Paper

Efficient Performance and Lower Complexity of Error Control Schemes for WPAN Bluetooth Networks

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Abstract—This paper presents a new technique of reduction retransmission time by decreasing the discarded packets and combating the complexity through error control techniques. The work is based on Bluetooth, one of the most common Wireless Personal Area Network. Its early versions employ an expurgated Hamming code for error correction. In this paper, a new packet format using different error correction coding scheme and new formats for the EDR Bluetooth packets are presented. A study for the Packet Error Probability of classic and Enhanced Data Rate (EDR) packets is also presented to indicate the performance. The simulation experiments are performed over Additive White Gaussian Noise (AWGN) and Rayleigh flat-fading channels. The experimental results reveal that the proposed coding scheme for EDR packets enhances the power efficiency of the Bluetooth system and reduce the losses of EDR packets.

Keywords—Bluetooth, EDR, packet loss, power efficiency, Wireless Personal Area Network.

1. Introduction

Bluetooth is a short-range radio communication technology specified in the IEEE 802.15.1 standard, which evolved as a wireless alternative to cable connections [1]. It provides a universal wireless interface for different devices to communicate with one to another. The low cost of implementation and low power of Bluetooth systems have fueled popularity this technology, which has emerged as a good solution to form Wireless Personal Area Networks (WPANs) [2].

Bluetooth operates in the Industrial Scientific Medical (ISM) 2.4 GHz band with Frequency Hopping Spread Spectrum (FHSS) modulation to avoid interferences caused by other wireless technologies, i.e., IEEE 802.11b-g, IEEE 802.15.4 [3] or cordless telephones. The Bluetooth supports industrial specifications for WPANs [4], where it provides wireless media to connect and exchange information between devices.

Bluetooth employs variable-size packets occupying different numbers of 625 μs time-slots up to a maximum of five. There are several types of packets, which are chosen according to the channel conditions. Big packets increase the throughput of the system and are used with good conditions. For bad channel conditions, small packets are used, which decreases the throughput.

Bluetooth 2.1 has introduced the EDR packets types using Differential Phase Shift Keying (DPSK) modulation [5] and supports 2–3 Mbit/s air rates of through π/4-DQPSK and 8-DPSK modulation formats [6]–[8].

The performance of classic Bluetooth packets with expurgated Hamming (15, 10) code was analyzed in [9]. The concept of Forward Error Correction (FEC) bearing Data Medium (DM) packets for EDR was proposed in [10].

In this paper, the authors investigate the performance of EDR Bluetooth packets with the Hamming (15, 10) code and different error controls, i.e. convolutional codes. The Packet Error Probability (PEP) of classic and EDR Bluetooth are analytically presented. $2DM_1$ and $2DM_5$ packets are employed in presented simulations, carried out over AWGN and Rayleigh flat-fading channels [11].

This paper is organized as follows. In Section 2, the Bluetooth system is described. Section 3 highlights the issue of channel coding in Bluetooth. In Section 4, the Packet Error Probability is discussed. The proposed modifications are presented in Section 5. The simulation and the results are introduced in Section 6. The computational complexity is discussed in Section 7. Finally, the paper is concluded in Section 8.

2. Bluetooth System

The Bluetooth standard encompasses two types of links: Synchronous Connection Oriented (SCO) and Asynchronous Connection Less (ACL). SCO are aimed for transmitting real-time signals, which is delay-sensitive, i.e. voice. ACL links are intended for transmitting asynchronous data traffic (file transfer). The recent versions introduced a different packet format [12], i.e. Bluetooth v2.1+EDR add a number of ACL formats to the basic rate packets. Generally, the Bluetooth packet contains three main fields: access code (AC), header (HD), and payload (PL). AC identifies the packets exchanged within a piconet, with unique access code and used to synchronize the slaves in a piconet to its master [13]. The main function of HD is to determine an individual slave address in the piconet by Logical Transport-Address (LT_ADDR). The last field of the Bluetooth packet is the payload [14].

EDR achieves higher data throughput by using Phase Shift Keying (PSK) modulation, instead of Gaussian Frequency Shift Keying (GFSK). PSK is used in EDR packets for payloads field only, the rest of EDR packets still use GFSK in headers (AC and HD fields). This papers focus on Asynchronous Connectionless Link packets, and its types: DM$_x$, DHM$_x$, and EDR DHM$_x$. The M refers to medium data rate, while H to high data rate. The symbol x denotes the number of time slots between two hops used in the frequency hopping system [15]. It takes value 1, 3, 5 referring to 1, 3, or 5 time slots between consecutive frequency hops. Always DMM$_x$ are coded and DHx are uncoded.

3. Channel Coding in Bluetooth

To protect data in wireless communication against errors channel coding is required. There are implemented several channel coding schemes using data payload to reduce retransmission times [16]. There are three types of error control coding systems: rate 1/3 error control code, rate 2/3 error control code, and ARQ (Automatic Repeat Request). Research concentrates on varying PL field coding schemes, which means dividing the payload between data and checksum.

The performance of classic Bluetooth packets with the expurgated Hamming (15, 10) code have been analyzed in many papers [15]. The most appreciable work in the coding of the payload field and EDR was introduced by Galli *et al.* and Ling *et al.* in [17]. The authors of [14] proposed other error control codes for improving performance such as convolutional codes. They improved the performance but reduced the PL field length. The propositions of Forward Error Control (FEC) bearing DM packets for EDR were proposed in Chen [12]. In [13] the improvements of EDR packets through FEC and interleaved FEC were investigated. In the same manner, all proposed cases improved the performance with throughput reduction.

4. Packet Error Probability

The throughput performance is affected by the PEP, which is related to packet size as [8]:

$$PEP = 1-(1-P_b)^L \tag{1}$$

$$P_b = \frac{1}{2}\left(1-\sqrt{\frac{E_b/N_o}{1+E_b/N_o}}\right) \approx \frac{1}{4E_b/N_0},$$

where P_b is Bit Error Probability (BEP) of single bit and L stands for packet length.

PEP value is decreased on low packet sizes. In the following analysis, the perfect interleaved channel is assumed for independent error over wireless channel. Eq. (1) gives PEP of uncoded packets. In the case of encoded packets, the PEP equation is [9]:

$$PEP_{FEC} = 1-(1-P_{CW})^{Nc}, \tag{2}$$

where PEP_{FEC} is packet error probability of encoded packet, P_{CW} is the codeword error probability and Nc is the number of codeword in the packet.

The codeword error probability is a function of BEP, the number of correctable error t, and the length of codeword N_b. It can be expressed as

$$P_{CW} = \sum_{n=t+1}^{N_b}\binom{N_b}{n}P_b^n(1-P_b)^{N_b-n}. \tag{3}$$

The Bluetooth classic and EDR packet contains three main fields: access code, header and payload. Therefore, the encoded and uncoded PEP is given by:

$$PEP_{BT} = 1-(1-P_{AC})(1-P_{HD})(1-P_{PL}), \tag{4}$$

where P_{AC} is the access code error probability, P_{HD} stands for header error probability and P_{PL} is the payload error probability.

The AC and HD fields are encoded by BCH (64, 30) code and repetition (3, 1) code. P_{ecw}, and P_{HD} are given by Eqs. (5)–(7) [7], [14]:

$$P^{AC} = \sum_{i=7}^{64}\binom{64}{i}P_b^i(1-P_b)^{64-i}, \tag{5}$$

$$P_{ecw}^{HD} = \sum_{i=3}^{3}\binom{3}{i}P_b^i(1-P_b)^{3-i}, \tag{6}$$

$$P_{HD} = 1-(1-P_{HDW})^{18}. \tag{7}$$

The last field in Bluetooth packets is the payload. There are two types of PL: uncoded and encoded.

4.1. Classic Bluetooth Encoded Packets

The error probability for classic encoded Bluetooth packets is described in [9]. These packets are encoded by expurgated Hamming code (15, 10). The codeword error probability can be expressed as

$$p_{ecw}^{PL} = \sum_{i=2}^{15}\binom{15}{i}p_b^i(1-p_b)^{15-i}. \tag{8}$$

Then the probability of encoded payloads is

$$P_{PLm} = 1-(1-P_{PLW})^m, \tag{9}$$

where $m = 16, 100, 183$ for the DM$_1$, DM$_1$, and DM$_5$ packets, respectively.

$$P_{BT_{coded}} = 1-(1-P_{AC})(1-P_{HD})(1-P_{PLm}). \tag{10}$$

4.2. Classic Bluetooth Uncoded Packets

DH are uncoded Bluetooth packets. Its payloads are transmitted without FEC. The PEP of these packets is given by

$$P_{PL_{uncoded}} = 1-(1-P_b)^L, \tag{11}$$

where L is the length of uncoded payloads and $L = 240, 1500, 2745$ for the DH$_1$, DH$_3$, and DH$_5$ packets, respectively. Then the uncoded classic Bluetooth packets error probability $P_{BT_{uncoded}}$ can be expressed as

$$P_{BT_{uncoded}} = 1-(1-P_{AC})(1-P_{HD})(1-P_{PL_{uncoded}}). \tag{12}$$

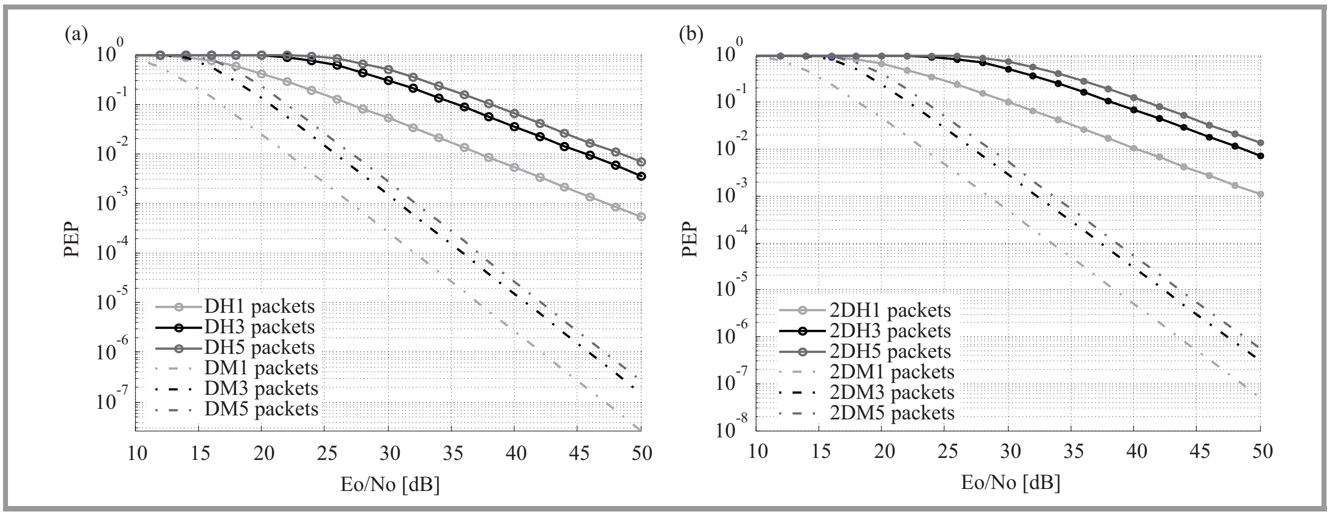

Fig. 1. PEP versus E_b/N_o of DHM$_x$ and DMM$_x$ packets over fading channel: (a) classic Bluetooth and (b) EDR.

Figure 1a gives the PEP versus Eb/No parameter for classic packets and Fig. 1b relates to EDR DHM$_x$ and DMM$_x$ packets. As shown the encoded packets performs better than uncoded ones. The PEP of the EDR packets is higher than the PEP of classic packets for the same E_b/N_o.

4.3. Uncoded EDR Packets

The PEP of EDR packets is given by Eq. (13). The difference is the last term $P_{PL_{uncoded}}$, which is affected by the length of payloads.

$$P_{PL_{EDR-uncoded}} = 1-(1-P_b)^{L_{EDR}}\,, \qquad (13)$$

where $P_{PLE_{EDR-uncoded}}$ is PEP of EDR payloads, P_b is Bit Error Probability and L_{EDR} is the length of EDR payloads. The PEP of EDR Bluetooth packets can be expressed as

$$P_{BT_{uncoded}} = 1-(1-P_{AC})(1-P_{HD})(1-P_{PL_{EDR-uncoded}})\,. \quad (14)$$

4.4. Encoded EDR Packets

DM packets are encoded packets in classic Bluetooth using FEC schemes, called 2DMM$_1$, 2DMM$_3$, and 2DMM$_5$ [18]. The PEP of encoded EDR packets can be expressed as Eqs. (9)–(10). The difference in PEP of classic Bluetooth packets and encoded EDR ones is the number of codeword in the packets with using the same FEC scheme [19].

It can be concluded from the previous studying that the EDR long packets performance is degraded than the classic ones. Several of papers proposed different error control schemes such as convolutional codes. Its complexity increases with the length of packet. Splitting packet or segmented packet format can decrease the complexity and enhance the EDR performance.

5. Proposed Modifications

This section proposes the usage of different schemes, the use of error correction schemes in Bluetooth EDR packets and investigates the effect of segmentation of EDR packets using expurgated Hamming (15, 10) code for encoding PL$_1$ field 1 and convolutional code (1, 2, and $K = 3$) for PL$_2$ [16].

Figure 2 shows the proposed packet format called segmented encoded EDR packets. The proposition depends on using error control for reduction the number of dropped packets and leads to reduce the retransmission requirements.

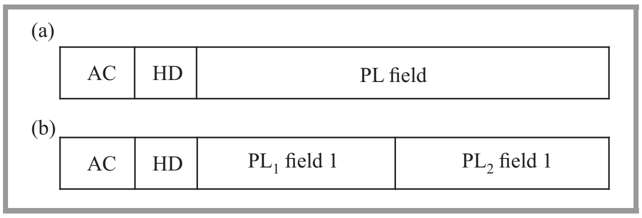

Fig. 2. Bluetooth packet contents: (a) standard format and (b) the proposed segmented encoded EDR packets.

There are two motivations for presenting the proposed technique of packet splitting. The EDR packets performance is much degraded compared to the classic version, and therefore, this work shows the error control schemes of classic packets for EDR with its evaluation. Also, the FEC utilizing causes more complexity to the data transmitting and receiving process especially with the complex encoding and decoding. Then the second motivation is decreasing the complexity of FEC scheme (convolutional codes) through reducing the input data length (processed data). It is worth to note that the complexity of convolutional codes is proportional to the number of input bit streams.

6. Simulation and Results

The Monte Carlo simulation method is used in the simulation experiments to compare between the traditional expurgated Hamming (15, 10) code used in the standard Blue-

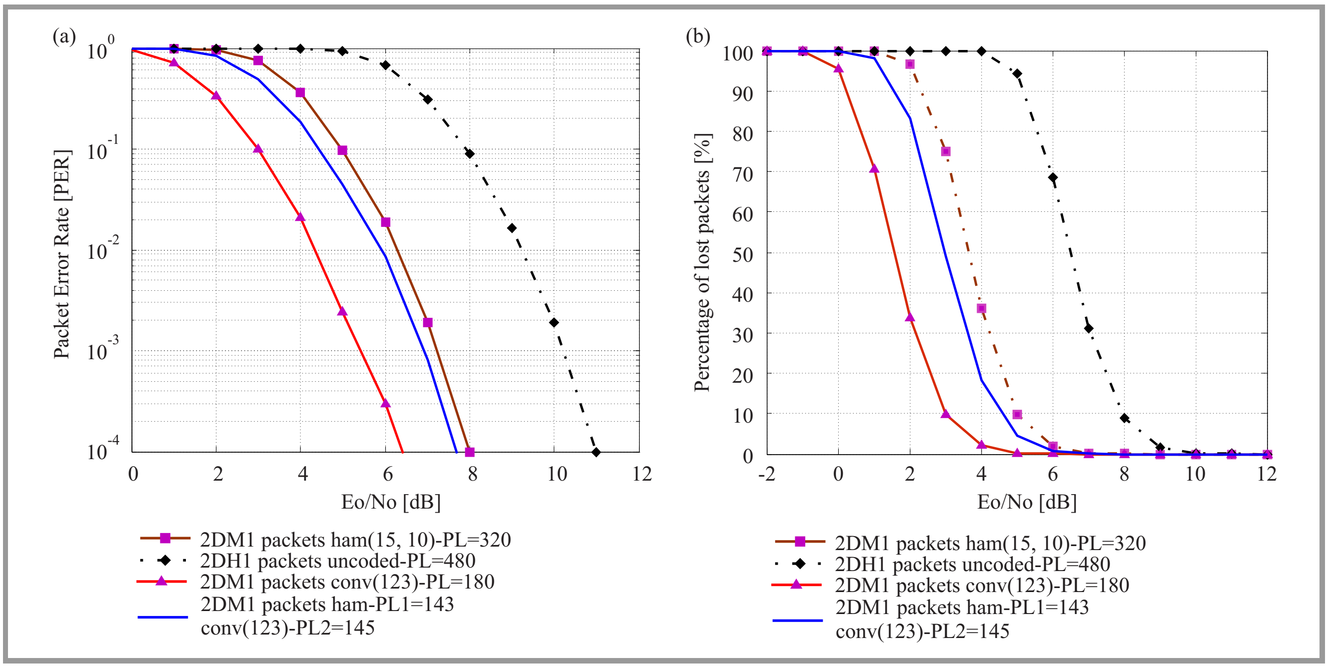

Fig. 3. (a) PER and (b) NLP versus E_b/N_o for $2DH_1$ and $2DM_1$ over AWGN channel with EDR and segmented EDR packets.

tooth packets and the proposed schemes. This method ensures obtaining correct statistical results. The simulation experiments are carried out over AWGN and Rayleigh flat-fading channels [24].

An important assumption used in the simulation is that a packet is discarded if there is an error in the AC, HD, or PL (after decoding), which was not corrected using the error correction. This is a realistic assumption to simulate the real Bluetooth systems operation. In this simulation, hard decision is assumed at the receiver in the decoding process for all channel codes. In the simulation, the interference effects are neglected. The packets lengths in all experiments are kept fixed for all coding schemes. This is at the expense of payload lengths. In some simulation experiments, a block-fading channel is assumed. It is slow and frequency nonselective channel, where symbols in a block undergo constant fading effect [22].

The experiments are concentrated on $2DH_1$ and $2DH_5$ (the shortest and longest uncoded EDR packets), the proposed encoded EDR packets ($2DM_1$ and $2DM_5$), and the proposed segmented encoded EDR packets, the results can be generalized for the rest EDR. Theses cases are expected improve the performance of the rest packets. MATLAB was used for carrying our simulation experiments of different cases. All simulations results have been gotten by transmission of 10000 trails (packets) over several SNR values [23].

6.1. AWGN Channel

This section is devoted to measure the number of packet loss and the efficiency of power transmission using classic, EDR, and proposed EDR Bluetooth packets. The first experiment is performed for uncoded $2DH_1$, proposed $2DM_1$, $2DM_1$ using convolutional code, and segmented $2DM_1$ packets transmission over an AWGN channel. The segmented $2DM_1$ packets using expurgated Hamming code (15, 10) for first part from PL_1 field and convolutional code (1, 2, and $K = 3$) for second part from PL_2 field. The results of these experiments are shown in Fig. 3a, $2DM_1$ EDR packets perform better than $2DH_1$, which means improving the Bluetooth power efficiency by using encoded EDR packets. As shown in Fig. 3b, the Number of Packets Loss (NPL) is decreased with using encoded EDR. The proposed segmented encoded EDR ones performs better than $2DM_1$ with using standard coding scheme and the redundancy is lesser than convolutional code for encoded EDR packets.

The first experiment is repeated over AWGN channel for $2DH_5$ and $2DM_5$ using different cases. The result of this experiment is shown in Fig. 4a,b, these figure reveals, segmented EDR packets perform better than $2DH_5$ and $2DM_5$ packets also, and this packet has lesser redundancy than EDR packets with convolutional code. The proposed format improves the power efficiency and reduces the number of packet losses. As shown in the results the proposed schemes are effective in the case of $2DM_5$ more than $2DM_1$.

6.2. Fading Channel

The previous experiments were repeated over Rayleigh flat-fading channel. The results of $2DH_1$ and $2DM_1$ packets are shown in Fig. 5a,b, PER and NPL respectively. The error control schemes are useful for improving the power efficiency and reduce the probability of retransmission request.

Same result of $2DH_5$ and $2DM_5$ packets over Rayleigh flat-fading channel are shown in Fig. 6a,b. The error control schemes are useful for improving the power efficiency espe-

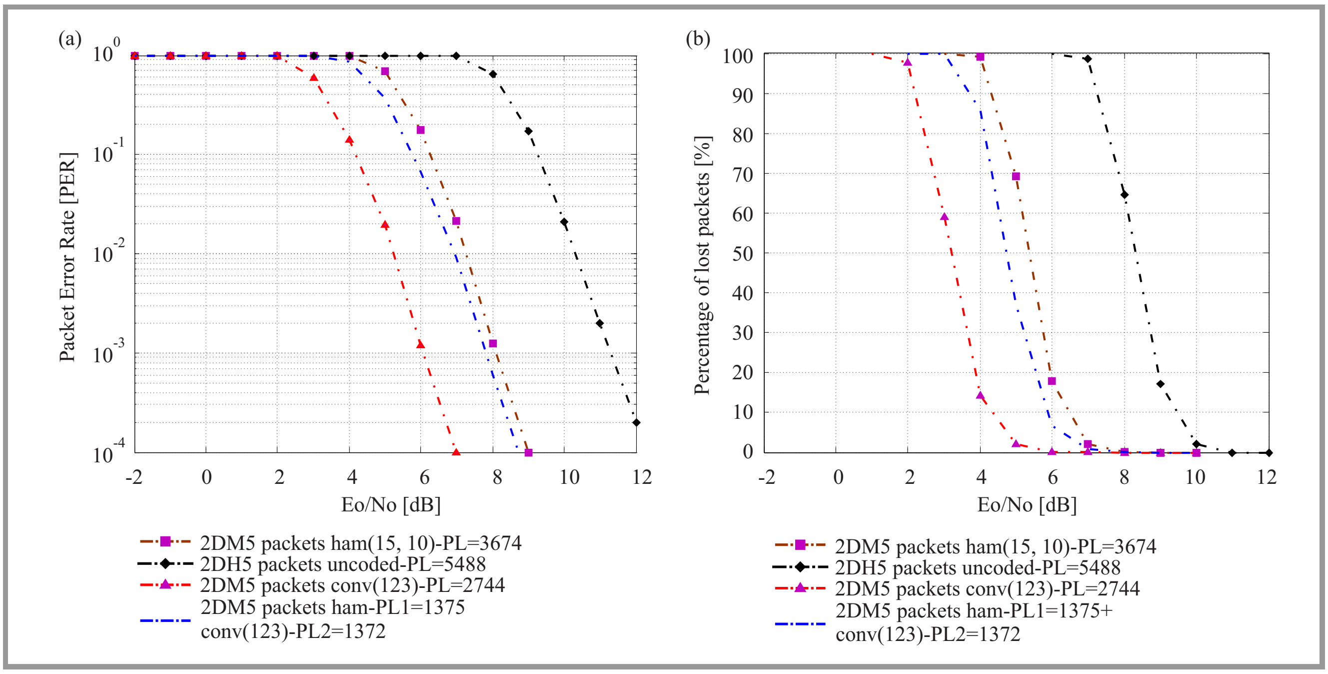

Fig. 4. (a) PER and (b) NLP versus E_b/N_o for 2DH$_5$ and 2DM$_5$ over AWGN channel with EDR and segmented EDR packets.

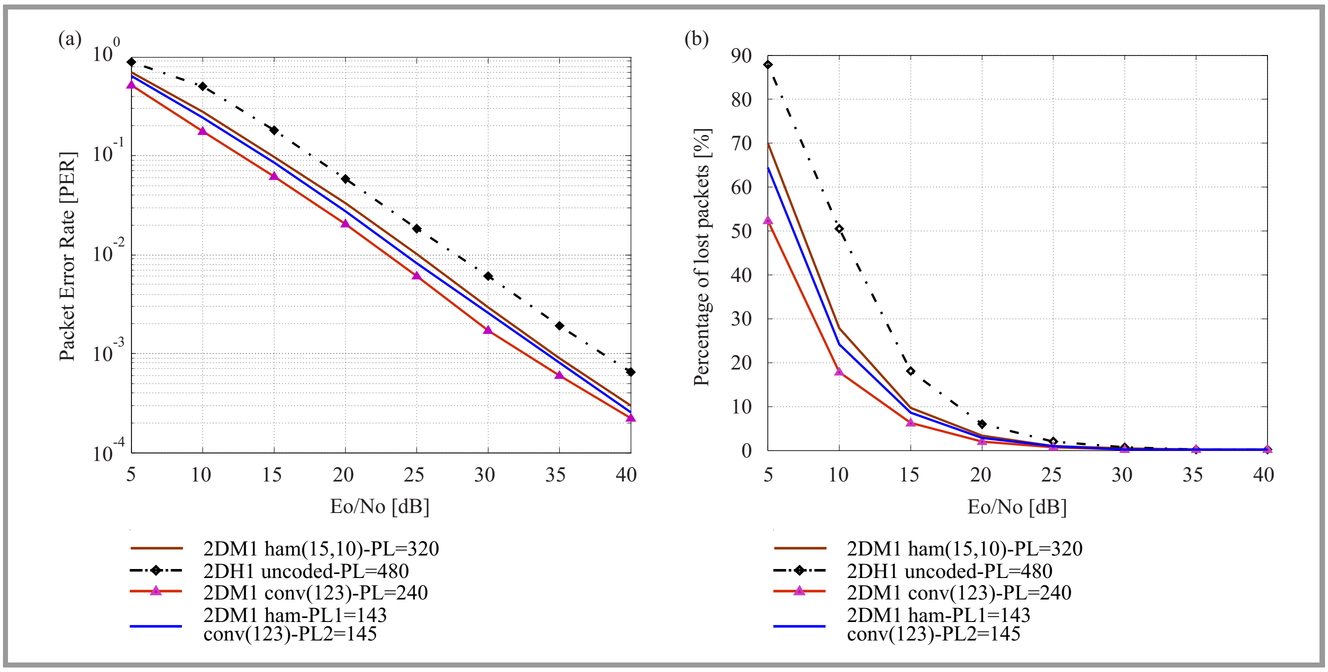

Fig. 5. (a) PER and (b) NLP versus E_b/N_o for 2DH$_1$ and 2DM$_1$ over fading channel with EDR and segmented EDR packets.

cially in the case of longer packets such as 2DHM$_5$ packets. The proposed formats perform better than standard one. The segmented encoded EDR 2DM packets are trade-off between NPL and the redundancy.

The segmented encoded EDR packet gives performance better than encoded EDR. It reduces the redundancy bits more than convolutional code. The effectiveness of proposed schemes is good in the case of longer packets as shown in the results. With increasing the SNR this negative effect is reduced.

The throughput is related to the payload length and the PEP. Equation (15) gives the formula of the throughput calculating of Bluetooth system [24].

$$Throughput = \frac{PL(1-PSER)}{(x+1)t}. \tag{15}$$

PL is the user payload length, x is the number of time slots occupied by the packet, and t is the duration of the Bluetooth time slots. Figure 7a gives the amount of throughput variation with the channel SNR for 2DH$_1$ and 2DM$_1$

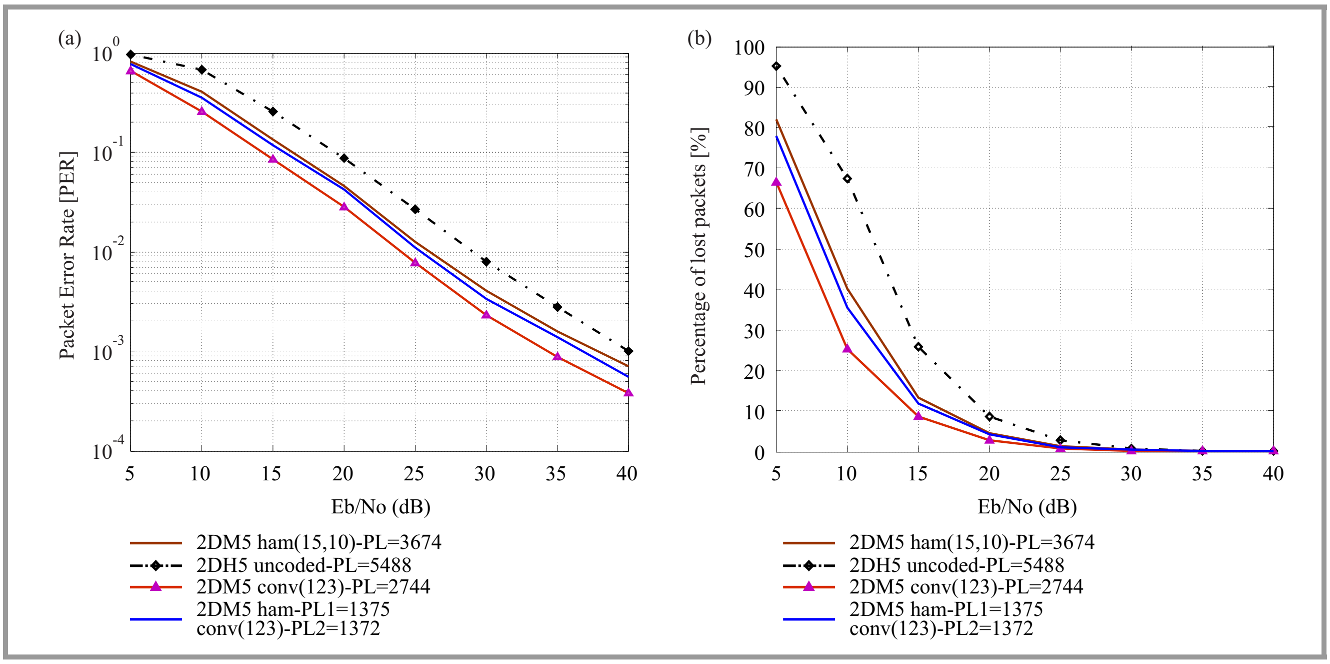

Fig. 6. (a) PER and (b) NLP versus E_b/N_o for $2DH_5$ and $2DM_5$ over fading channel with EDR and segmented EDR packets.

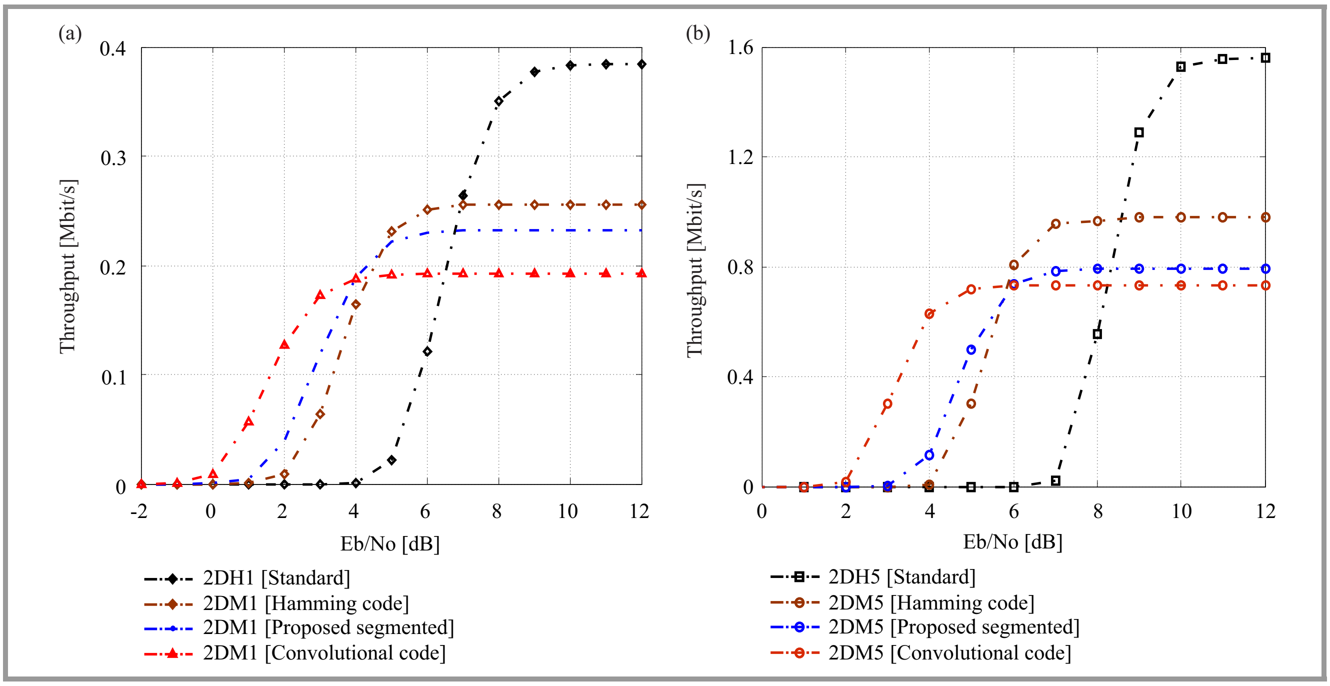

Fig. 7. Throughput versus E_b/N_o for AWGN with EDR and segmented EDR packets for: (a) $2DH_1$ and $2DM_1$ and (b) $2DH_5$ and $2DM_5$.

packets with the standard and proposed schemes over AWGN channel. As shown, the proposed schemes packets give high throughput at lower SNR values. Figure 7b shows the throughput with the SNR of the channel for $2DH_5$ and $2DM_5$ with different schemes. The proposed encoded packets using different error control scheme have different extra redundant bits. The segmented encoded packet format balances the PEP and the length of the redundant bits.

7. Computational Complexity

In many communications systems, the error control schemes have become an important tool in the computational complexity. In addition, the length of the transmitted and processed data increases the complexity.

The EDR packets are longer and their performance is worse than the classic ones. Many of papers proposed and studied different error control schemes for EDR packets such as the convolutional codes. Its complexity is proportion to the length of input data. This work presents a simple method to decrease this complexity through segment or splitting the packet to two fields, as shown in Section 5.

The block codes are defined by (n, k) where k is the number of input data bits and n is the number of bits in the encoded frame, i.e. Hamming code [21]. These codes have low complexity than the other schemes. The computational complexity of the block codes is determined by the values of n and k.

The computational complexity of convolutional codes is higher than block codes. In general, convolutional code, the input information sequence contains $k \times L$ bits, where k is the number of parallel information bits at one time interval and L is the number of time intervals. These results in $m+L$ stages, in trellis diagram there are exactly $2^k \times L$ distinct paths in the trellis diagram. As a result the ML sequence would have a computational complexity on the order of $O[2^k \times L]$ the Viterbi algorithm reduces it by performing the ML search on stage at a time in the trellis at each node (state) of trellis, there are 2^k calculations. The number of nodes per stage in the trellis is 2^m. There for the complexity of Viterbi calculation is on the order of $O[(2^k)(2^m)(m+L)]$. In this work, the value of $k = 1$, $m = 2$, and $L =$ length of uncoded payload, it is different according to the packet type [22], [23]. As mentioned before, the reduction of bits stream leads to decreasing the complexity. The splitting of packets to two FEC schemes provides a trade-off between performance upgrading and the redundant bits. It is cleared from the previous simulation experiments, the proposed technique results curve located between the traditional FEC of classic packets and the convolutional codes curves as shown in Figs. 4–5. Also, the length of user data is increased at the expense of the overall redundant bits of the encoded packets. The overall redundant bits intended to the sum redundant bits of two FEC schemes, which is utilized to encode the two-segmented packet.

8. Conclusions

The authors have proposed a new segmented EDR packets type in Bluetooth using expurgated Hamming (15, 10) and convolutional code. The experimental results reveal that at low SNR values, $2DM_1$ and $2DM_5$ packets perform better than uncoded $2DH_1$ and $2DH_5$ packets, respectively. At high SNR values, the effect of proposed schemes is decreased. Therefore, the $2DH_1$ and $2DH_5$ packets are better on high throughput. Using convolutional codes with $2DM_1$ packets reduces the probability of retransmission process. It improves the performance especially at low SNR values. Segmented encoded EDR packets reduce the loss of packets with decreasing the redundancy compared to the use of convolutional codes. In the case of applying proposed schemes over $2DM_5$ packets, it was more effective than $2DM_1$. Proposed schemes improve the power efficiency and reduce the losses of packets. The segmented encoded EDR packet improves the performance of $2DM_5$ with redundancy reduction. Finally, segmented encoded EDR $2DM_x$ packets are trade-off between NPL and the redundancy.

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