Improving Bluetooth EDR Data Throughput Using FEC and Interleaving

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Abstract. Wireless communication is inherently vulnerable to errors from the dynamic wireless environment. Link layer packets discarded due to these errors impose a serious limitation on the maximum achievable throughput in the wireless channel. To enhance the overall throughput of wireless communication, it is necessary to deploy link layer transmission schemes that is robust to the errors intrinsic to the wireless channel. In this paper, we investigated the impact of three link layer enhancement techniques on the new Enhanced Data Rate (EDR) mode detailed in the new Bluetooth spec v2.0. We first studied the APT algorithm, and used it to obtain the optimal packet type for different bit error rates. We then evaluated FEC/IFEC coding schemes for the new EDR packet types, assessed their ability to alleviate the impact of burst errors, and discussed the tradeoffs. Using analysis and simulation, we show that the performance of the new Bluetooth EDR mode can be significantly improved when FEC and/or IFEC techniques are employed.

Keywords: Bluetooth, EDR, Adaptive Packet Type, FEC, Interleaving.

1 Introduction

Bluetooth [1] is a short-range radio technology specified in the IEEE 802.15.1 standard [2]. Bluetooth was first aimed as a cable replacement technology for the numerous proprietary cables, providing a universal wireless interface for different devices to communicate with one another. The low cost, low power, and small footprint of Bluetooth chips have fueled the popularity of Bluetooth technology, which has emerged as a good solution to interconnect different devices to form the so-called Personal Area Networks (PANs) [3].

Bluetooth operates in the unlicensed 2.4GHz ISM (Industrial-Scientific-Medical) frequency band, which is also utilized by various wireless and radio technologies, such as IEEE 802.11b/g standard [4], IEEE 802.15.4 standard [5], cordless telephones, and even microwave ovens. Although Bluetooth employs Frequency Hopping Spread Spectrum (FHSS) technique to alleviate the interferences caused by other wireless technologies, coexisting in the crowded 2.4GHz frequency band is still challenging for Bluetooth in general.

To improve Bluetooth's throughput performance in the crowded 2.4Ghz ISM frequency band, several approaches have been proposed in the literature. For instance, Golmie et al have proposed a Bluetooth Interference Aware Scheduling (BIAS) scheme to determine the frequency hopping pattern based on a *Frequency Usage Table* [6]. Since then, Adaptive Frequency Hopping (AFH), a BIAS-like approach, has been included in the Bluetooth Specification v1.2 [7][8]. In AFH, the Bluetooth channels are classified into two groups: one group is termed *unused* which had better not to be used (i.e., these channels might have been heavily interfered), the other is termed *used* which is to be used for transmission. A mapping function is then employed by AFH to uniformly map *unused* channels to the *used* channels. As a result, AFH can avoid the heavily interfered channels that is not to be used (the *unused* channels), and improve data throughput.

However, BIAS and AFH schemes would only improve Bluetooth link performance when there exists a portion of channels that are not interfered by other wireless technologies. If most channels are interfered by other radio sources, BIAS and AFH would still experience lower SNR (Signal to Noise Ratio), higher bit error rate, and overall lower data throughput performance. To resolve this problem, Chen et al have proposed an Adaptive Packet Type (APT) scheme [9], which adapts Bluetooth link layer packet type to the optimal one based on the measured bit error rate and the developed analytical model.

In addition to the methods described above, another link layer enhancement technique, called Interleaving FEC (IFEC) [10], has been proposed to enhance Bluetooth data throughput amid wireless burst errors. Since wireless errors are bursty in nature, by combining Forward Error Correction (FEC) and interleaving techniques, it became effective in correcting minor error in FEC codewords and in alleviating the impact of contiguous bit errors. Moreover, since IFEC interleaves the data in the bit level instead of the packet level, the additional latency caused by interleaving is minimized.

In this paper, our goal is to study the impacts of these three error alleviating schemes, namely APT, FEC, and IFEC, for the new Enhanced Data Rate (EDR) packet types, as defined in the Bluetooth Specification v2.0 [11]. It is the interest of this paper to illustrate/compare the potential benefits to Bluetooth V2.0 with the three enhancement schemes described. First, using APT algorithm, we analyzed and obtained the optimal EDR packet types under different bit error rates. We then applied FEC/IFEC coding schemes to the EDR packet types, and evaluated the packet error rate and the maximum achievable data throughput of the various FEC/IFEC enabled EDR packet types. The results confirmed that FEC coding does indeed provide more robust data throughput, and IFEC coding can effectively alleviate the impact of burst errors for the new Bluetooth EDR mode.

The rest of the paper is organized as follows. In section 2, we present an overview of Bluetooth technology. We present and evaluate three link layer enhancement strategies for Bluetooth EDR mode, namely APT, FEC, and IFEC in section 3, 4, and 5. Section 6 concludes the paper.

2 Background

2.1 Bluetooth Overview

Bluetooth is a short-range, low cost, and low power consumption radio technology operating in the unlicensed 2.4GHz ISM (Industrial-Scientific-Medical) frequency band. It employs FHSS (Frequency Hopping Spread Spectrum) technique and implements stop and wait ARQ (Automatic Repeat reQuest), CRC (Cyclic Redundancy Check), and FEC (Forward Error Correction) to achieve high reliability on the wireless links and to alleviate the interferences caused by other radio technologies, such as 802.11b [4], cordless phones, and microwave ovens. The FEC scheme used in Bluetooth is a (15, 10) shortened Hamming code, in which each block of 10 information bits is encoded into a 15 bit codeword, and it is capable of correcting single bit error in each block.

Bluetooth units can be connected to other Bluetooth units to form a piconet, which can support up to eight active units. One of the units in a piconet acts as a master and the other units act as slaves. All the data/control packet transmissions are coordinated by the master. Slave units can only send in the slave-to-master slot after being addressed in the preceding master-to-slave slot. Each slot lasts for 625 microseconds.

For real-time data such as voice, Synchronous Connection Oriented (SCO) links are used. For data transmission, Asynchronous Connectionless Link (ACL) is used. There are several ACL packet types, differing in packet length (and consequently, data transmission rate) and whether it makes use of FEC coding. Table 1 depicts the different ACL basic packet types and their respective properties.

Table 1. Basic Data Types in Bluetooth ACL Mode

Mode	FEC	Packet		Symmetric Throughput (Kbps)	Asymmetric Throughput (Kbps)	
		Size (bytes)	Length (slots)			
DM1	Yes	17	1	108.8	108.8	108.8
DM3	Yes	121	3	258.1	387.2	54.4
DM5	Yes	227	5	286.7	477.8	36.3
DH1	No	27	1	172.8	172.8	172.8
DH3	No	183	3	390.4	585.6	86.4
DH5	No	339	5	433.9	723.2	57.6

Note that, in the symmetric connection mode, both master and slave nodes will occupy the same amount of Bluetooth time slots (625 microseconds in each time slot); whereas in the asymmetric connection mode, the Bluetooth link will occupy 1/3/5 time slots (for DM1/DM3/DM5 or DH1/DH3/DH5 mode) in one direction of this link and only one time slot in the opposite direction.

2.2 Bluetooth Enhanced Data Rate (EDR)

The most recent version of Bluetooth specification proposes a set of new baseband packet types, called Enhanced Data Rate (EDR) [11]. EDR achieves higher data throughput by using Phase Shift Keying (PSK) modulation, instead of Gaussian Frequency Shift Keying (GFSK) modulation, which was used for Bluetooth basic packet types. Similar to other basic Bluetooth packet types, the new EDR packet types occupy 1/3/5 time slots, and each time slot is 625 microseconds length. For ACL mode, the new packet types are called 2DH1/2DH3/2DH5 when $\pi/4$-DQPSK modulation is employed, or 3DH1/3DH3/3DH5 when 8DPSK modulation is used. Unlike the basic packet types, Bluetooth EDR does not provide FEC enabled packet types (i.e. DM series packet types). Table 2 shows the properties and the maximum achievable data rates of EDR packet types in ACL mode.

Table 2. Bluetooth ACL Mode EDR Data Types

Mode	Modulation	Payload Size (bytes)	Symmetric Throughput (Kbps)	Asymmetric Throughput (Kbps)	
2DH1	$\pi/4$-DQPSK	54	345.6	345.6	345.6
2DH3	$\pi/4$-DQPSK	367	782.9	1174.4	172.8
2DH5	$\pi/4$-DQPSK	679	869.7	1448.5	115.2
3DH1	8DPSK	83	531.2	531.2	531.2
3DH3	8DPSK	552	1177.6	1766.4	235.6
3DH5	8DPSK	1021	1306.9	2178.1	177.1

It should also be mentioned that EDR packet types still use GFSK in the packet headers and use the same process for link establishment. Therefore, EDR devices are backward compatible with legacy Bluetoth devices. In fact, the symbol transmission rate (1 mega-symbol per second) remains unchanged in the new specification, the PSK modulation simply allows each symbol in the packet payload to carry more bits.

2.3 Wireless Error Model

In reality, wireless channel errors are usually burst and dependent in occurrences, rather than independently and identically distributed. To capture such behavior in the wireless channel, a Discrete Time Markov Chain (DTMC) model depicted in Fig. 1, commonly known as the Gilbert-Elliott model [12][13], is used to model the true nature of wireless channel errors. The Gilbert-Elliott model consists of two states, namely the *Good* state and the *Bad* state. Events originated from these states are denoted as g and b respectively. Four transition probabilities, P_{gg}, P_{gb}, P_{bg}, and P_{bb}, are then given and they specify the state transition

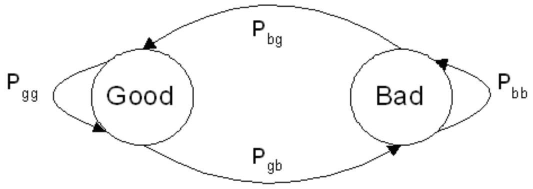


Fig. 1. Markov Model for Wireless Link

probabilities. For example, P_{gb} defines the probability of transition from the good state to bad state, and P_{bb} defines the probability of remaining in bad state, which actually reflects the degree of burst errors. The Markov chain is ergodic with stationary probabilities $P_g = \frac{1-P_{bb}}{1-P_{bb}+P_{gb}}$ and $P_b = \frac{P_{gb}}{1-P_{bb}+P_{gb}}$, and P_b is the average bit error rate (BER) [14].

3 Bluetooth EDR Enhancements (I): Adaptive Packet Type (APT)

We first perform analysis to determine the "optimal" packet type, which yields the maximum data throughput, using the APT algorithm described in [9]. We assume the random error model is used for the wireless channel, and the bit error rate is b. The packet error rate (PER, denoted as p) of Bluetooth DH packet types is given by Eq. 1 and the PER of Bluetooth DM packet types is given by Eq. 2, where s is the packet size (bits) [9].

$$p = 1 - (1-b)^s \tag{1}$$

$$p = 1 - ((1-b)^{15} + 15b(1-b)^{14})^{s/15} \tag{2}$$

The maximum achievable data throughput, T, of each Bluetooth packet type is then obtained by:

$$T = \frac{s(1-p)}{(n+1) \times 625\mu s} \tag{3}$$

where n is the length of packet in Bluetooth slots, and 625 μs is the length of a Bluetooth slot.

Using Eq. 3, we plot the maximum achievable throughput of Bluetooth packet types versus bit error rates in Figure 2. The "optimal" packet types for different BERs are then determined by selecting the packet type that gives the largest T for that BER. The thresholds for selecting the "optimal" packet type are shown in Table 3.

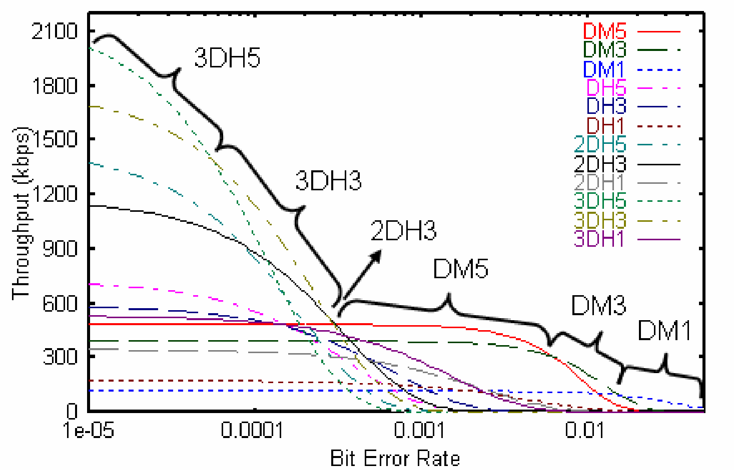


Fig. 2. Analytical results of Bluetooth EDR throughput of different ACL packet types.

Table 3. Calculated threshold for Bluetooth EDR for Adaptive Packet Type.

Packet Type	BER Range
DM1	0.0157813 < BER
DM3	0.0060695 < BER < 0.0157813
DM5	0.0003034 < BER < 0.0060695
2DH3	0.0002758 < BER < 0.0003034
3DH3	0.0000558 < BER < 0.0002758
3DH5	BER < 0.0000558

Since Bluetooth has a built-in system function call, *Get_Link_Quality*, to obtain the ongoing link quality information, which can be easily converted to bit error rate, the APT algorithm thus adapts the Bluetooth link layer packet type to the optimal one accordingly. As a result, systems with APT capabilities are able to achieve higher data throughput in wireless networks.

4 Bluetooth EDR Enhancements (II): FEC Coding

FEC coding has been well studied [15][16][17], and it has been implemented in many wireless standards, e.g. Bluetooth [1] and IEEE 802.11a [4]. FEC coding is the preferred error-control scheme to fight random losses, even though perfect recovery cannot be guaranteed. However, the main drawback of FEC technique is the incurred redundancy overhead, which may degrade the effective data throughput of a link.

FEC coding has been implemented by Bluetooth basic packet types, i.e. DM packet types, which employs a (15, 10) shortened Hamming code to protect

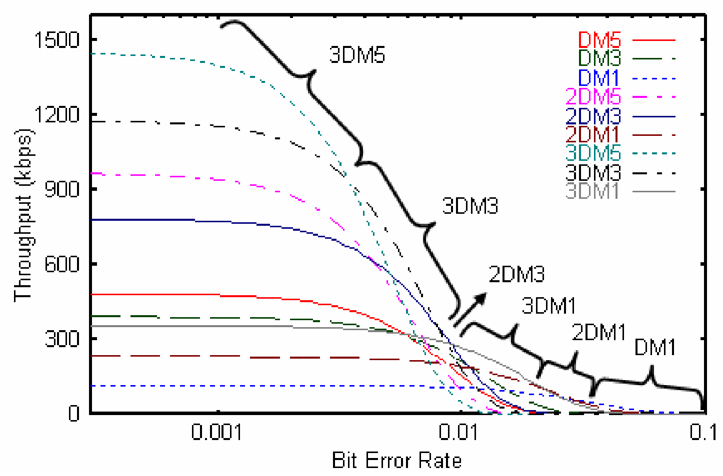


Fig. 3. Analytical results of Bluetooth EDR throughput of different ACL packet types with FEC coding enabled.

packets from transmission errors. More specifically, for each DM mode packet, each block of 10 information bits is encoded into a 15 bit codeword, and the FEC scheme is able to correct any single bit error in each block. Analysis has shown that the deployment of FEC coding in DM mode enhances the transmission performance when the bit error rate surpasses a certain threshold [18].

Here, we propose to apply the same FEC coding scheme to Bluetooth EDR packet types, and name the resulting packet types 2DM1/3/5 and 3DM1/3/5 respectively. Since the (15, 10) FEC coding is employed in 2DM and 3DM series packet types, the effective data payload size becomes 2/3 of the corresponding 2DH and 3DH EDR packet types. Similar to the analysis presented previously for DM packet types, we model the packet error rate of the new packet types using Eq. 2 and maximum achievable data throughput using Eq. 3. We plot the maximum achievable throughput of FEC enabled packet types versus the bit error rate in Figure 3.

Combining the analytical results in Figure 2 and Figure 3, we apply APT algorithm to obtain the optimal packet type for different bit error rates. We show the calculated threshold in Table 4.

5 Bluetooth EDR Enhancements (III): Interleaved FEC Coding

So far, we have evaluated two link layer enhancement schemes (i.e. APT and FEC) for Bluetooth EDR mode. However, as pointed out in [10], APT and FEC techniques improve the effective data throughput of Bluetooth links only when the wireless errors are identically and independently distributed (i.e. using

Table 4. Calculated threshold for Bluetooth EDR (with FEC enabled DM packet types) for Adaptive Packet Type.

Packet Type	BER Range
DM1	$0.0285627 < \mathrm{BER}$
2DM1	$0.0220129 < \mathrm{BER} < 0.0285627$
3DM1	$0.0090206 < \mathrm{BER} < 0.0220129$
2DM3	$0.0079932 < \mathrm{BER} < 0.0090206$
3DM3	$0.0034665 < \mathrm{BER} < 0.0079932$
3DM5	$0.0000496 < \mathrm{BER} < 0.0034665$
3DH5	$\mathrm{BER} < 0.0000496$

random error model). When wireless errors are mostly bursty in presence, these techniques fail to provide good data throughput unless interleaving technique is applied [10].

In this section, we used the Interleaved FEC (IFEC) coding technique [10] to Bluetooth EDR packet types, and the resulting packet types are called DMI1/3/5, 2DMI1/3/5, and 3DMI1/3/5 respectively. Figure 4 conceptually illustrates the difference between IFEC and FEC schemes.

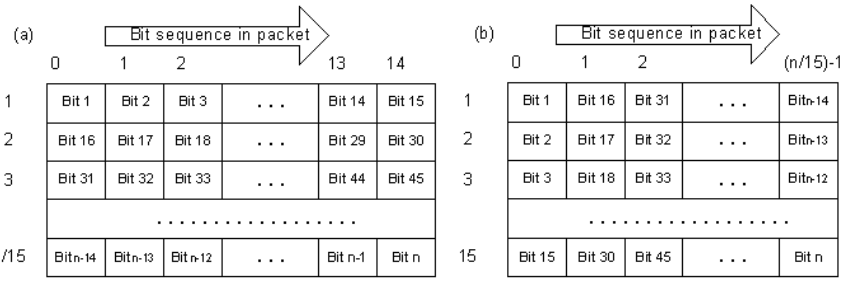
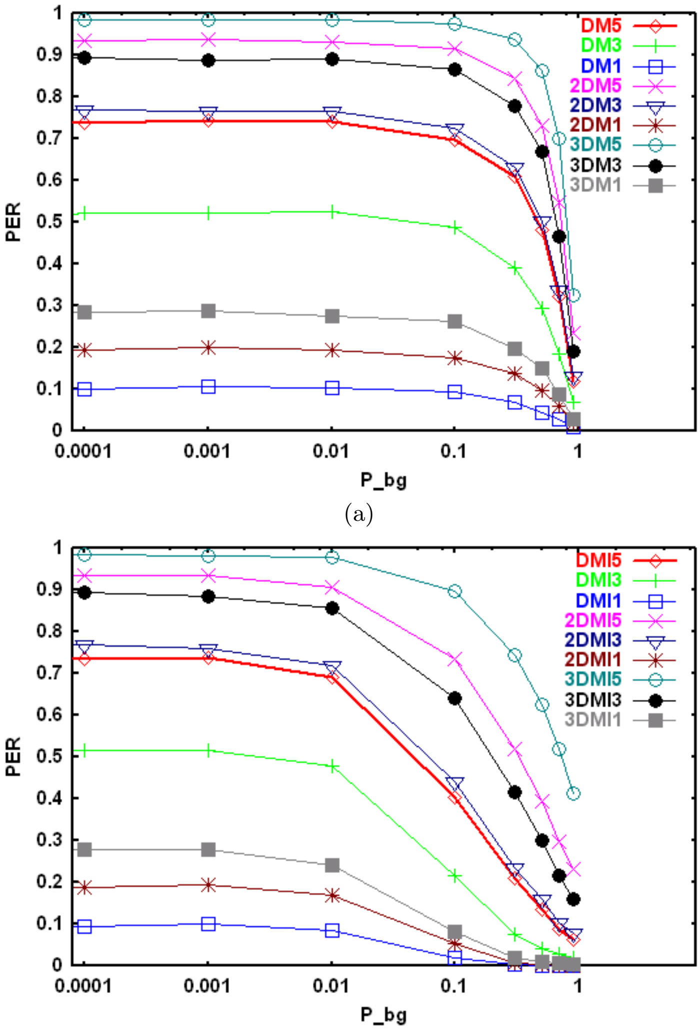


Fig. 4. The proposed link layer bit arrangement for Bluetooth EDR: (a) FEC coding (b) Interleaved FEC coding.

Specifically, for the FEC scheme, a packet of size n bits is segmented into several $n/15$ bits blocks, and each block is a FEC codeword consisting of 10 data bits and 5 FEC coded bits. On the other hand, for the IFEC scheme, each packet is divided into 15 blocks with $n/15$ bits each. It then constructs the first 15 bit FEC codeword by applying FEC coding to the first bit of each block, the second 15 bit codeword is constructed by applying FEC coding to the second bit of each block, and so on and so forth. Therefore, each codeword in IFEC scheme inherits the ability to correct single bit error like it was in the FEC scheme, but it is more robust to burst errors since the 15-bit codeword contains no consecutive bits.



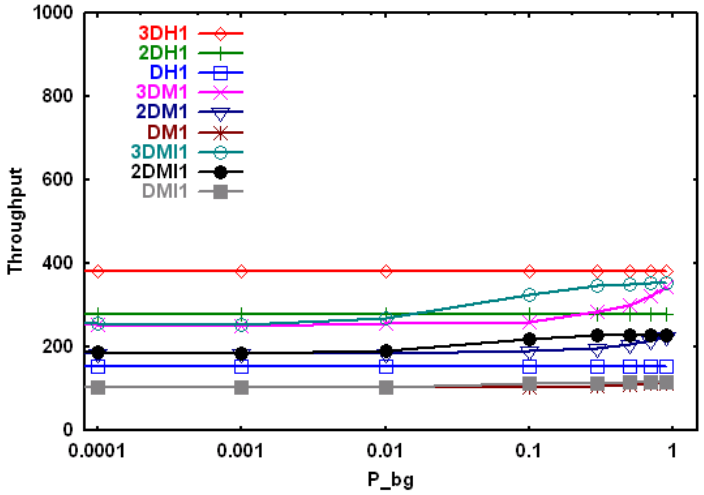
(a)

(b)

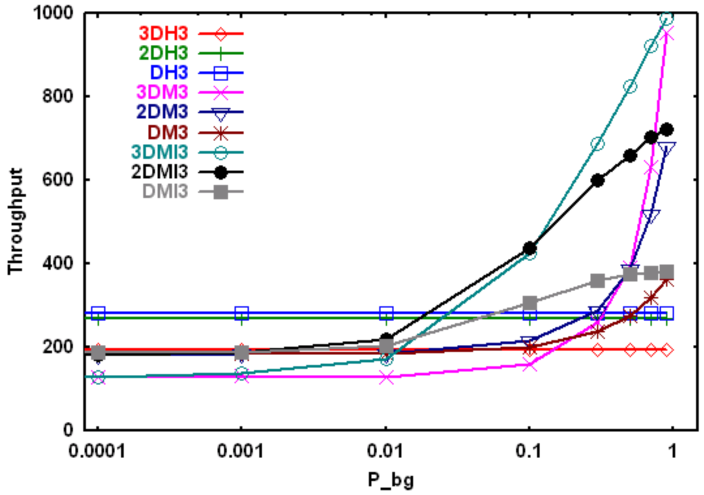
Fig. 5. Packet error rates versus different bit error rates: (a) FEC coding; (b) IFEC coding. ($P_{gb} = 0.0005$ and $P_{bg} = 1 - P_{bb}$)

Using Gilbert-Elliott model (i.e. burst error model), we let $P_{gb} = 0.0005$ and vary P_{bb}, which determines the burst level of wireless errors, from 0.9 to 0.9999. We use Monte Carlo method to simulate the packet error rates of DM and DMI series packet types versus different bit error rates. The results are shown in Figure 5.

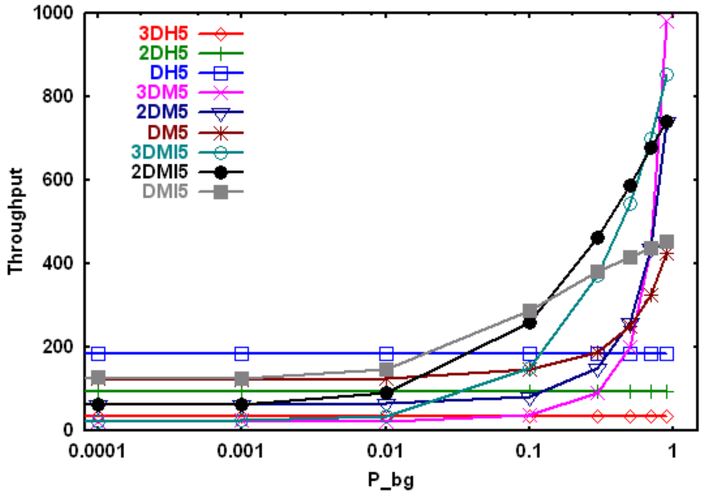
In Figure 5, the results clearly show that DMI packets are more robust against burst errors than DM packets. For instance, the packet error rates of DM packets



(a) one-slot packet type



(b) three-slot packet type



(c) five-slot packet type

Fig. 6. Maximum achievable data throughput of DM and DMI packet types with different burst error levels, given P_{gb}=0.0005.

increase rapidly and become converged when P_{bb} becomes as large as 0.9 (i.e. $P_{bg} = 0.1$); whereas the PER of DMI packets increases more moderately as P_{bb} increases and becomes converged after P_{bb} becomes larger than 0.999.

We suppose P_{gb} is fixed at 0.0005, the first bit of each packet is 'good', and s is the effective payload size (i.e. excluding FEC overhead) of DM/DMI packets. Using Eq. 3 and the analytical PER results of Figure 5, we plot the maximum achievable data throughput of DM and DMI packet types of different burst levels in Figure 6.

Figure 6 shows that the data throughput of DH series packet types is very consistent regardless of burst error levels (P_{bb}). This is explained by the fact that DH packets are not protected by FEC/IFEC coding, any single bit error in a DH type packet will result in an error of the whole packet, and the packet would be dropped.

Moreover, the results also show that DM and DMI packet types outperform the corresponding DH packet types only when the burst error level is moderate. The results match our expectation since DM and DMI packets are able to improve link performance only when the wireless errors are recoverable (i.e. at most one bit error in each 15-bit codeword). If wireless errors are very slight or extremely serious, the overhead from FEC redundancy in DM and DMI packets degrades the effective data throughput instead.

In addition, the results also confirm previous results presented in [10], i.e. DMI series packet types outperform the corresponding DM series packet types when the burst error model is used for the wireless channel. This is due to the fact that, in IFEC scheme, most contiguous bit errors are distributed into different interleaved FEC codewords. As a result, since the deployed FEC scheme can correct single bit error in a codeword, DMI is able to recover the packet from burst bit errors as long as there are no multiple bit errors in any of 15-bit codewords.

6 Conclusion

In this paper, we studied the impact of three various link layer enhancement techniques on the new Enhanced Data Rate (EDR) mode detailed in Bluetooth spec v2.0. It is the interest of this paper to illustrate/compare the potential benefits to Bluetooth v2.0 with the three enhancement schemes described, namely APT, FEC, and IFEC. We first employed APT algorithm to obtain the optimal packet type for various bit error rates. We then evaluated FEC coding scheme for EDR packet types, which provided more robustness against wireless errors. Moreover, we evaluated IFEC coding, which is a technique combining the benefits of interleaving and FEC, and assessed its ability to alleviate the impact of burst errors in wireless channels. Using analysis and simulation, we show that the performance of the new Bluetooth EDR mode can be significantly improved when FEC and/or IFEC techniques are utilized.

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