exceed when the retransmission is received. In the future, we are going to construct the system which can decide retransmission by consideration of both PHY and MAC.

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## **Ultra Wideband Communications: Novel Trends - System, Architecture and Implementation**

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This book has addressed few challenges to ensure the success of UWB technologies and covers several research areas including UWB low cost transceiver, low noise amplifier (LNA), ADC architectures, UWB filter, and high power UWB amplifiers. It is believed that this book serves as a comprehensive reference for graduate students in UWB technologies.

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Slavka Krautzeka 83/A  
51000 Rijeka, Croatia  
Phone: +385 (51) 770 447  
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中国上海市延安西路65号上海国际贵都大饭店办公楼405单元  
Phone: +86-21-62489820  
Fax: +86-21-62489821

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