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Bluetooth: Channel Coding Considerations

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***Abstract* – We have noted that several papers that address the performance of Bluetooth (BT) over a fading channel implicitly assume a perfectly interleaved channel and neglect the *bursty* nature of a fading channel. The goal of this paper is to analyze the effects of this incorrect assumption on BT's performance over a frequency-flat Rayleigh block fading channel. Despite the simplicity of the analysis, we obtain interesting results not previously reported in the literature. We will show that neglecting the bursty nature of the channel leads to overly-pessimistic conclusions about the performance of Bluetooth in the low SNR region and, thus, that many reported results on the coexistence of Bluetooth and 802.11 are overly-pessimistic. Moreover, we also conclude that the coding strategy used in Bluetooth has little or no effectiveness on a frequency-flat Rayleigh block fading channel.**

I. INTRODUCTION

The main aim of Bluetooth (BT) is to eliminate interconnection cables and to connect devices using a universal radio link in the 2.4 GHz Industrial Scientific and Medical (ISM) band. Basically, BT is a point-to-point protocol intended to wirelessly connect a variety of digital devices. It operates over short distances of up to 10-100 meters and operates with a transmitted power of 1 mW or 100 mW. BT offers an open system platform for the wireless connection of voice and data services and will open up new horizons in assuring the interoperability of all equipment, from laptops to mobile phones, in "virtual" networks. These wirelessly-connected devices create what is called a Wireless Personal Area Network (WPAN). One of the most interesting applications of a WPAN is in the office workspace where desktops, mobile computers, printers, handheld devices, mobile phones, pagers, portable stereos, etc., can be all tied together.

Several papers have addressed the performance of a BT link over a fading channel. However, several contributions *implicitly* neglect the *bursty* nature of a fading channel and assume a perfectly interleaved channel. For example: in [1], errors are generated on a bit-by-bit basis using a binary symmetric channel model with crossover probability equal to the average bit error rate; in [2], individual errors are randomly spread across the packet. Another common assumption made in the evaluation of the effects of 802.11 interference on BT is that a packet is lost whenever a collision occurs [3], [4].

In this contribution, we analyze the effects of neglecting that, on a fading channel, errors are not independent but occur in bursts. We proceed by comparing the analytical Packet Error Probability (PEP) on a perfectly interleaved Rayleigh frequency-flat fading channel with the simulated Packet Error Rate (PER) of the corresponding non-interleaved (bursty) channel. We will show that neglecting the bursty nature of the channel leads to overly-pessimistic conclusions about the performance of BT in the low SNR region. This result can also be used to state that the effects of 802.11 interference on BT may not be as deleterious as reported in several studies. In fact, since the power spectral density of 802.11 is approximately flat, occupies a bandwidth much larger than the band occupied by BT during any hop and experiences Rayleigh fading, whenever a packet collision occurs the BT receiver will basically experience an increase of the noise level as if the interference simply were additional AWGN [6]. Moreover, we also conclude that the coding strategy used in Bluetooth has little or no effectiveness on a frequency-flat Rayleigh block-fading channel.

The paper is organized as follows. The packet formats and the Forward Error Correcting (FEC) scheme adopted in BT are described in Sect. II. In Sect. III, the theoretical PEP for the perfectly interleaved channel is derived and simulation results on the PER for the bursty Rayleigh fading channel are given. Results are discussed in Sect. IV and conclusions are drawn in Sect. V.

II. PACKET FORMAT AND CHANNEL CODING IN BLUETOOTH

This Section is devoted to the lower level baseband functionalities of the BT specification, and is based upon version 1.1 of the BT Core and Profile specifications [7], as well as various supporting documents.

Bluetooth packets are comprised of three major portions. The first is a 72-bit Access Code (AC) that consists of a 4 bit preamble, a 68-bit sync word, and a 4-bit trailer. The AC provides the means for synchronization, DC offset compensation and identification. The AC identifies all packets exchanged within a piconet, which is a collection of BT devices associated with the same master device. In the receiver of the BT unit, a sliding correlator correlates against the AC and triggers when a threshold is exceeded. The access code is resilient to errors since sync words have large Hamming distance, i.e. at least 14. An 18-bit Header (HD) follows the AC. The HD contains retransmission and flow control information. The HD is encoded with a rate 1/3 repetition code, resulting in a 54-bit encoded HD. The Payload (PL) follows the HD and can contain anywhere from 0 to 2745 bits. PL data may or may not be protected by FEC, depending on the packet type. In the present study we have focused on ACL packets, in particular on the Medium (High) Rate packets denoted by DMx (DHx) (x=1, 3, 5, and it denotes the number of consecutive time-slots between two-consecutive hops utilized to transmit the packet). For the coded DMx packets, the FEC consists of a rate 2/3 (15,10) shortened Hamming code. Each block of 10 information bits is encoded into a 15 bit codeword. This code can correct all single errors and detect all double errors in each codeword.

III. PERFORMANCE OF ACL PACKETS OVER RAYLEIGH FREQUENCY-FLAT BLOCK-FADING CHANNELS

The fading is supposed frequency-nonselective, constant over one hop, and independent from hop to hop (block fading channel). Rayleigh fading statistics are also considered, which well represent the case of non-line-of-sight links. Coherent detection and hard decision decoding is also assumed.

In our analysis, we have also considered a BPSK-modulated signal. In BT, the modulation is GFSK where the modulation index ranges between 0.28 and 0.35 and the bandwidth of the shaping function normalized to the bit rate is equal to 0.5. It is not straightforward to simulate precisely a GFSK link in a simple way. For this reason, in the present paper, the performance of the BT link is analyzed considering a BPSK link. The reason why a BPSK modulation format has been chosen is due to the fact that a modulation similar to GFSK, GMSK, may be simulated as if it were a BPSK link [8]. The theoretical basis for this approximation is that any *M*-ary CPM signal (an MSK signal represents a sub-class of binary partial-response CPM signals with modulation index equal to 0.5) may be exactly decomposed into the sum of a few PAM waveforms [9]. Obviously, it is not trivial to derive the real performance of a GFSK link from the one of a BPSK link. Nevertheless, the analysis of the results obtained for the BPSK case can certainly be considered indicative of the behavior of the corresponding GFSK one.

In Section III.A we will calculate the analytical PEP for the interleaved channel, while in Section III.B we will give simulation results for the PER in the case of a non-interleaved channel, e.g. the normal case for BT links. In both cases, no interference (either from other piconets or form 802.11) is considered. However, the considerations we have made and the results given in [6] also allow us to extend our results to the scenario where 802.11 interference is present, simply by treating the interference as additional AWGN.

A. Theoretical PEP for the Interleaved Rayleigh Fading Channel

The theoretical expression of the bit-error probability P_b of uncoded BPSK over Rayleigh frequency-flat fading channels and coherent detection is given by [10]:

$$P_b = \frac{1}{2}\left(1-\left[\frac{E_b/N_o}{1+E_b/N_o}\right]^{1/2}\right) \cong \frac{1}{4\cdot E_b/N_o} \tag{1}$$

where the approximation holds for high E_b/N_o, typically E_b/N_o>13 dB. The underlying assumption used in this section is that the errors are uniformly distributed along the packet. Let us consider the case of a packet *L* bits long, with an FEC code rate *k*/*n* and capable of correcting *t* errors (obviously, *L* has to be a multiple of *n*, i.e. $L=m\cdot n$). Given that a number of errors greater than *t* occurs, the decoder will fail to decode correctly but, when this occurs, only some of the *k* bits delivered by the decoder will be erroneous. In general, the exact calculation of the BER at the output of the decoder is not straightforward. However, if we are not interested in the BER after decoding but only in the probability p_{ew} of erroneous detection of the entire codeword of *n* bits, the problem is much simpler and we have:

$$p_{ew} = \sum_{i=t+1}^{n}\binom{n}{i}p^i(1-p)^{n-i} \tag{2}$$

where *p* is the BER prior to decoding. Note that eq.(2) only holds for the case of independent errors and not for the case of burst errors. The value of *p* can be calculated using eq.(1) but E_b/N_o should be substituted by E_S/N_o, where E_S is the code symbol energy. For binary signaling, E_S/N_o is related to E_b/N_o as follows:

$$\frac{E_S}{N_o} = \frac{k}{n}\frac{E_b}{N_o} \tag{3}$$

since the energy available per codeword transmission is kE_b joules and this is distributed among *n* code symbols.

At this point we can compute the probability that a packet is bad and, therefore, dropped. In fact, a packet is not dropped if and only if *all* the *m* codewords are decoded correctly. Therefore, the probability $P_{BadPacket}$ that there is at least one error in the packet after decoding is simply:

$$P_{BadPacket} = 1 - P_{GoodPacket} = 1-(1-p_{ew})^m\,. \tag{4}$$

BT packets are composed of three parts: the AC, the HD and the PL. Three different coding schemes are used in each of these parts and, therefore, the calculation of the error probability has to be done separately for each coding scheme.

<u>Access Code</u>

In this case, the codeword is *n*=64 bits long and can correct up to *t*=6 errors (the AC is actually 72 bits long, but 8 bits are used as a trailer sequence). Using eq.(2) the probability that the AC contains more than 6 errors is:

$$P_{Bad}^{AC} = p_{ew}^{AC} = \sum_{i=7}^{64}\binom{64}{i}p^i(1-p)^{64-i}\,.$$

<u>Header</u>

In this case, *m*=18 bits are encoded with a rate 1/3 simple repetition code capable of correcting *t*=1 error. The packet length is *L*=*mn*=54 bits. Therefore, we have:

$$p_{ew}^{HD} = \sum_{i=2}^{3}\binom{3}{i}p^i(1-p)^{3-i}\,.$$

The probability that the HD is discarded after decoding is then:

$$P_{Bad}^{HD} = 1-\left(1-p_{ew}^{HD}\right)^{18}.$$

Coded Payload (DMx packets)

In this case, bits are encoded with a (15,10) shortened Hamming code capable of correcting t=1 error and we have:

$$p_{ew}^{PL-DM} = \sum_{i=2}^{15} \binom{15}{i} p^{i} (1-p)^{15-i} .$$

Since m=16, 100, 183, for the DM1, DM3, and DM5 packets, respectively, the probability that the PL is discarded after decoding is then:

$$P_{Bad}^{PL-DM1} = 1-\left(1-p_{ew}^{PL-DM}\right)^{16} ;$$

$$P_{Bad}^{PL-DM3} = 1-\left(1-p_{ew}^{PL-DM}\right)^{100} ;$$

$$P_{Bad}^{PL-DM5} = 1-\left(1-p_{ew}^{PL-DM}\right)^{183} .$$

Since a packet is accepted only if the AC *and* the HD *and* the PL are fine, we can write:

$$P_{BadPacket}^{DMx} = 1-\left(1-P_{Bad}^{AC}\right)\left(1-P_{Bad}^{HD}\right)\left(1-P_{Bad}^{PL-DMx}\right). \qquad (5)$$

Using the previous equations we can calculate accurately the theoretical Packet Error Probability (PEP) versus E_b/N_o for all the DMx packets.

These probabilities are plotted in Figure 1, where it can be seen that DM1 packets exhibit a performance gain of 3.5 dB over DM3 packets, whereas DM3 packets exhibit a gain of only 1 dB over DM5 packets. Given the similar performance that DM3 and DM5 packets offer, it would be preferable to always choose the longer DM5 packets instead of the DM3 ones. In fact, DM5 ensure higher throughput at a negligible performance degradation.

B. *Simulated PER for the Bursty Rayleigh fading Channel*

We have resorted to Monte Carlo simulations to assess the performance of BT’s DMx packets when no interleaving is performed (the actual situation of BT). The simulation results presented here consider the case of a BPSK link over a frequency-flat Rayleigh block-fading channel

For the simulation of frequency hopping, each sequence of packets transmitted between two consecutive hops (1, 3, or 5 packets) is convolved with a channel realization which is different and independent from the channel realization used for the packets transmitted in the following hop. Between hops, the channel is considered time-invariant (i.e., zero Doppler spread). No equalization is performed at the receiver’s side. The receiver performs a one shot coherent (perfect phase information) detection via a minimum Euclidean distance decision device that outputs the detected data.

Both the coded and uncoded cases were simulated. We have considered that every packet had the maximum allowed data in the PL:

Packets: DH1➔ 240 bits and no FEC;
Packets: DH3➔ 1500 bits and no FEC;
Packets: DH5➔ 2745 bits and no FEC;
Packets: DH1➔ 160 bits Hamming encoded rate 2/3;
Packets: DM3➔ 1000 bits Hamming encoded rate 2/3;
Packets: DM5➔ 1830 bits Hamming encoded rate 2/3;

Finally, a packet is dropped if there is at least one error after decoding the AC, the HD or the (eventually coded) PL. In order to obtain statistically meaningful results, packets necessary to ensure at least 100 dropped packets were generated (with a minimum of 10^4 packets).

Simulation results are shown in Figure 2 for the DMx packets and in Figure 3 for the DHx packets. The PER curve for DMx packets in Figure 2 is in perfect agreement with Figure 4 of [5] (case of Δf=0), where an analytical approach to the evaluation of the effects of 802.11 interference on BT was followed.

As expected, DMx packets perform better than DHx packets and this is due to the presence of FEC in the PL of DMx packets. However, the performance gain is limited to 1.5-2 dB, or to a factor of 2 in the error probability. Similarly to the interleaved case considered in the previous Section, simulations have also confirmed that the shorter DH1 packets perform better than the longer DH3 and DH5 ones, whereas DH3 packets have nearly the same performance as the DH5 ones.

IV. DISCUSSION OF RESULTS

Figure 4 compares the performance of DM1 packets (both interleaved and bursty channel cases) with the performance of DH1 packets. Similarly, Figures 5 and 6 deal with DM3/DH3 and DM5/DH5 packets.

A comparison between the uncoded DHx packets and the coded DMx ones (bursty channel case) shows that the slope of the PER curve versus E_b/N_o is the same. This may be explained by the fact that, without interleaving, the channel is not memoryless and, therefore, coding provides only a multiplicative gain for the error probability. In the presence of interleaving, the asymptotic coding gain appears as an exponential factor of E_b/N_o and the slope of the PEP curve is higher than the PER ones obtained for the bursty channel. It is worth pointing out that the usual negative exponential dependence of P_b on E_b/N_o for non-faded channels (AWGN) is no longer valid when considering fading channels. The fact that the error probability for uncoded transmissions on the Rayleigh channel exhibits a weak inverse dependence on E_b/N_o, is a general result regardless of modulation format and, therefore does not depend on having chosen BPSK in place of GFSK. On the other hand, information theoretic results show that the channel capacity of the interleaved Rayleigh channel is only marginally less than that of the AWGN channel. Block codes are indeed able, in many cases, to improve the situation, but careless application of coding techniques may produce poor results.

BT does not use interleaving. Although this choice may be in line with the desire of cheap transceivers, it is also true that the repetition code and the shortened Hamming code employed by some BT packets are not the best choice for the case of fading channels. However, as Figures 4-6 clearly show, the advantage of using an interleaver is manifest at high SNR, whereas at low SNR transmission over a bursty channel allows better performances. Crossover points are reached at E_b/N_o = 21, 27 and 29 dB for the DM1 , DM3, and DM5 cases, respectively. For the specific applications of BT, it is not necessary to reach extremely low PERs, so we can say that the use of ARQ is probably a better choice than the use of an interleaver, especially since it allows better performances at low E_b/N_o, the regime where BT operates in the presence of interference. Moreover, it is also possible to conclude that, in the case when no interference is present, the use of FEC in BT is not a good engineering tradeoff because the very small protection FEC provides does not counterbalance a reduction of 33% in the throughput of the ACL link due to the added redundancy.

Another conclusion that can be drawn by looking at Figures 4-6 is that the assumption of independent errors causes a non-negligible overestimation of the PER in the low SNR region. Moreover, the common assumption that *every* packet collision leads to a packet loss seems overly-pessimistic as well. This aspect is important when evaluating the performance of BT in the presence of 802.11 interference which causes BT devices to experience a very low SNR at the input of the decision device. In fact, on the basis of the considerations made here and in [6], the effects of 802.11 on BT can be well described by simply varying the E_b/N_o level. Obviously, the amount of variation that needs to be introduced depends on several parameters (transmitting powers, distance between devices, frequency offset between useful and interfering carriers, timing between colliding packets, etc.) and needs to be computed on a case-by-case basis.

V. CONCLUSIONS

The performance of the BT ACL link on a Rayleigh block-fading channel has been analyzed in the absence of interference for both a bursty and a perfectly interleaved channel. The considerations made here and the results given in [6] also allow us to extend our results to the scenario where interference is present, simply by treating the interference as additional AWGN. The main results obtained are summarized below:

- The block codes used in BT are basically ineffective on Rayleigh faded channels and do not allow a change in the asymptotic slope of the PER versus SNR curve.
- In the absence of interference, DHx packets are always preferable to DMx packets because the limited gain FEC provides does not counterbalance a 33% reduction in throughput of the ACL link.
- DH5 (DM5) packets are always preferable to DH3 (DM3) packets since they allow for higher throughput at the price of a negligible performance degradation.
- When interference is present, the PER of BT on a bursty channel can be as much as four times smaller than in the case of an interleaved channel. Thus, previous analyses on the effects of 802.11 interference on BT based on a memoryless channel assumption may be considered overly pessimistic.
- The effects of 802.11 on BT can be analyzed to a good degree of accuracy by considering the performance of BT on an interference-free link and, then, simply varying E_s/N_o.

Current and future work will be directed to include explicitly 802.11 interference in the PER calculation, as well as to evaluate the effects of self-interference created by adjacent and overlapping piconets [11]. Moreover, for the case when 802.11 and BT are co-located on the same device, the Authors are also looking at the definition of a strategy that maximizes the throughput of both systems.

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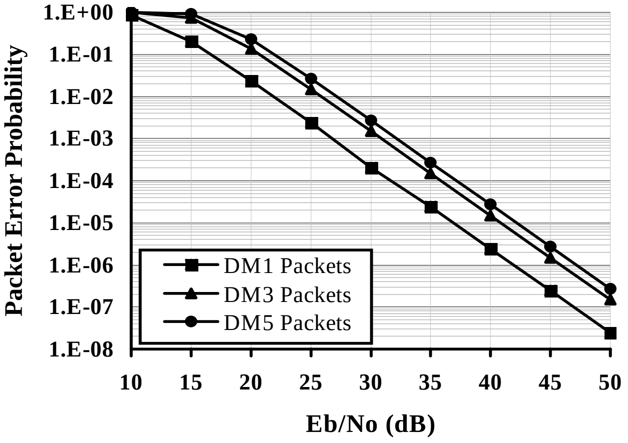

Figure 1: Analytical PEP of DMx packets (interleaved channel case).

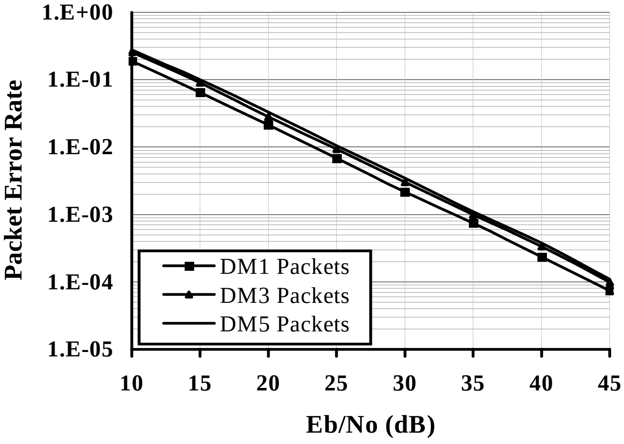

Figure 2: Simulated PER of DMx packets (bursty channel case).

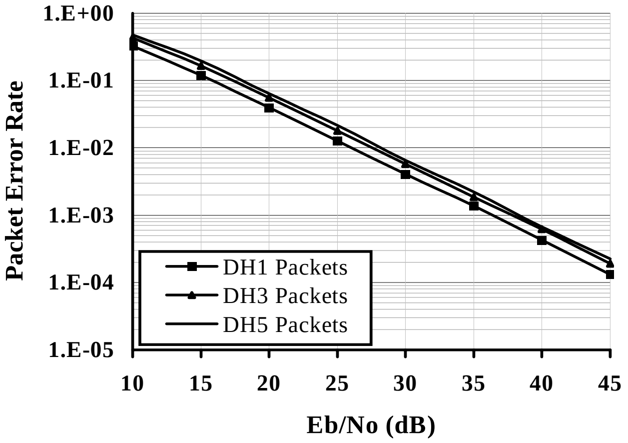

Figure 3: Simulated PER of the uncoded DHx packets (bursty channel case).

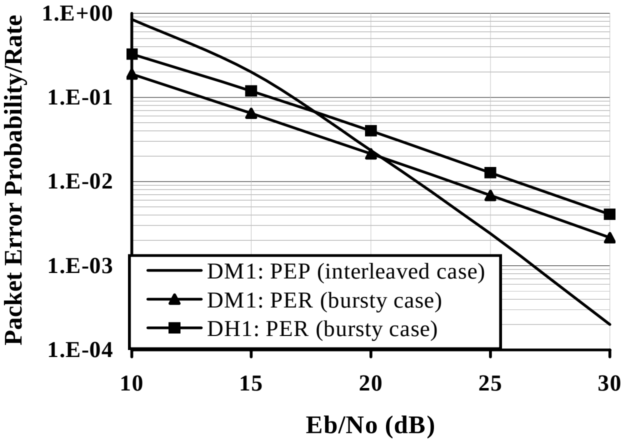

Figure 4: Comparison between the performance of DM1 (both interleaved and bursty channel cases) and DH1 packets.

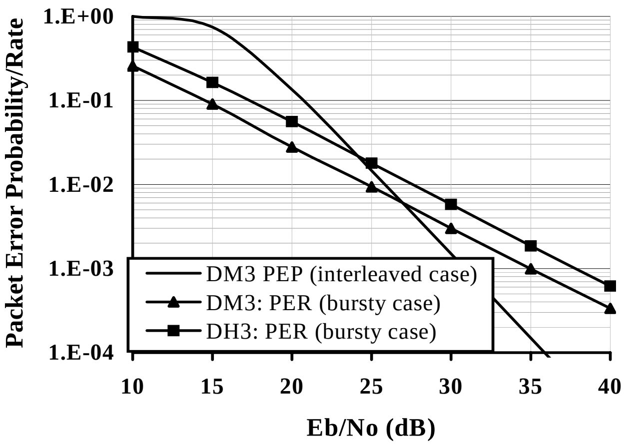

Figure 5: Comparison between the performance of DM3 (both interleaved and bursty channel cases) and DH3 packets.

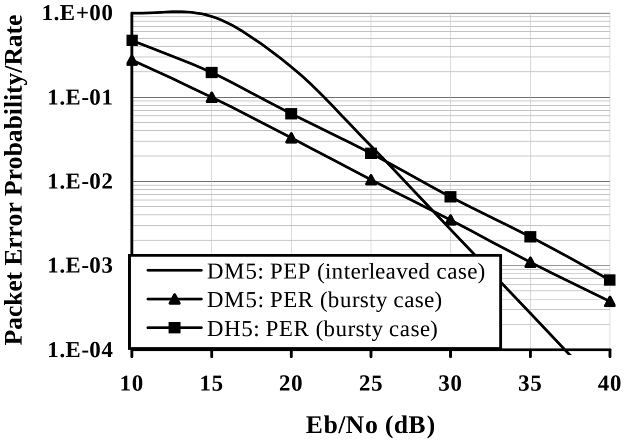

Figure 6: Comparison between the performance of DM5 (both interleaved and bursty channel cases) and DH5 packets.