Effects of adaptative equalization on the performance of broadband wireless communications

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Abstract

The performance of wireless wideband high data rate indoor communications systems is affected by the channel propagation conditions. In this context, the channel delay profile characteristics constitute a significant contraint by imposing an irreducible error rate which results in a limitation of the transmission rate. In this paper, we examine the effects of equalization techniques on the performance of broadband wireless communications with CQPSK modulation. Although general in nature, this study is carried out in the context of its application to high data rate wideband transmission at millimeter-wave frequencies. The performance results are based on Monte Carlo simulations with a simplified model of the generated received signal which depend on the power delay profile characteristics. Two power delay profile models are considered: a one sided exponential model and a uniform model. Simulations results show that the relative performance of linear and non-linear equalization techniques strongly depends on the characteristics of the power delay profile model.

1 Introduction

The next generation of indoor wireless communications will attempt to provide high data rate services (10 to 150 Mbs/s). Such high data rates in indoor channels are bounded due to intersymbol interference (ISI). The ISI is directly related to the multipath phenomena resulting from objects in the propagation medium between the transmitter and the receiver. This multipath propagation and the effect of the delay profile affect the received signal by introducing intersymbol interference, particulary when the delay spread is significant in comparison to the transmitted symbols duration. In this condition, the effect of the intersymbol interference becomes dominant and the error probability becomes irreducible [1]. In this situation the bit error rate performance can be improved by using diversity techniques, coding, adaptative antennas [2]. Another method to reduce the ISI effects and to maximize the probability of correct decisions is the use of an adaptative equalizer [3].

This paper is concerned with the study of the effect of adaptative linear and nonlinear equalization on the performance of broadband wireless communications systems with CQPSK modulations over Rician fading channels. The performance results are based on Monte Carlo simulation with two power delay profile models, a one-sided exponential model and a uniform model. We consider a simplified method for generating the received signal which is based on the knowldege of the scattering components. These components are related to the power delay profile characteristics.

The paper is organized as follows. Section 2 describes the channel and the power delay profile models. A description of the simulation technique is provide in section 3. Section 4 presents the results of the BER performance with and without equalizers and offers a discussion of the results and of their applicability to real situations. Section 5 gives the conclusions.

2 Channel System

2.1 Channel model

The channel model used for this study is the one suggested by Turin [4] to describe multipath fading channels and used successfully in the analysis of a variety of digital communications systems where the transmitted waveform is propagated through a noisy fading multipath channel. The multipath comprises N fading paths. Each path n (n = 0, 1,.. , N) is described by a strength coefficient r_n, a time delay τ_n and a carrier phase shift ϕ_n. The receiver used here is the classic coherent quaternary phase-shift keying receiver [3]. The received signal *r(t)* can be written as [1]

$$r(t) = \sqrt{\frac{2E_s}{T_s}} \sum_{n=0}^{N-1} \sum_{i} r_{n,i}(\tau_{n,i}) v(t - iT_s - \tau_{n,i}) \cos(2\pi f_c t + \theta_i + \phi_{n,i}) + n(t) \quad (1)$$

where E_s is the energy per symbol, *v(t)* is a unit amplitude rectangular pulse of duration T_s, f_c is the carrier frequency, θ_i is the carrier phase and T_s is the symbol duration. The noise signal, n(t), is assumed to be an additive, zero-mean, white gaussian noise (AWGN) statistically independant of the multipath with spectral density $N_0/2$.

For the Rician channel, an LOS signal is present, and we assume that the average power of the first path (LOS) is stronger than that of the others paths signals, and that the receiver is synchronized to the first path signal (τ_0 = 0). We also assume that the intersymbol interference affects only adjacent data pulses [5], this condition being satisfied if the power delay profile $p(\tau) = 0$ for $\tau > aT_s$, where *a* is an integer. Under this assumption, if *a* = 4, the statistics of *r(t)* depend on four consecutive data symbols $[S_{i-3}, S_{i-2}, S_{i-1}, S_i]$. A received symbol is then affected by its own interference and by the interference generated by the three previous symbols. The corresponding in-phase term of the received signal can be expressed as [6]

$$X(i) = D_X(i) + \sum_{j=0}^{3} I_{i-j}^X(i) + N_X(i) \quad (2)$$

where D_X, the term due to the main path, is the *LOS* signal

$$D_X(i) = \sqrt{E_s} r_0^i \cos(\theta i) \quad (3)$$

The expressions of the intersymbol interferences of the in-phase term of the received signal due to the present and the previous symbols $(i, i-1)$ are given by

$$I_i^X(i) = \sum_{n=1}^{N-1} \sqrt{E_s} r_n^i(\tau_n)(1 - \frac{\tau_n}{T_s})(cos(\theta_i + \phi_n) \quad (4)$$

$$I_{i-1}^X(i) = \sum_{n=1}^{N-1} \sqrt{E_s} r_n^{i-1}(\tau_n)(1 + \frac{\tau_n}{T_s})(cos(\theta_{i-1} + \phi_n) \quad (5)$$

while the expressions for the ISI generated by the two other previous symbols $(i-2, i-3)$ can be deducted from (5) by taking into account the power delay profile, the phase and the delay of the interfering symbol. $N_X(i)$ is the noise term.

2.2 Power delay profiles models

In this paper the performance of CQPSK is considered for two examples of power delay profile, the exponential profile given by

$$p_e(\tau) = \alpha \exp(-\tau/D_e) \quad \text{si} \quad \tau \geq 0 \quad (6)$$

and the uniform model given by

$$p_r(\tau) = \alpha/T_s \quad \text{si} \quad 0 \leq \tau \leq \alpha/T_s \quad (7)$$

Parameter "α" is the power level of the main signal component relative to the power level implied in the delay spread model. D_e and $D_r = T_s/2\sqrt{3}$ are the root-mean-squareds (rms) delay spread for the exponential and rectangular models. The rms delay spread is determined by the following expression

$$D = [\frac{\int (t - t_m)^2 p(t) dt}{\int p(t) dt}]^{1/2} \quad (8)$$

where

$$t_m = \frac{\int t p(t) dt}{\int p(t) dt} \quad (9)$$

We define the power delay profile as the average of the echoes arriving with time delay τ: $p(\tau) = E[r^2(\tau)]$.

2.3 Adaptative equalization

In digital communications systems equalization is an important technique in the reduction of intersymbol interference produced by the channel propagation conditions. Linear and decision feedback (DF) equalization techniques are used in this study. The first one consists of a transversal filter and its input is the received sequence. The second one consists of two filters, a feedforwad filter and a feedback filter. Both have taps spaced at the symbol interval T_s. The input to the feedforward section is the received signal sequence. The feedback filter has as input the sequence of decisions on previously detected symbols. Functionally, the feedback filter is used to remove that part of the intersymbol interference, caused by previously detected symbols, from the present estimate. The most common criterion used for the optimization of the equalizer coefficients is the minimisation of the mean square error (MMSE) between the desired and the actual output [3]. The LMS algorithm is used to accomplish recursively the minimisation of the MSE.

3. Simulation technique

Let β be the relative precision obtained from *M* simulations to estimate the mean error probability P_e.

When M is large enough, the estimation error can be considered as Gaussian and the bound of M , for a confidence of 0.99, can be improved by [7]

$$M \geq \frac{3.96}{\beta^2}(\frac{1}{P_e} - 1) \quad (10)$$

For a precision better than 2% for $P_e = 10^{-2}$ and a precision of 19% for $P_e = 10^{-4}$, we used 10^6 simulations. This degree of precision is adequate considering the order of magnitude of the average error probability to estimate. We have considered that the channel's statistics, (r_n, τ_n, ϕ_n, N) are time-invariant over 10^4 symbol periods. This is a reasonable assumption for communications systems at high data rates.

The expression of the in-phase term *X* of the receiver output is given by equation (2), while the quadrature term is developed by replacing the cos(.) by sin(.) in the equations (3), (4) and (5). We have concentrated on the simulation of the two components *X* and . We have to generate:

- a carrier phase $\theta_i = [(2m-1)\pi/4, m = 1..4]$,
- a path amplitude r_n of each echo following a Rayleigh distribution [8],
- the arrival time τ_n of the echoes uniformly distributed over [0,T_s] [9],
- a carrier phase shift ϕ_n introduced by the path and uniformly distributed over [0,2π] [9],
- the number of echoes, N, following a Poisson distribution with Poisson parameter ν [9],
- the additive Gaussian noise.

We are interested to obtain the bit error rate performance after equalization. If we consider that the transmitted signals are equiprobable, the average error probability is defined as $P_e = P(X < 0 \text{ or } Y < 0 \mid \theta_i = \pi/4)$.

4. Results and discussion

In this section, we examine the effectiveness of adaptative linear and feedback equalizers in reducing the ISI effects of wireless communications systems with CQPSK modulation over Rician fading channels. The channel model and the simulation technique have been specified previously.

The simulation results are presented for two specific values of the normalized rms delay spread μ which is defined as $\mu = D/T_s$. The first one, $\mu = 0.1$, illustrates cases where all echoes are concentrated in the first part of the symbol; the intersymbol interference affects two consecutive data symbols, the previous and the desired symbols. The second one, $\mu = 0.51$, shows a case where all the echoes take place within the duration of the symbol; the ISI affects then four consecutive data symbols.

In general, the results show that channel equalization improves the performance considerably compared with the unequalized channel case. Decision feedback equalizers have shown a performance superior to linear equalizers for certain channel parameters and have shown approximately the same performance as linear equalizers for other channel parameters.

4.1 Analysis

Figures 1 and 2 give the bit error rate performance comparisons for coherent QPSK system without equalizer (*PSE*), with linear equalizer (*ELR(q)*) and with decision feedback equalizer (*ENLR(q,p))* for the one sided-exponential delay profile model. *q* and *p* are the number of linear and the feedback coefficients of the equalizers.

The curves correspond to two sets of values, namely a first set $(\nu = 3, \mu = 0.1, \alpha = 0.5)$ and a second set $(\nu = 5, \mu = 0.1, \alpha = 0.8)$ where ν is the average number of echoes, μ is the normalized rms delay and where α is a parameter which describes the power level implied in the delay spread relative to that of the main signal component. The curves show that channel equalization improves the performance compared with the unequalized channel case and that linear equalizers have the same performance as decision feedback equalizers. Although not shown here, little improvement has been noted if one increases the number of coefficients in the equalizers. It is observed that the BER improvements obtained with $\alpha = 0.5$ and $\nu = 3$ are lower than those obtained with $\alpha = 0.8$ and $\nu = 5$.

Figure 3 represents the BER performance of CQPSK with linear and non-linear equalizers for the uniform power delay profile model. The curves are for the Poisson parameter $\nu = 3$, the normalized rms delay spread $\mu = 0.1$ and the parameter $\alpha = 0.4$. Compared with the simulation results for the exponential delay profile (figures 1 and 2), it is observed that the DF equalizer performs better than the linear equalizer and that increasing the number of taps reduced the effects of ISI.

Figures 4 and 5, similarly to other figures, show the performance comparisons for CQPSK without equalizer, with linear and feedback equalizers, for exponential and uniform power delay profile models having different channel parameters. The ISI is generated by the present and the three past symbols. The results show that the DFE can achieve significantly better BER performances than the linear equalizer. On the other hand, increasing of the number of taps $(M > 5)$ for the uniform delay profile provides the best performances.

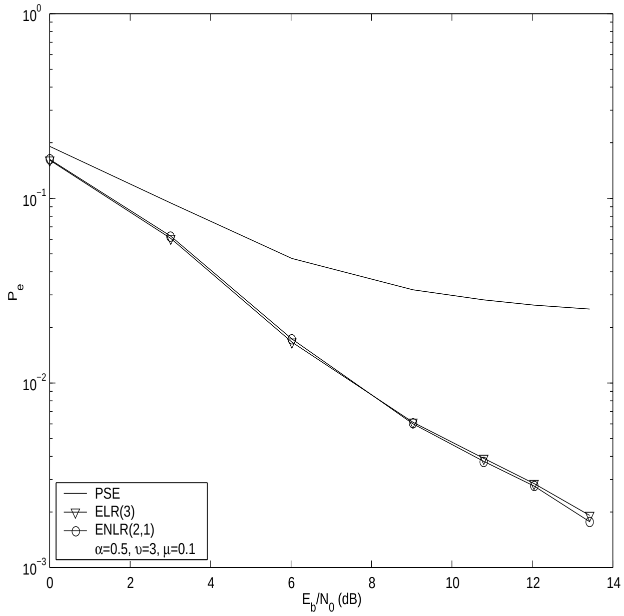

Figure 1. BER performance of CQPSK with linear and DF equalizers. Exponential model, $\mu = 0.1$.

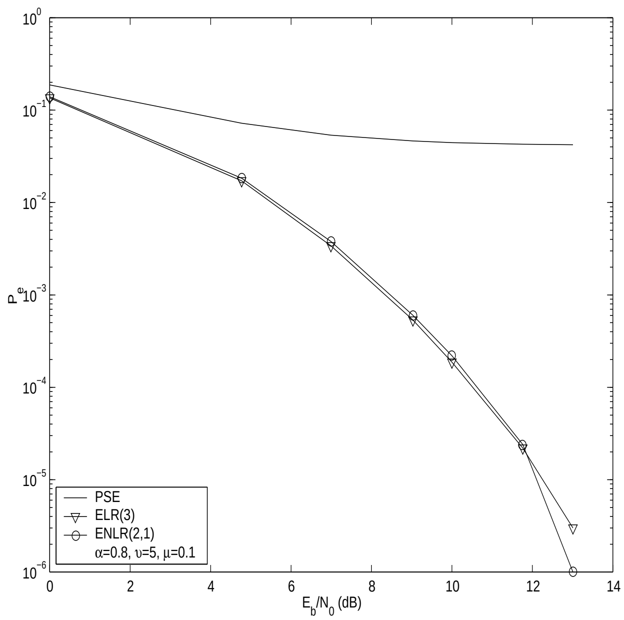

Figure 2. BER performance of CQPSK with linear and DF equalizers. Exponential model, $\mu = 0.1$.

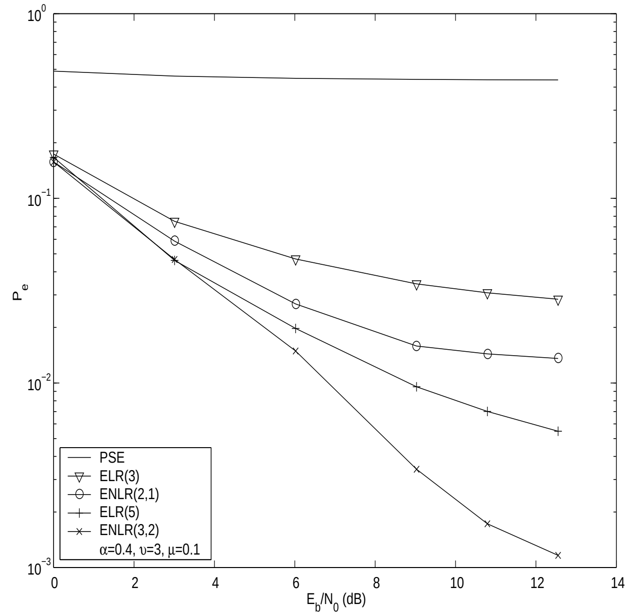

Figure 3. BER performance of CQPSK with linear and DF equalizers. Uniform model, $\mu = 0.1$.

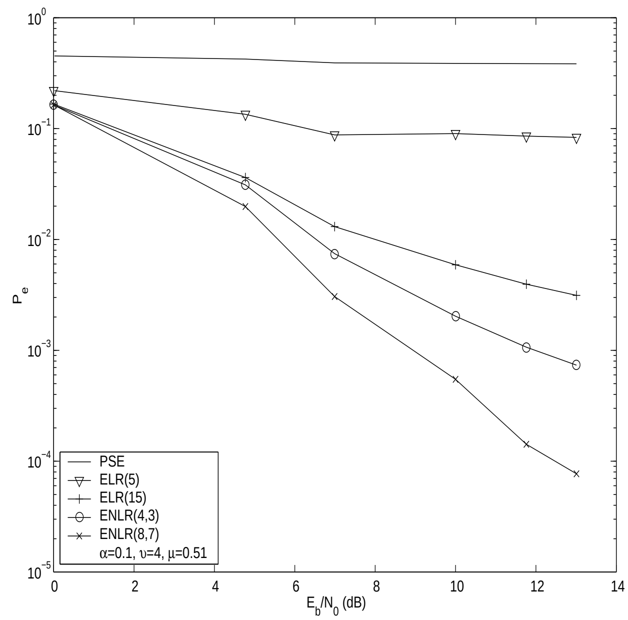

Figure 4. BER performance of CQPSK with linear and DF equalizers. Uniform model, $\mu = 0.51$.

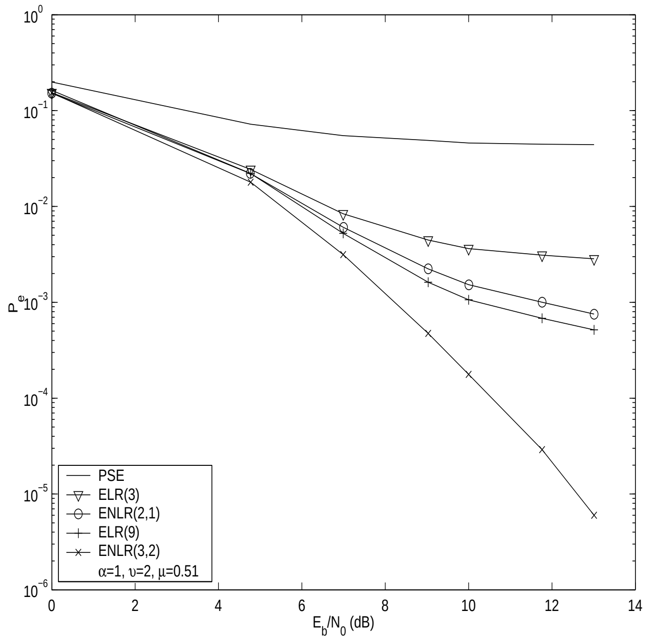

Figure 5. BER performance of CQPSK with linear and DF equalizers. Exponential model, $\mu = 0.51$.

4.2 General observations

The simulation results presented in this paper as well as other cases which have been studied permit to make a number of observations on the relative performance of linear and decision feedback equalization techniques for different implementations of the equalizers and different characteristics of the delay profiles.

With the exponential delay profile model and for relatively small values of the normalized rms delay spread, $\mu = 0.1$, which represent the case where the ISI is limited to two successive symbols, our results show that:

- linear equalizers generally have a performance equivalent to decision feedback equalizers,
- linear equalizers with three taps are adequate,
- little performance improvement is noted if one increases the number of coefficients in the equalizers
- the performance improvement (in term of the ratio between the BER with and without equalization) is more significant when the total power and number of the ISI components is important.

With the uniform delay profile, $(\mu = 0.1, \mu = 0.51)$ and the one-sided exponential power delay profile $(\mu = 0.51)$, it is generally observed that:

- the relative performance of the DF equalizers is notably superior,
- the equalizers have a maximum performance improvement (as define above) for relatively high values of the normalized rms delay spread, of the average number of scattering paths and of the power level implied in the scattering paths relative to that of the main signal component,
- increasing the number of equalizer coefficients, up to certain limit, gives a significant error reduction.

4.3 Applicability to real situations

The BER performance of CQPSK system with linear and decision feedback equalizers presented in the latest section have been analyzed in function of the normalized root-mean-squared delay spread μ for different values of the parameters α and ν. In order to show that these results are applicable to real situations susceptible to be met in practice, we indicate in this section typical values of transmission rates attainable considering the quoted delay spread values.

The root-mean-squared delay spread D have been estimated in a number of indoor propagation measurements. Numerical values depend on the size and the type of the buildings, and the existence or absence of an LOS signal. Reported values for three examples are:

Ex.1: 39.5 ns and 48.7 ns for two buildings of different construction [10]. The measurements were conducted at fully equipped and operational factories in central Indiana for a frequency of 1300 MHz.

Ex.2: 9 ns for residential buildings in Ottawa [11]. The measurement are made at 28 GHz.

Ex.3: 15.6 ns and 7.5 ns for a laboratory and an office respectively [12]. These results have been obtained by Hollaway for a frequency of 1.5 GHz.

From figure 2, where the channel parameters are defined by: $(\nu = 5, \mu = 0.1, \alpha = 0.8)$, it can be shown that decision feedback or linear equalizers with three taps is adequate to support data transmission at 22 Mbs/s in the case of the residential buildings (**Ex.2**) and 12.8 Mbs/s and 26 Mbs/s for the laboratory and the office (**Ex.3**). One can see that the error rate can become as low as $P_e = 3.10^{-6}$ for signal to noise ratios of about 13 dB.

If we consider other channel parameters represented by figures 4 and 5, where the probability of error falls below 6.10^{-6} for the exponential model and 7.10^{-5} for the uniform model, at $E_b/N_0 = 13$ dB, we can note an increase the data transmission to 25.8 Mbs/s for **Ex.1** , 113 Mbs/s for **Ex.2** and 65.4 Mbs/s for **Ex.3** . At those error rate levels and with $\mu = 0.51$, a CQPSK/DFE system would attain a transmission rate of 136 Mb/s in the office refered to by Holloway [12].

5 Conclusion

A performance analysis with linear and decision feedback equalizers of broadband wireless communications systems with coherent QPSK modulation in channels representative of Rician fading has been carried out. The results for the bit error rate were based on Monte Carlo simulations with the exponential and the uniform power delay profile models. A simplified method was presented and used for generating the received signal. It was shown that the performance of CQPSK with linear or DF equalizers strongly depends on the normalized rms delay spread, the number of echoes and the power delay profile model. For severe ISI conditions with relatively high values of the normalized delay spread and for both power delay profile models, results show that a DFE performs better than a linear equalizer. For low values of the normalized delay spread, for instance $\mu = 0.1$, a system with a linear equalizer can achieve the same performance as one with a DF equalizer. For a typical indoor environment with rms delay spread of 7.5 ns, it was shown that data rates up to 136 Mbs/s with low error rate can achieved.

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