HomeRF and Bluetooth:
Assessment of the Point-to-Point Link Performance

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Abstract – **The common denominator of today's wireless home networks is the absence of equalization at the receiver. This choice is currently viewed as mandatory in order to keep down the costs of a wireless home network. In fact, it is a common assumption that in indoor environments the effects of multipath interference may be considered negligible. However, this is not always true. It has been ascertained on the basis of Monte Carlo simulations that the effects of a time delay as small as 50 ns may cause a performance loss of several dBs in the receiver Signal-to-Noise Ratio (SNR). In the present contribution, we give a quantitative measure of the performance degradation suffered by a receiver when no equalization is performed. In particular, we analyze the performance of the Home Radio Frequency and Bluetooth solutions.**

1. Introduction

For the past 10-15 years of network evolution, "intelligence" has moved towards the home. This "intelligence" is not limited to PCs. Home control systems, appliances and consumer electronics devices are all becoming significantly more intelligent, with built-in computing and communications capabilities. However, the potential of this built-in intelligence often goes unused, as these devices remain isolated. The idea behind a Home Network is to provide an infrastructure that will allow users to connect together several PCs, share resources and connect consumer electronics devices to the PC. The increase in the number of multi-PC and online households, the increasing number of digital consumer electronics devices, as well as tens of million households that do some or all of their work at home, are other key factors driving the consumer demand for a Home Network.

Among several working groups involved in the definition of a common standard for a wireless home network, the Home Radio Frequency (HomeRF) Working Group is one of the most active. This working group is a consortium established in March 1998 by Compaq, Hewlett-Packard, IBM, Intel and Microsoft. It is focused on the development of a standard protocol for wireless interoperability in the 2.4 GHz band and for data rates of 1-2 Mb/s, using an hybrid TDMA/CSMA technique. System parameters are designed so that a range of 150 feet is achieved. The goal of the HomeRF Working Group is to provide a single foundation for a broad range of interoperable consumer devices. The Shared Wireless Access Protocol (SWAP) specification is intended to be a standard that will allow PCs, peripherals, cordless telephones and other consumer electronic devices to communicate and interoperate with one another. The SWAP protocol combines elements of the existing Digital Enhanced Cordless Telephone (DECT) and IEEE 802.11 standards. The protocol architecture closely resembles the IEEE 802.11 wireless LAN standard in the Physical Layer and extends the Medium Access Control layer with the addition of a subset of the DECT standard to provide isochronous services. The SWAP protocol does not use forward error correcting codes but rather only error detecting codes.

Another industry consortium that is very active the area of wireless connectivity is the Bluetooth (BT) Consortium. The BT Consortium was founded in May 1998 by Ericsson, Intel, IBM, Toshiba and Nokia and now has over 2000 members. The main aim of BT is to eliminate interconnection cables and connect one device to another via a universal radio link in the Industrial Scientific and Medical (ISM) band, i.e. 2.4 GHz. System parameters were initially designed so that a range of 30 feet could be achieved; recently, the range has been extended up to 150 feet. BT offers an open system platform for wireless connection of voice and data services and will open new horizons assuring the interoperability of all equipment, from laptops to mobile phones, in "virtual" networks. These wirelessly-connected devices create a network called Wireless Personal Area Network (WPAN). Some obvious applications of a WPAN are in the office workspace where desktops, mobile computers, printers, handheld devices, mobile phones, pagers, can all be tied together. The capabilities provided by BT, approximately 700 Kb/s, can be used for cable replacement and several other applications such as speech, LAN, and so on. The main advantages of BT are minimal hardware dimensions, projected low price components, and power consumption. The standard defines two kinds of forward error correcting codes: 1) a simple rate 1/3 repetition code; 2) a rate 2/3 shortened Hamming code. BT technology was initially developed as a cable replacement solution but, in the long term, BT could also become an important component of the wireless home network market.

The absence of equalization at the receiver is a common denominator for both HomeRF and BT solutions. This choice is currently viewed as mandatory in order to keep down costs of the wireless home network. In fact, it is a common assumption that in indoor environments the effects of multipath interference may be considered negligible. However, this is not always true. In order to give a quantitative measurement of the performance degradation due to multipath interference, Monte Carlo simulations have been carried out. The main result of this analysis is that the common assumption of negligible multipath interference is overly optimistic. In fact, the effects of a time delay as small as 50 ns may cause a performance loss of several dBs in the receiver SNR.

2. Indoor Radio Propagation and Multipath

The propagation of radio signals is impaired by multipath interference. Multipath interference is present when the transmitted signal arrives at the receiver following multiple propagation paths. The presence of multiple propagation paths leads to fading and Inter-Symbol Interference (ISI) in the received signal.

Since radio signals propagate in all directions, the received radio signal is comprised of by a multiplicity of (randomly) attenuated, delayed and phase-shifted replicas of the transmitted signal. The superposition of these echoes causes random fading and broadening of the time duration of the transmitted pulse (delay spread) that, in turn, leads to ISI in the received signal. The presence of ISI means that subsequent symbols interfere with each other, thus leading to a Bit Error Probability (BEP) floor that is independent of the SNR. A major difference between indoor and outdoor propagation is that the former is much more sensitive to changes in the geometry of the environment than the latter. For example, a door being shut rather than open can have a major impact on the indoor propagation environment whereas a comparable event in an outdoor environment would have a little impact. In addition, indoor propagation is very dependent on the type of materials used for the construction of the building.

Multipath interference causes a broadening of the time duration of the transmitted pulse. A common measure used to express this broadening is the Root Mean Square (RMS) of the time-delay spread, i.e. the standard deviation of the amount of widening that the transmitted pulse experiences across the radio channel. Typical values of RMS time-delay in indoor environments are between 25 and 300 ns [1]. Telcordia Technologies has also performed measurements on the delay spread in indoor environments and found that the RMS time-delay spreads were under 100 ns when there was a direct path between the transmitting and receiving antenna. However, in the absence of such direct path, something very likely to happen unless there is at least one antenna per room, the measured RMS time-delay spreads were as high as 270 ns.

If the RMS time-delay is very small with respect to the signaling time T_S, multipath interference essentially leads to fading phenomena of the received signal. However, as the RMS time-delay increases, multipath interference leads to ISI as well. The amount of ISI present in the received signal can be evaluated looking at the low-pass equivalent T_S-sampled input delay spread function. The latter is obtained taking into account the interpolation effects of a raised-cosine-like receiving filter, i.e. convolving the continuous low-pass input-delay spread function of the channel with a waveform of the form $\sin x/x$ (if, for the sake of simplicity, we assume zero roll-off) and, then, sampling at the signaling period T_S.

In Figures 1-2, some typical cases are shown for several values of the delay spread and of the signaling period. For a given delay spread, as the signaling period decreases, the power of the channel taps at lags 1, 2, etc., increases, thus meaning that more ISI is present in the received signal. For baud rates of 1 Mbaud, the power-delay profile of the low-pass equivalent T_S-sampled input delay spread function reported in Figure 1 shows that the indoor channel can still be considered approximately a flat fading channel, so that the presence of an equalizer at the receiver is not mandatory. On the other hand, Figure 2 shows that for baud rates of the order of 10 Mbauds the indoor radio channel is indeed a frequency selective channel.

3. Simulation Results

The performance of the point-to-point radio link will be expressed in terms of Bit and Frame Error Probability (BEP, FEP) versus Signal-to-Noise Ratio (SNR) and has been obtained by means of Monte Carlo simulations. The radio link has been simulated considering a BPSK-modulated signal transmitted over a Rayleigh fading channel. The channel is either constituted of one path (flat fading) or two equal-power paths with a delay spread equal to 50, 100 and 200 nanoseconds (see the Appendix for more details on the simulation technique adopted).

3.1. HomeRF

When the data rate is around 1 Mbaud and the RMS time-delay is around 100 ns (see Figure 1), an equalizer may not be necessary but the performance degradation due to multipath interference is not negligible. In order to evaluate the amount of this performance degradation in terms of BEP and FEP versus SNR, we have simulated some typical indoor environments and the results are shown in Figures 3-4. Looking at Figure 3, it can be seen that, at a BEP of 10^{-3}, there is a 5 dB performance degradation from a Rayleigh flat fading channel to a channel with 50 ns of delay-spread. Moreover, for a delay spread as small as 50 ns the BEP floor is around 10^{-3}.

We have also measured the FEP (see Figure 4) for a packet payload of 5,000 bits. It is also assumed that no coding is present, so that a frame that contains at least one error is discarded and retransmitted. Frame error rates below 10^{-2} are difficult to achieve even when the time delay spread is as small as 50 ns. This is a poor result and shows that multipath interference should not be neglected in indoor environments when the bit rates are around and above 1 Mb/s.

3.2. Bluetooth

For a range of 10 meters or less, delay spreads ranging from zero up to 50 ns should be considered. Values of delay spread between 50 and 100 ns can also be used to test the robustness of BT for the long range case. In the simulations, we have considered the following payload lengths (as indicated in the BT specifications): 240 bits (packets DH1, HV1, HV2, HV3) and 2745 bits (DH5, DM5). The error correcting codes considered in the BT specifications are a repetition code rate 1/3 (labeled "Rep") and a shortened Hamming code rate 2/3 (labeled "Ham"). In the evaluation of the FEP, a packet is discarded as erroneous if it is received with at least one error after decoding.

As can be seen from Figures 5-6, the performance of the radio link looks quite good when the delay spread is limited to 50 ns. In this scenario, channel coding provides a FEP between 10^{-3} and $5 \cdot 10^{-3}$ whereas for the uncoded case it would not be lower than 10^{-2}. On the other hand, when delay-spreads between 50 and 100 ns (typical values for home-networking applications) are considered, the performances are not very good even if the link is protected by channel coding. In particular, neither the repetition code (see Figures 5-6) nor the shortened Hamming code (see Figures 7-8) are sufficient to balance the effects of fading and multipath if the payload length is too big. In particular, simulations have shown that only if the payload is not longer than few hundred bits and if the repetition code is used, the FEP can be kept below 10^{-2}. These results tend to suggest that BT technology is best suited for short-range applications, whereas for long range applications the performance degradation is not negligible.

4. Conclusions

The simulation results tend to indicate that environments that are commonly believed to be benign such as indoor radio links, may yield non trivial performance degradation if an equalizer is not employed at the receiver side. The major effect due to poor link performance is the increase of the number of retransmissions and the consequent reduction of the throughput of the link.

In particular, the performance of the SWAP protocol may not be as good as claimed, since it appears that multipath interference effects have been neglected. The simulation results reported in Section 3 seem to indicate that a FEP of 10^{-3} is possible only by neglecting the aforementioned impairments. If multipath interference is taken into account, even time delay spreads as small as 50 ns cause several dB of performance degradation (see Figures 3-4).

Certainly, the benefits of using error-correcting codes in such an environment (as it is done in BT) is something that can enhance the overall system performance. However, not every code performs well on Rayleigh fading channels, especially if the bursty nature of the channel is not taken into account. For example, the Hamming code used for the protection of the longer packets (DM3 and DM5) does not perform well and this is not a surprise since the Hamming code used in the BT specification is a code effective on AWGN channels and does not provide good coding gains on channels that experience burst errors. Finally, these results tend to suggest that BT is best suited for short-range applications, whereas for long range applications (up to 50 meters) the performance degradation is not negligible.

5. Appendix

The modulation adopted in both BT and HomeRF is GFSK. It is not straightforward to simulate precisely a GFSK link in a simple way. For this reason, in the present paper, the performance of HomeRF and BT are analyzed considering a BPSK modulation with coherent detection. The reason why a BPSK modulation format has been chosen is due to the fact that a modulation similar to GFSK, GMSK, is usually simulated as if it were a BPSK link. 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 [2]. Obviously, it is not trivial to derive the real performance of a GFSK link from that 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. Finally, if the performance of a *coherent* system (the BPSK link here simulated) degrades in some way when a nonzero delay spread is present in the link, it is obvious to expect a degradation also in a *noncoherent* system (the simple frequency discriminator receiver in Bluetooth or HomeRF), since a noncoherent system is more sensitive to intersymbol interference than a coherent one [3].

The simulation results presented in Section 2 consider the case of a BPSK link over a Rayleigh fading channel. The transmitted bits are grouped in packets and a packet is comprised of a preamble and a payload containing the information to be transmitted. The preamble is a sequence of 200 bits known at the receiver and ensures a good estimate of the channel phase.

Each packet is convolved with a different channel realization. Each channel realization is independent from the other and, within a packet, the channel is considered time-invariant (i.e., zero Doppler spread). The considered channels are comprised of one path (flat fading) or two equal-powered paths with a delay spread τ equal to 50 and 100 nanoseconds. In order to obtain statistically meaningful results, packets necessary to ensure at least 100 errors, with a minimum of 10^4 packets, were generated. For the case of two paths, the following technique has been employed:

1. A Fast Fourier Transform (FFT) of the transmitted data is performed;
2. The obtained sequence is then delayed in the frequency domain by τ ns using the well know expression:
   $z(t)=x(t-\tau) \Rightarrow Z(f)=X(f)e^{-j2\pi f\tau}$;
3. Convolution with the channel is performed in the frequency domain by multiplying the

delayed sequence obtained in step 2) with the FFT of the channel realization;

4. The Inverse FFT (IFFT) operation performed on the sequence obtained in step 3) finally yields the observation sequence.

Finally, no equalization is performed at the receiver's side. The receiver, after estimating the phase of the channel exploiting the preamble, performs a one shot coherent detection via a minimum Euclidean distance decision device that outputs the detected data.

6. References

[1] G. Okamoto, G. Xu, "The Smart Wireless LAN System: Physical Layer Design and Results", *IEEE Vehic. Tech. Conf.*, VTC'97, Phoenix, USA, May 4-7, 1997.

[2] U. Mengali, M. Morelli, "Decomposition of *M*-ary CPM Signals into PAM Waveforms", *IEEE Trans. on Inform. Theory*, vol.41, no.5, September 1995.

[3] R. Petrovic, A.F. Molisch, "Multipath Effects of FSK with Frequency-Discriminator Detection", *IEEE Trans. on Vehicular Tech.*, vol.49, no.3, May 2000.

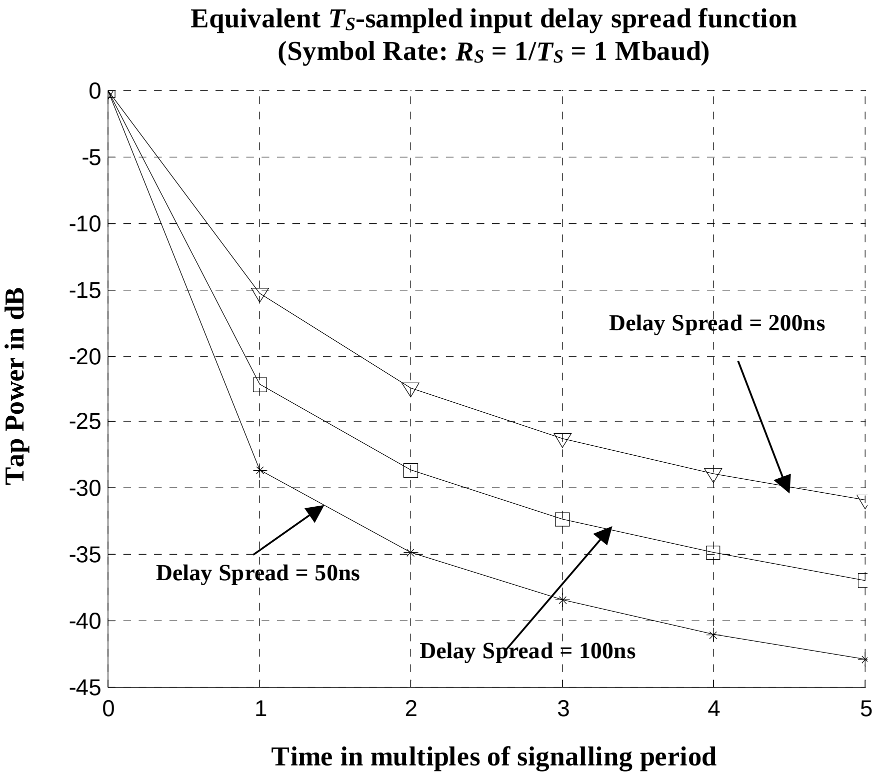

Figure 1 - Equivalent T_S-sampled input-delay spread function for some typical values of the delay spread in indoor environment. The symbol rate is 1 Mbaud.

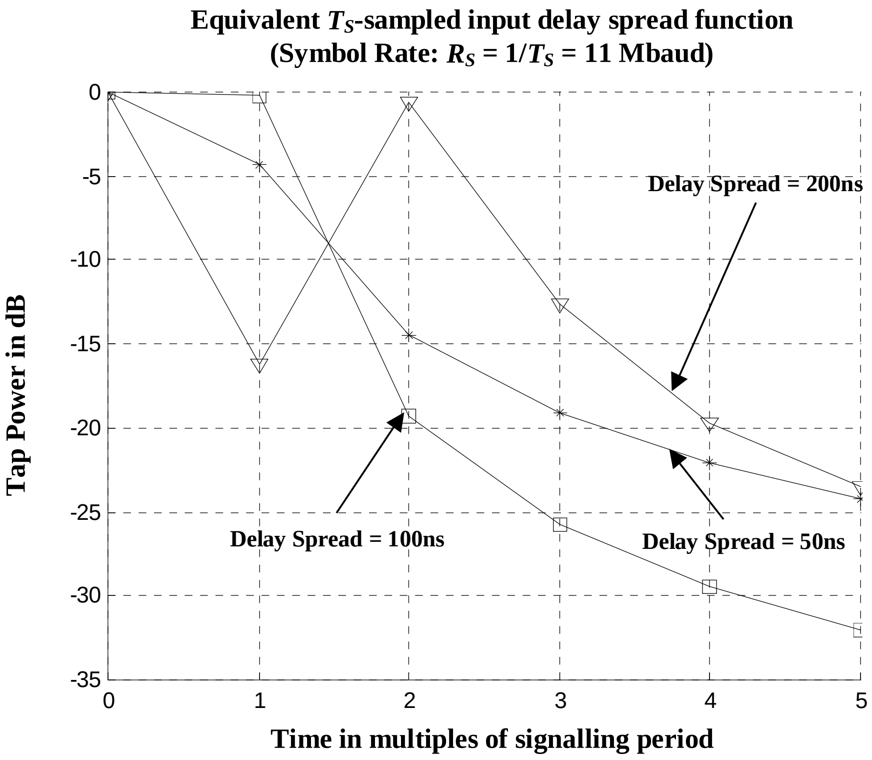

Figure 2 - Equivalent T_S-sampled input-delay spread function for some typical values of the delay spread in indoor environment. The symbol rate is 11 Mbaud.

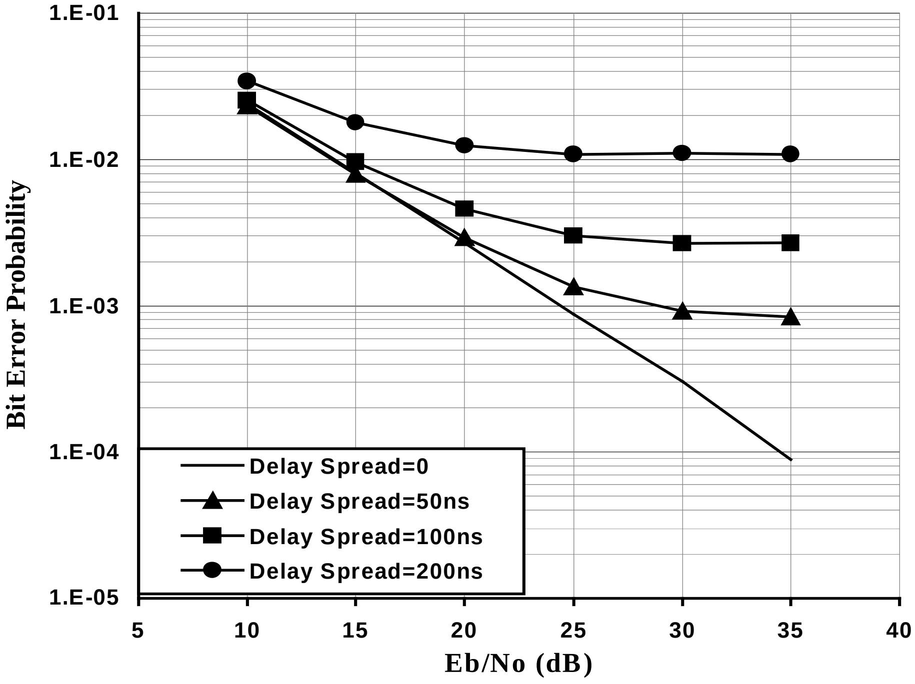

Figure 3 - Performance, in terms of BEP versus E_b/N_o, of an uncoded BPSK-modulated signal over a Rayleigh fading channel for different values of the delay spread. Payload length of 5,000 bits.

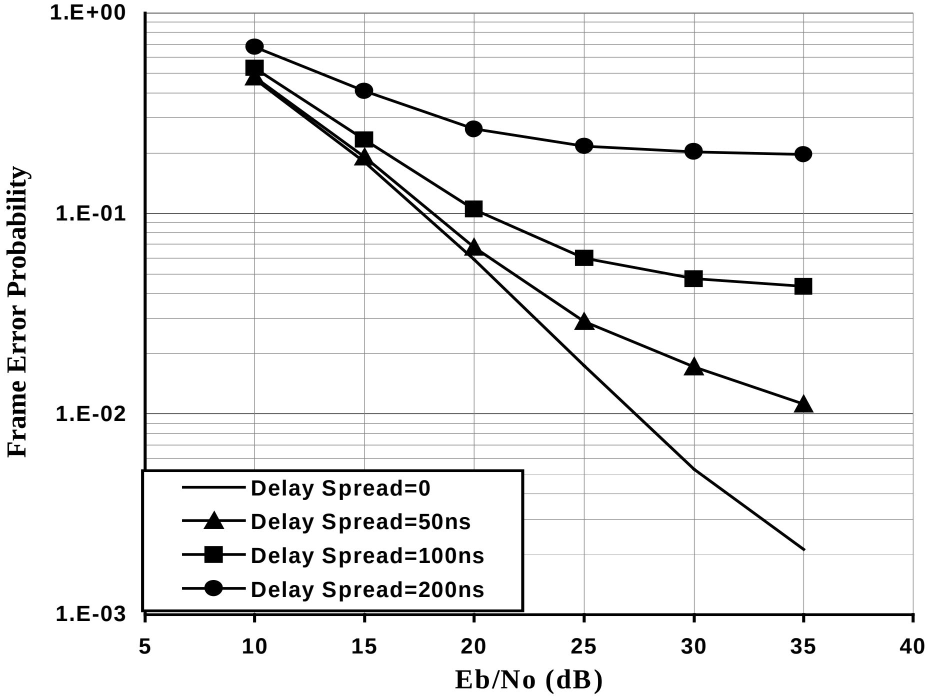

Figure 4 – As in Figure 3, but performance in terms of FEP (b) versus E_b/N_o .

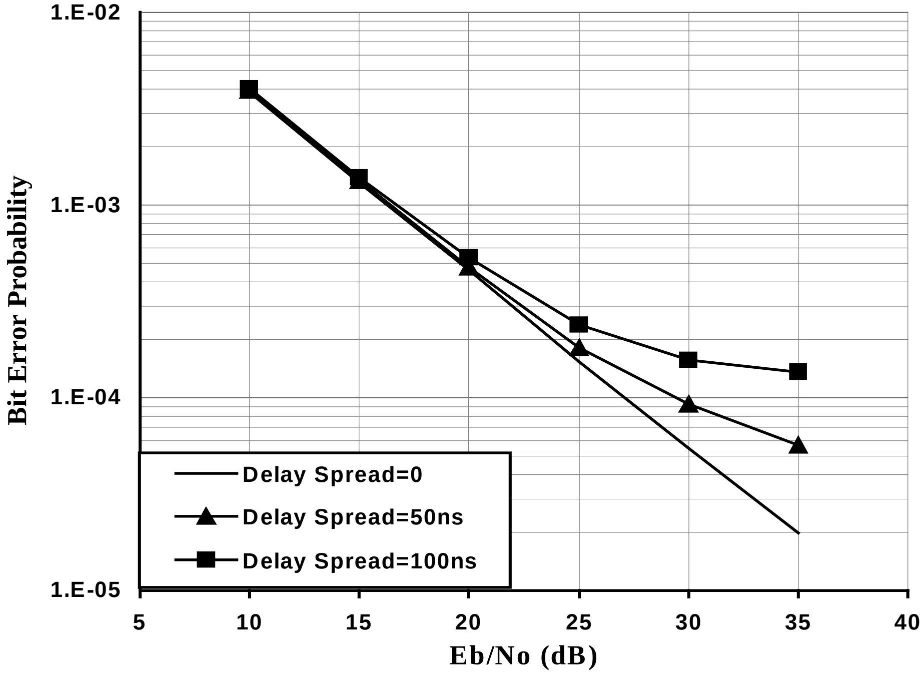

Figure 5 - Performance, in terms of BEP versus E_b/N_o, of a BPSK-modulated signal over a Rayleigh fading channel for different values of the delay spread. Case of rate 1/3 repetition code and payload length of 240 bits.

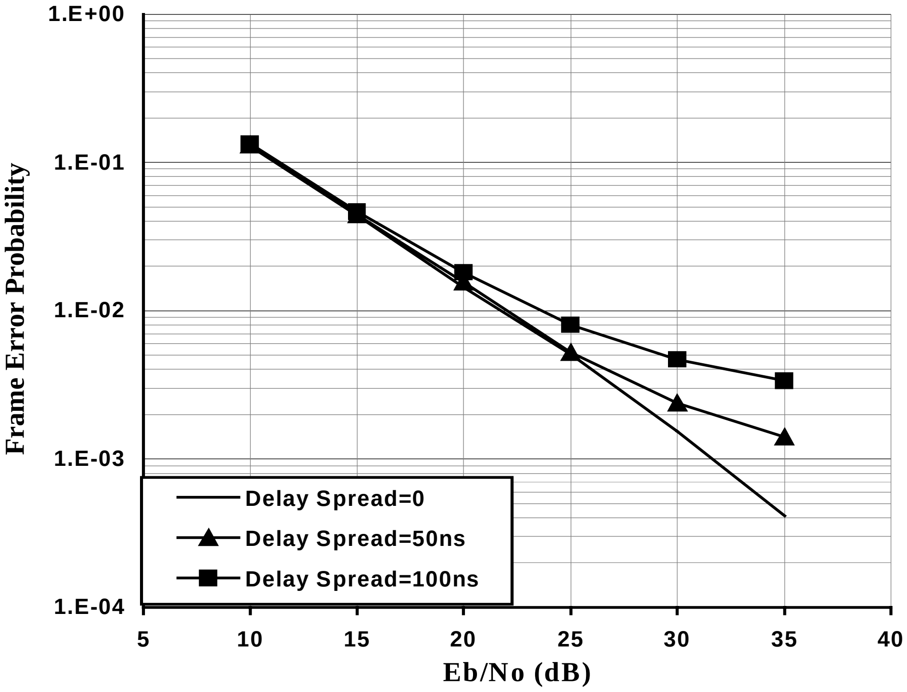

Figure 6 - As in Figure 5, but performance in terms of FEP versus E_b/N_o .

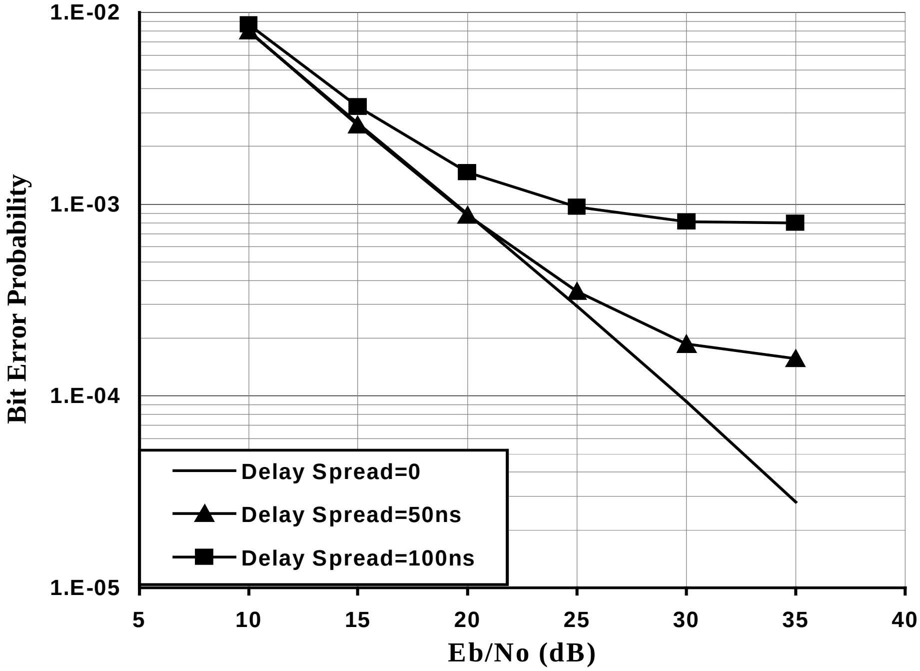

Figure 7 - Performance, in terms of BEP versus E_b/N_o, of a BPSK-modulated signal over a Rayleigh fading channel for different values of the delay spread. Case of shortened Hamming code and payload length of 2,745 bits.

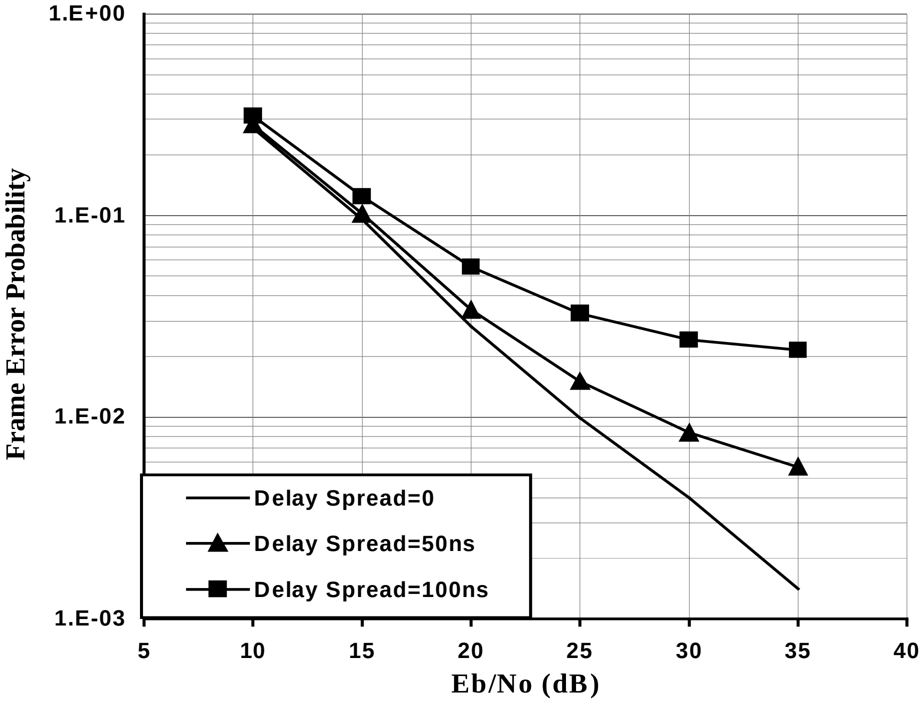

Figure 8 - As in Figure 7, but performance in terms of FEP versus E_b/N_o .