Correct Bluetooth EDR FEC Performance with SEC-DAEC Decoding

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By selecting from Bluetooth's Enhanced Data Rate (EDR) packet types according to channel conditions, optimal data-rates are approached, especially if Forward Error Control (FEC) is extended to EDR. This Letter presents correct calculation of these packet types, which also accounts for Double Adjacent Error Correction (DAEC) in addition to conventional Single Error Correction (SEC).

Introduction: IEEE 802.15.1 (Bluetooth) [1] is a low-power (1-35 mA), short range (<10 m) wireless interconnect, to which version 2.0 has brought Enhanced Data Rates (EDR) modes with maximum gross user payload (mgup) of 1.4485 Mbps and 2.1781 Mbps. As Bluetooth reduces frequency selective interference through Spread Spectrum Frequency Hopping at 1600 hop/s, there ensues a variety of packet types, depending on number of 625 μs time-slots occupied and EDR mode. In video streaming over Bluetooth [2], selection of packet length affects the throughput, achievable error resilience, and exposure to error bursts. Forward Error Correction (FEC) is a means of reducing that exposure without the delay imposed by packet retransmissions, which in video streaming may result in missed display deadlines or the need for larger playback buffers. A suggestion is to add link-layer FEC to Bluetooth's EDR modes. Unfortunately, much research assumes that Bluetooth's existing FEC provision for basic rate transmission is only suitable for Single Error Correction (SEC), whereas it has been pointed out [3] that

Double Adjacent Error Correction (DAEC) is also possible. If this misapprehension is combined [4] with a failure to account for the effect on Carrier-to-Noise Ratio (CNR) of differing modulation types, the result is incorrect packet optimality across CNR boundaries in channels with memory, where double adjacent errors are common [5]. This Letter provides correct EDR packet boundaries and includes the impact of a SEC-DAEC decoder on FEC-enabled EDR modes.

Bluetooth FEC: Bluetooth v. 2.0 EDR supports gross air rates of 2.0 Mbps and 3.0 Mbps through respectively π/4−DQPSK or 8DPSK modulation. In EDR, the symbol rate (1 Msps) remains the same as in basic rate GFSK modulation at 1 Mbps, with mgup of 0.732 Mbps. The basic rate Bluetooth systematically encoded FEC type for the user payload is considered in this Letter for EDR modes. This is an expurgated (15, 10) Hamming code, with minimum distance increased from 3 to 4. Unlike the original (15,11) code, the (15,10) code is able to detect 14 new patterns of the form $x_i + x_{i+1}, 0 \le i \le 13$. The generator is identified as $g(X) = (1+X)(1+X+X^4)$ and mistakenly called a shortened not expurgated code in the version 2 specification, whereas this generator removes odd weight code words not even ones. Unfortunately, a shortened code is normally associated as in [6] with the same error correction functionality as the original code, which is SEC. However, a low-complexity SEC-DAEC error-trapping decoder is readily available [5].

A classic Bluetooth approach is Channel Quality Driven Data Rate (CQDDR) in which packet size and modulation mode is selected according to channel conditions, possibly established through a Received Signal Strength Indicator. In considering packet selection, it is important to take into account the symbol error rate for different forms of modulation, as in [6], and not directly apply the bit error rate, as in [4]. The purpose of this procedure is to establish optimal packet sizes for a given E_s/N_0 range. Some Bluetooth packet sizes may also be redundant unless latency or data-length considerations require them. Given a probability of a bit error *p* the packet error rate for SEC is:

$$PER = 1-((1-p)^{15}+15p(1-p)^{14})^{\frac{s}{15}} \quad (1)$$

where *s* is the user payload length in bits and 15 bits per protected block are assumed. If DAEC-SEC occurs then

$$PER = 1-((1-p)^{15}+15p(1-p)^{14}+14p^{2}(1-p)^{13})^{\frac{s}{15}} \quad (2)$$

Throughput is found as

$$T = \frac{s(1-PER)}{(v+1)t} \quad (3)$$

where *v* is the number of time slots occupied by the Bluetooth packet and *t* is the duration of the Bluetooth time slot. A header error may also lead to a packet error, though the risk is much reduced compared to payload error, because the header is transmitted at the basic rate and always protected by a (3,1) triple redundancy code. Header error is included in the results.

Table 1 summarizes all the additional ACL mode EDR packet types currently available (according to the specification), as well as EDR Data Medium (DM)-type packets (suggested as additional packet types) in the event that symbol-level FEC were to be added to EDR.

Results: Figure 1, are the correctly calculated throughputs by packet type for an AWGN channel, and Figure 2 are equivalent results for a Rayleigh fading channel, representing upper and lower performance bounds. In Figure 2, though available, for clarity of presentation basic rate plots are omitted. Table 2 represents the optimal packet CNR boundaries for all rates, including basic rate, in a Look-up Table (LUT) form suitable for application of CQDDR. It will be apparent that the EDR FEC-enabled DM packet types can play a significant role, as they are optimal for some ranges of CNR. It is immediately apparent that Table 2 is different from Table 4 of [4], as in the latter 3DM3 has a role, 3DM1 appears and at worse channel conditions than 2DM3, and 2DH5 does not appear.

Conclusion: If an effective Bluetooth CQDDR policy is to work, proper calculation of CNR boundaries should take place, together with consideration of the error decoder type. This Letter has provided a revised CNR LUT, allowing, for example, a video streaming to smoothly step up its quality when channel conditions permit by choosing successively longer packet lengths.

Acknowledgement

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Figure captions:

Fig. 1 Throughput versus CNR for different EDR packet types, with and without symbol level FEC, using SEC-DAEC over an AWGN channel.

Fig. 2 Throughput versus CNR for different EDR packet types, with and without symbol level FEC, using SEC-DAEC over a Rayleigh fading channel.

Table captions:

Table 1. EDR packet types in Bluetooth ACL mode.

Length and master to slave bitrates, for a single ACL master-slave logical link, with DM = Data Medium rate (FEC enabled) and DH = Data High rate (no FEC). 2-DH3 is a 2.0 Mbps modulation three time-slot packet.

Table 2. Bluetooth packet type CNR boundaries for AWGN and Rayleigh fading channels.

Table 1.

Packet type	User payload in bytes	Asymmetric max. rate in kb/s
2-DM1	0-36	230.4
2-DM3	0-245	782.9
2-DM5	0-453	965.7
2-DH1	0-54	345.6
2-DH3	0-367	1174.4
2-DH5	0-679	1448.5
3-DM1	0-55	354.1
3-DM3	0-368	1184.3
3-DM5	0-681	1452.0
3-DH1	0-83	531.2
3-DH3	0-552	1776.4
3-DH5	0-1021	2178.1

Table 2.

AWGN Channel		Rayleigh fading channel	
Optimum Packet Type	Channel CNR (dB)	Optimum Packet Type	Channel CNR (dB)
DM1	0<CNR< 7.17	DM1	0<CNR< 14.60
2-DM1	7.17 <CNR<8.25	DM2	14.50<CNR<18.68
2-DM3	8.25 <CNR< 9.06	DM3	18.68<CNR< 24.60
2-DM5	9.06 <CNR< 10.95	2-DM3	24.59<CNR< 26.19
2-DH5	10.95<CNR< 14.89	3-DM3	26.19<CNR< 28.82
3-DM5	14.89 <CNR< 15.15	3-DM5	28.82<CNR< 41.26
3-DH5	15.15 > CNR	3-DH5	41.26 > CNR

Fig. 1

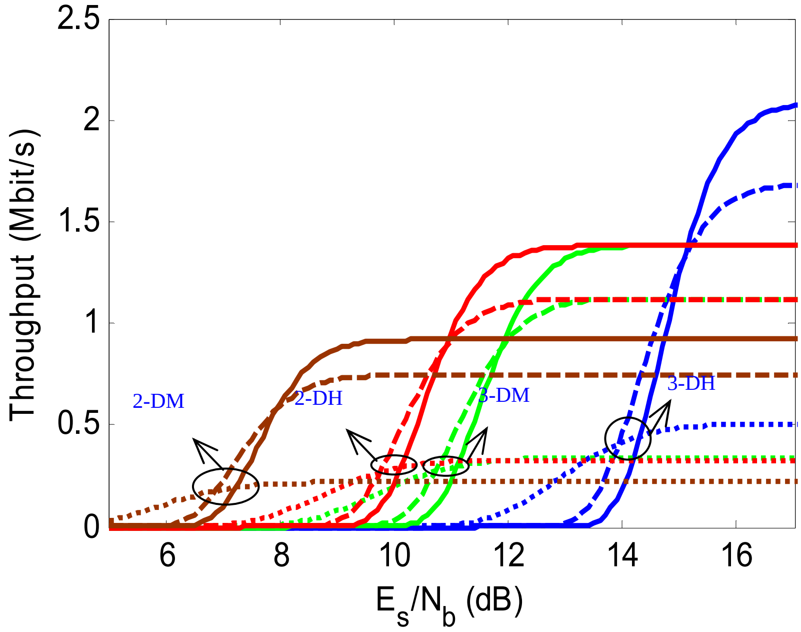
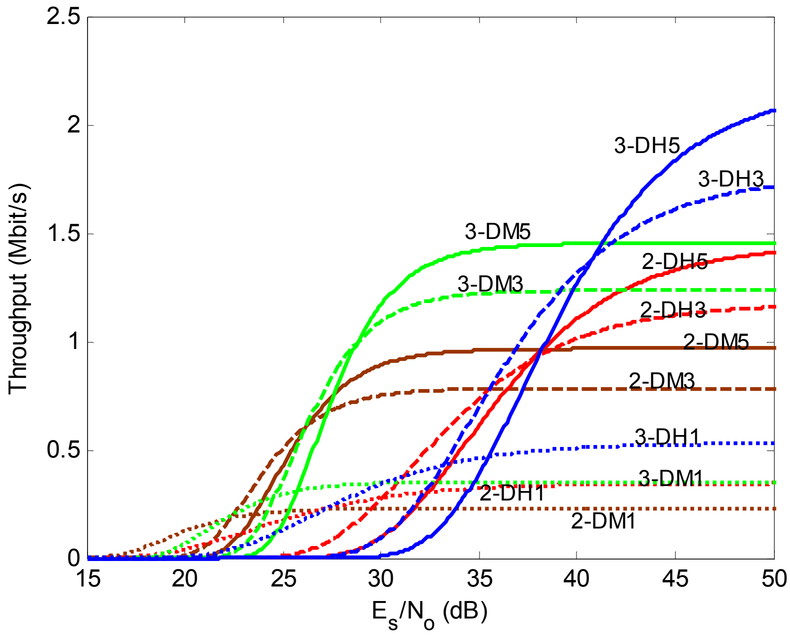

2.5
2
1.5
1
0.5
0
Throughput (Mbit/s)
6
8
10
12
14
16
E_s/N_b (dB)
2-DM
2-DH
3-DM
3-DH

Fig. 2


2.5
2
1.5
1
0.5
0
Throughput (Mbit/s)
15
20
25
30
35
40
45
50
E_s/N_o (dB)
3-DH5
3-DH3
3-DM5
3-DM3
2-DH5
2-DH3
2-DM5
2-DM3
3-DH1
3-DM1
2-DH1
2-DM1