On the Impact of Fading and Inter-piconet Interference on Bluetooth Performance

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Abstract

In this paper we propose a simple method to evaluate the impact of fading and inter-piconet interference on Bluetooth performance. We consider in detail the joint effect, on packet error statistics, of interference produced by adjacent Bluetooth piconets and fading. Hence, we illustrate the proposed method by investigating the potential performance tradeoff among the different radio packet formats supplied by Bluetooth, as a function of the radio channel conditions and interference levels.

Keywords

Bluetooth performance, fading, inter-piconet interference.

INTRODUCTION

Bluetooth is an emerging radio interface that operates in the 2.4 GHz ISM unlicensed band, providing a raw bit rate of 1Mb/s by using a binary Gaussian–shaped FSK modulation [1], [2]. To reduce interference with other devices operating in the ISM band, Bluetooth adopts a frequency hopping (FH) spread spectrum technique, spanning 79 RF carriers, 1–MHz wide each. In order to communicate, two up to eight Bluetooth units may connect in a small network, called piconet. In each piconet, a unit acts as master, controlling the channel access by means of a simple polling scheme. Time is divided into consecutive slots of 625µs each, that are used for downlink (master-to-slave) and uplink (slave-to-master) transmissions, alternatively, in a time division duplex (TDD) fashion. Namely, each time-slot is associated to a hop in the hopping sequence, resulting in a nominal hop rate of 1600 hop/s.

Different piconets are associated to independent FH channels. This allows more piconets to share the same physical space and spectrum without increasing excessively the mutual interference. However, since the frequency hopping sequences are not orthogonal and the channels are asynchronous, interference among different piconets may occur. With the perspective of having Bluetooth integrated in almost every electronic device, in the near future, the inter-piconet interference issue becomes of high importance. Furthermore, the standard provides up to six packet formats for asynchronous data traffic that differ for time duration, data capacity and error–protection. Therefore, the performance yielded by such different packet formats may show a tradeoff as the radio channel conditions and interference levels vary.

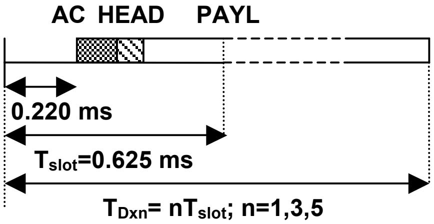

Figure 1. Bluetooth packet format

In this paper we propose a general method to evaluate the impact of fading and inter-piconet interference on Bluetooth performance. Although some analysis of the effect of inter-piconet interference has been done in literature, most of the work is either based on simulations only [3], [4] or it makes restrictive assumptions as fixed length packets, destructive interference, absence of fading, [5], [6]. Our approach relaxes most of these assumptions. In particular, we take into account the statistic of the received signal and interference power, number of potential interferers, probability of packets collision and type of packets used. We analytically derive the distribution of the interference power along the desired packet. Then, we derive the distribution of both the desired signal and interference power. From the above statistics, we can derive the bit error rate distribution along the packet, and consequently, the packet error rate. This approach allows us to remove the restriction of destructive interference, i.e., even a single bit collision is sufficient to declare the packet loss. An analysis that overcomes this restriction was already presented in [7]. However, the model was very complicated and its application to the case with more than 3 interfering piconets was unpractical. On the contrary, the method we propose can be easily applied to the case of many interferes. Furthermore, we evaluate the performance yielded by all the different packet formats provided by Bluetooth, considering the effect of forward error correction (FEC) and different packet lengths. To conclude the paper, we report a comprehensive set of performance curves that illustrates the behavior of the Bluetooth network as a function of its parameters, such as number of piconets, channel propagation conditions and packet format considered.

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BLUETOOTH PACKET FORMATS

Bluetooth provides both Synchronous Connection Oriented (SCO) and Asynchronous Connection Less (ACL) links, for coded voice and best-effort data traffic (symmetric and asymmetric), respectively. In the following, we will focus on ACL links only.

Figure 1 depicts a generic Bluetooth data packet format. Each packet contains three main fields: the access code (AC), the packet header (HEAD) and, optionally, the payload field (PAYL). The 72-bit AC field is used for synchronization and piconet identification. The receiver correlates the incoming signal against the expected AC. If the correlator output does not exceed a given threshold, the packet is discarded. The AC is followed by an 18-bit packet header field (HEAD). The HEAD is coded with a 1/3 forward error correction (FEC) code, which is obtained by two-time repetition of every bit, resulting in a total field length of 54 bits. Finally, the packet is trailed by the PAYL field, whose length can vary from 0 up to 2728 bits, depending on the packet type. The PAYL can be unprotected or protected by a 2/3 block code for FEC able to correct a single error in each codeword of 15 bits. ACL packets can extend over one, three or five consecutive time slots. When a multi-slot packet is used, the transmitter frequency remains unchanged for the entire packet duration, thus reducing the loss of capacity due to the guard time of 0.220 ms that is required at each frequency hop. ACL packets are usually denoted by *Dxk*, where *x* stands for M and H and distinguishes between protected *Medium-capacity* and unprotected *High-capacity* packets, while *k* denotes the number of slots occupied by the packet (k=1,3 or 5).

SYSTEM MODEL

We focus on the performance of a target receiver (TR), which is positioned r_0 meters apart from the corresponding transmitter. We consider the joint effect of noise, path loss, fading and interference from adjacent Bluetooth piconets, while, at this phase of the work, the shadowing effect is neglected.

Interference may be produced by each terminal in the coverage area. However, the number N_p of *potential interferes* is given by the total number of adjacent piconets, since only one terminal at a time is allowed to transmit in each piconet. A potential interferer becomes an *effective interferer* when it transmits a packet on the same carrier frequency of the target packet.

Radio Propagation and Interference Models

In the typical scenario defined for Bluetooth, the fading process can be assumed flat on the 1 MHz bandwidth and constant for the entire duration of a data packet. Furthermore, signals from different transmitters incur in independent fading and, because of the FH mechanism, even successive packets from the same transmitter are interested by independent fading.

The performance of the GFSK receiver depends on the instantaneous signal to noise/interference ratio. However, the effect of the noise and interference power on the bit error rate (BER) is, in general, different. Following the approach proposed in [3], we consider a gross bit error rate function given by

$$BER = \beta\left(\frac{Prx}{P_I R_I + N_0 R_0}\right), \qquad (1)$$

where $\beta(\cdot)$ is the receiver performance curve, Prx is the instantaneous signal power at the receiver, P_I is the total instantaneous interference power and N_0 is the white noise power [3]. The weight factors R_I and R_0 correspond to the signal-to-interference (SIR) and signal-to-noise (SNR) power ratios, respectively, which are required to have a raw BER of 10^{-3} for the corresponding type of interference.

The instantaneous signal power at a distance r from the transmitter is given by $\gamma=P_T A r^{-\eta}\alpha^2$, where P_T is the nominal transmitted power, $Ar^{-\eta}$ accounts for the deterministic path loss, and α represents the normalized fading envelope, which may be Rice or Rayleigh distributed. The values of P_T, A and η are assumed constant and equal for all the users in the system, so that the statistic of γ is determined by the statistic of the *normalized power* $\lambda=\alpha^2 r^{-\eta}$. The total power of n interfering signals is assumed to be given by the sum of the power of each interferer [3], [7], i.e., $P_I=P_T A\Lambda_n$, where $\Lambda_n=\sum_i\lambda_i$, $i=1,2,\ldots,n$, is the total normalized power.

Since the random variables λ_i are assumed to be independent and identically distributed (iid), the probability density function (pdf) of Λ_n is given by $f_{\Lambda_n}(\Lambda) = f_\lambda^{(n)}(\Lambda)$, where $f_\lambda(\cdot)$ is the pdf of λ and $f_\lambda^{(n)}(\cdot)$ denotes the n-fold convolution of $f_\lambda(\cdot)$ with itself. The pdf of λ can be expressed in terms of the pdf of α^2 and r, i.e.,

$$f_\lambda(\lambda) = \int_0^D dr\, f_r(r) r^\eta f_{\alpha^2}\left(\lambda r^\eta\right). \qquad (2)$$

By assuming the interfering piconets to be uniformly distributed around the TR, within a circle of ray D, the distance r from the TR is a random variable with pdf $f_{r_i}(r)$ $=2r/D^2$, $r\in[0,D]$. The pdf of the square envelope α^2 is found to be

$$f_{\alpha_i^2}(\rho) = (1+K)e^{-K}e^{-(K+1)\rho}\mathrm{I}_0\left(\sqrt{4K(K+1)\rho}\right),$$

where K is the Rice factor, and $\mathrm{I}_0(\cdot)$ is the zero-order modified Bessel function of the first kind [8].

For K=0, we obtain the pdf for a Rayleigh fading model, which turns out to be exponential, $f_{\alpha_i^2}(\rho) = \exp(-\rho)$, $\rho\geq 0$.

In this case, (2) turns out to be given by

$$f_\lambda(\lambda) = \frac{2}{\eta D^2}\lambda^{-(2+\eta)/\eta}\Gamma_i\left(\frac{2+\eta}{\eta}, \lambda D^\eta\right), \qquad (3)$$

where $\Gamma_i(a,b)$ is the incomplete gamma function as defined in [9]. For η=2, (3) can be further simplified as follows

$$f_\lambda(\lambda)=\frac{1-e^{-D^2\lambda}\left(1+\lambda D^2\right)}{\lambda^2 D^2}. \qquad (4)$$

Packet Error Probability

The exact performance analysis of the system, which takes into account, in particular, the time shifts among piconets, turns out to be very complex in terms of computational resources and elaboration time required. Hence, we relax this constraint by assuming that all the piconets are synchronized to the time slot. Furthermore, we assume that interfering piconets use single-slot packets only.

Under these hypotheses, a packet from an adjacent piconet can be a potential danger to only *one* packet in the target piconet [6]. Hence, the model we consider is somewhat optimistic and yields to an upper bound for the actual system performance.

The packet error probability depends on the distribution of the signal and interference power along the target packet. Let $\lambda_0=\alpha_0^2 r_0^{-\eta}$ be the normalized signal power, which is assumed to be constant for the entire packet duration. Then, the average packet error probability for the generic *Dxk* target packet is given by

$$PER_{xk}=\int_0^\infty d\lambda_0 PEP_{xk}(\lambda_0) r_0^\eta f_{\alpha^2}\left(r_0^\eta \lambda_0\right), \qquad (5)$$

where $PEP_{xk}(\lambda_0)$ is the packet error probability given that the signal power is λ_0. Under the hypothesis of synchronous piconets, the number N_e of effective interferers and their power may change slot by slot in an independent way, as depicted in Figure 2 for a multi-slot target packet and two effective interferers.[1] (The shaded parts on the target packet indicate where collision occurs.) Let us partition the *Dxk* target packet in *k* different parts, so that each part occupies a single slot. The first part differs from the others in that it contains the AC and HEAD fields, besides a fraction of the PAYL field. Furthermore, the first 0.220 ms of the slot are not occupied by useful data. The other *k-1* parts have the same structure: they contain an equal fraction of the PAYL field, which is extended over the entire slot. Hence, the conditioned packet error probability can be expressed as

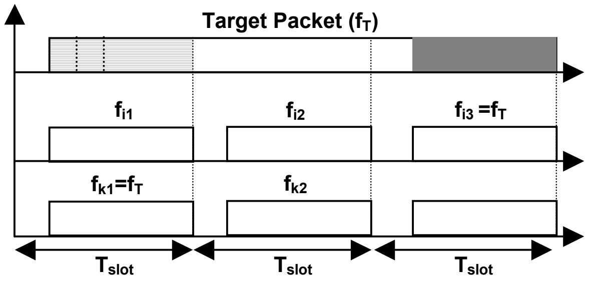

Figure 2. Interference in synchronized piconets

$$PER_{xk}(\lambda_0)=1-P_A(\lambda_0)P_B(\lambda_0)^{k-1}, \qquad (6)$$

where $P_A(\lambda_0)$ denotes the conditioned probability that the first part of the packet is correctly received, given that the normalized signal power is λ_0. Analogously, $P_B(\lambda_0)$ is the probability that any one of the other parts of the packet is correctly decoded. Such probabilities depend on the statistic of the number n_e of effective interferers and the aggregated interference power Λ_{n_e}. Hence, we can express the probability $P_{A(B)}(\lambda)$ as follows:

$$P_{A(B)}(\lambda_0)=\sum_{n_e=0}^{N_p}\mathrm{P}_{N_e}(n_e)\int_0^\infty d\Lambda_{n_e} P_{A(B)}(\lambda_0,\Lambda_{n_e}) f_{\Lambda_{n_e}}(\Lambda_{n_e}), \qquad (7)$$

where $P_{A(B)}(\lambda_0, \Lambda_n)$ is the probability that the part *A* (res. *B*) of the packet is correctly received, given that the normalized signal and interference powers are λ_0 and Λ_n. If all the carrier frequencies have the same probability to be chosen at each frequency hop, then the statistic of n_e is given by

$$P_{N_e}(n_e)=\binom{N_p}{n_e}(sP_F)^{n_e}(1-sP_F)^{N_p-n_e}, \qquad (8)$$

where $P_F=s/N_F$, N_F=79 is the total number of available channels and *s* is the probability that a packet is transmitted by an adjacent piconet in a given slot. To derive the expressions of $P_A(\lambda_0, \Lambda_n)$ and $P_B(\lambda_0, \Lambda_n)$, we need to introduce the correct-reception probability of each one of the fields that compose the Bluetooth packet. Let β_0 be the BER values obtained by (1) for $P_{rx}=P_T A\lambda_0$ and $PI=P_T A\Lambda$. The AC field is recognized when the number of erroneous bits in the AC does not exceed a correlator threshold value, CT. Hence, the probability that the AC is accepted is given by

$$AC_{ok}(\lambda_0,\Lambda)=\sum_{j=0}^{CT}\binom{72}{j}\beta_0^{\,j}(1-\beta_0)^{72-j}. \qquad (9)$$

The HEAD field contains 18 code-words protected by a 1/3 FEC code. Consequently, the field is well recognized provided that each one of the 18 code-words does not contain more than 1 erroneous bit. The probability of this event is

$$HEC_{ok}(\lambda_0,\Lambda)=\left(3\beta_0(1-\beta_0)^2+(1-\beta_0)^3\right)^{18}. \qquad (10)$$

Finally, let $PL_{ok}(h, \lambda_0, \Lambda)$ be the probability that a block of *h* consecutive bits in the payload field is correctly decoded. Then, for unprotected packet formats, we have

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[1] We neglect the possibility of multiple collisions of the target packet with packets from the same terminal. This assumption is partially motivated by the time division duplex mechanism adopted in each piconet, which guarantees a minimum distance of one slot between consecutive packets from the same terminal.

$$PL_{ok}(h,\lambda_0,\Lambda)=(1-\beta_0)^h; \tag{11}$$

while, for protected formats, we have

$$PL_{ok}(h,\lambda_0,\Lambda)=\left(15\beta_0(1-\beta_0)^{14}+(1-\beta_0)^{15}\right)^{\lceil h/15\rceil} \tag{12}$$

where the symbol $\lceil\cdot\rceil$ is used to indicate the ceiling function.

The probability $P_A(\lambda_0, \Lambda_n)$ is, then, given by

$$P_A(\lambda_0,\Lambda)=AC_{ok}(\lambda_0,\Lambda)HEC_{ok}(\lambda_0,\Lambda)PL_{ok}(L_A,\lambda_0,\Lambda), \tag{13}$$

where L_A is the length of the fraction of the payload field that is contained in the first part of the target packet. The probability $P_B(\lambda_0, \Lambda_n)$ is, instead, given by

$$P_B(\lambda_0,\Lambda)=PL_{ok}(220,\lambda_0,0)PL_{ok}(405,\lambda_0,\Lambda), \tag{14}$$

where we have considered that the first 0.220 ms of each slot are left idle by the interferer packets and, then, the BER on this part of the packet is determined by the white noise power only.

RESULTS

In this section, we first analyze the potential performance tradeoff between the different packet formats supplied by Bluetooth. Then, we investigate the accuracy of the analytic model proposed, by comparing the theoretical results with some simulations.

Table 1. Model parameters

P_T	A	η	R_I	R_0	N_0
1 mw	10^{-4}	2	+9dB	+17dB	-87 dBm

The analysis that follows has been carried out considering the values given in Table 1 for the system parameters [3]. In particular, the noise power N_0 was chosen to have a BER of 0.001 for a received power of -70 dBm, as required by the Bluetooth specifications [1]. The interfering piconets were scattered over an area of ray D=10 m around the TR.

Performance Analysis

In the following, we consider an asymmetric ACL link, where data flows in the forward direction, carried by D_{xk} packets, while acknowledgments are returned in the backward direction by means of single slot packets. We disregard the error statistic of the feedback channel and focus on the performance of the forward link only. Beside the PEP_{xk}, we consider the forward throughput, ν_{xk}, which is defined as the average number of user data bits transmitted without errors in the forward direction, per unit of time. Please, note that the actual throughput perceived at the upper layers may be lower than ν_{xk}, because of errors in the return link.

Figure 3 shows the packet error probability (upper part) and the throughput (lower part) achieved by the six ACL packet formats, for different numbers N_p of potential interferers. The curves have been obtained in the case of Rayleigh fading and for a distance r_0 of 8 meters between transmitter and receiver of the target piconet. A first evidence from the figure is that the PEP curves for DMk and DHk packet formats get close each other as the number N_p of potential interferers increases. In other words, in the presence of inter-piconet interference, the FEC code does not give any significant benefit to the packet error probability. The throughput curves in the bottom part of the figure, reveal the presence of a crossing point between the performance curves achieved by Dx5 and Dx3 packet formats, when the number of potential interferers is around 10. This was expected, since the collision probability is lower for shorter packet formats than for longer ones, at the expense of the maximum packet capacity.

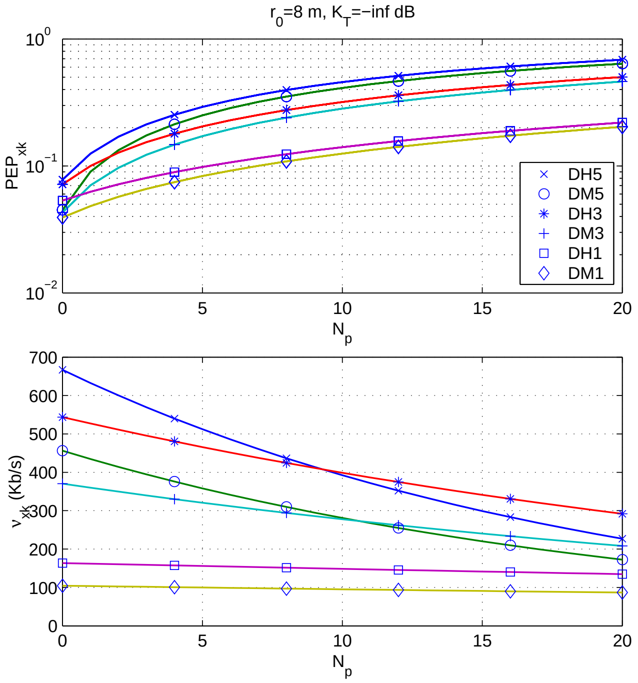

Figure 3. Performance of different packet formats

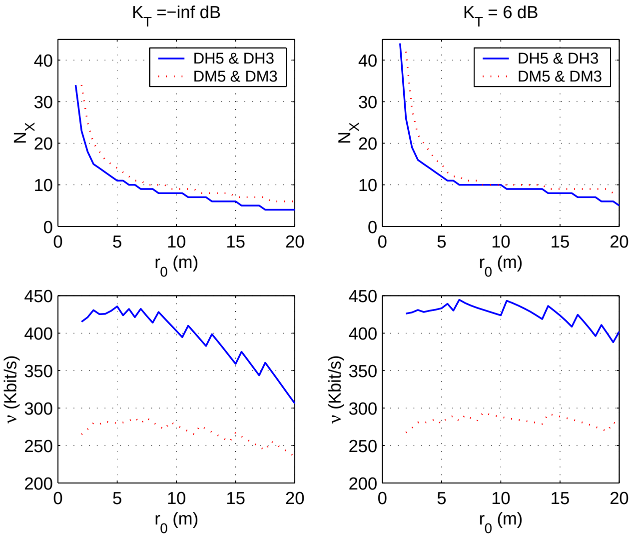

Figure 4. Performance-crossing points

Figure 4 is divided in fours parts. The graphs on the first row show the throughput crossing point N_X, i.e., the number of potential interferers for which ν_{x5} is approximately equal to ν_{x3}. The graphs on the second row show the throughput value at the crossing point. Curves have been obtained by considering a Rayleigh fading model for the interferers and both a Rayleigh (first column) and a Rice (second column) model, with K=6dB, for the desired signal. Curves are plotted against the distance r_0 between the TR and its transmitter. We can note that the presence of Line of Sight (LOS) between transmitter and receiver has a marginal impact on the throughput crossing point. However, in the case of Rice fading the throughput at the crossing point is higher and, hence, the system is less sensitive to inter-piconet interference.

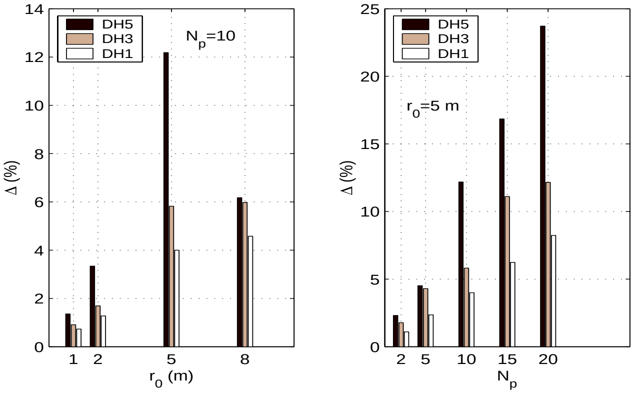

Figure 5. Analysis accuracy

Analysis Accuracy

In order to estimate the accuracy of the results provided by the analytical model, we have compared the theoretical results with some simulations. The simulator computes the real throughput assuming not synchronized piconets. On the other hand, recall that in the theoretical analysis users are assumed to be slot-synchronous.

Figure 5 shows the distance, in percentage, between the theoretical and the experimental throughput values. In the left-most graph, the error is evaluated for different values of r_0, while N_p was fixed to 10. In the right-most graph, r_0 was fixed to 5 meters, while N_p varied from 2 to 20. We can note that the bound provided by the analysis is fairly tight when the number of potential interferers is small and r_0 is either small or close to the maximum coverage range. On the contrary, for values of r_0 close to half the coverage range and for higher number of interferers the bound becomes loose.

CONCLUSIONS

In this paper we have presented a simple and general method to evaluate the performance of Bluetooth for various packet formats, in the presence of fading and inter-piconet interference.

The analysis has revealed that protected packet formats achieve very poor performance in case of inter-piconet interference, since the FEC code is not able to cope with the burst of errors produced by an interfering signal. As expected, long and short packet formats have shown a performance tradeoff as the number of potential interferers increases over a given threshold. The crossing point of the throughput curves is strictly related to the distance r_0 and the presence of LOS between transmitter and receiver.

Finally, we have analyzed the accuracy of the proposed model, by comparing theoretical and simulation results. The performance bound provided by the theoretical analysis has proved to be fairly tight when the number of potential interferers is small (less than 8) and the distance between transmitter and receiver is either small or large. On the contrary, when the distance between transmitter and receiver is around half the coverage range, the statistic of the interference along the packet becomes relevant for the packet error probability.

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