PERFORMANCE OF JOINT DIVERSITY AND EQUALIZATION TECHNIQUES IN M-QAM INDOOR RADIO SYSTEMS

Fernando J. CASADEVALL
Departament de Teoria del Senyal i Comunicacions
Universitat Politécnica de Catalunya
Apdo. 30002, 08080 Barcelona, SPAIN

In this paper we analyze the performances of the joint diversity and equalization techniques in an indoor radio environment. 4, 16 and 64 QAM modulation are considered. The system performances are described in terms of the Outage Probability. The results show that a system without protection has very limited performances. When the channel introduces low level of distortion, the diversity technique produces better performances than the equalizer technique, but if the channel introduces a high degree of intersymbol interference, then the equalizer techniques are slightly better than the diversity techniques. Moreover,the joint equalization and diversity techniques are very effective tools to combat the degrading effect introduced by the indoor channel. Improvement in the system performances , with respect to a system without any protection, ranging from 10 to 100 have been obtained. We will shown that the system performances remain almost unchanged for values of the correlation coefficient between diversity branches lower than 0.6 ,0.7 approximately.

INTRODUCTION

The use of radio in indoor data communications is an attractive proposition because it gives total mobility to the increasing number of terminal equipments in large buildings. However, indoor radio systems are affected by frequency selective fading caused by the multipath time delay spread that produces intersymbol interference (ISI), thus resulting in an irreducible bit error rate (BER) and imposing an upper limit on the data symbol rate. In order to combat this situation diversity techniques and or adaptive channel equalizers could be used.

Diversity techniques are efficient when low or medium bit rate transmission system are considered because in these cases the signal fading can be assumed to be non-selective. However, for systems operating at high bit rate, where the selective fading nature caused by the multipath propagation introduces ISI, the diversity techniques aren't suitable because they can't cope with the above mentioned ISI. On the other hand, the equalization techniques, that are able to compensate the ISI introduced by the multipath propagation, have limited performances due to the fluctuations on the signal to noise ratio produced by the Rayleigh nature of the propagation. Then, in order to increase the system performances it could be convenient to consider the behavior of the joint diversity and equalization techniques.

Even though some partial analysis about this subject have been carried out,[1],[2], for example taking into account specific bit rates, particular propagation conditions and/or asymptotic approaches to the equalizer behavior, in our knowledge, there is not yet a general analysis for indoor radio channels that provides a global characterization of the behavior of the diversity and equalization techniques working jointly when M-QAM modulations are considered.

In this paper, we assess the performances of M-QAM indoor radio systems that use joint diversity and equalization techniques. 4-QAM, 16-QAM and 64-QAM have been considered. The influences on the system performances of various system and channel parameters, like the shape and r.m.s. delay spread of the Power Delay Profile that characterize the propagation conditions, the equalizer structure (linear and non-linear) as well as the number of taps etc... have been taken into account. The system performances are described in terms of both averaged Bit Error Rate an Outage Probability.

TRANSMISSION MODEL

Figure 1 shows the low-pass equivalent model of the transmission system. The transmitted signal can be formulated as:

$$S(t)=\sum_{k=-\infty}^{\infty}(a_k+jb_k).\delta(t-kT)$$
$$=\sum_{k=-\infty}^{\infty}d_k.\delta(t-KT),$$

where $\{a_k\},\{b_k\}$ are data sequences of duration T for the in-phase and quadrature channels. They are ±1, ±3, ..., $\pm(M^{1/2}-1)$ with M=4 for 4-QAM, M=16 for 16-QAM,and M=64 for 64-QAM. Moreover, a_k and b_k are independent random variables. The overall filtering transfer function $H_T(f).H_R(f)$ is a raised-cosine type with a roll-off factor equal to 0.5. The filtering is split equally between the transmitter and the receiver. $h_c(t)$ models the channel behavior that introduces selective fading in the radio link. The channel is assumed to be wide sense stationary uncorrelated scattering (WSSUS) and it is represented by a unique correlation function referred to as the **Power Delay Profile**, P(t),[3]. A measure of the width of P(t) is the root mean-square delay spread, τ. From the Power Delay Profile function , a sample of the channel impulse response can be constructed by the following formula :

$$h_{c,i}(t)=\sqrt{t_n}\cdot\sum_{n=1}^{L}(h_{in,i}+jh_{qn,i}).\delta(t-nt_n)\qquad i=1,2$$

where $h_{in,i}$ and $h_{qn,i}$ are zero mean gaussian random variables with variance $P(n.t_n)/2$ and t_n is the time between samples. The number of samples, L, needed to represent the indoor mobile channel in an accurate form, depends on the shape of the Power Delay Profile, P(t), and on its rms delay spread. Measurements from many different buildings,[4],[5], allow us to consider that the most common shape for the Power Delay Profile is the one-side exponential profile, given by:

$$P(t)=\begin{cases}\frac{1}{\tau}.\exp[-\frac{t}{\tau}] & t\geq 0\\ 0 & t<0\end{cases}$$

In the analyzed cases it is sufficient to considered a time duration of the one-side exponential profile approximately equal to 14τ and $t_n=\tau/2$.

The received signal $r_1(t)$ (resp. $r_2(t)$) can be expressed by:

$$\begin{aligned}r_i(t)=&\sum_{k=-\infty}^{\infty}[a_k.h_i^R(t-KT)-b_k.h_i^I(t-kT)]+\\&+j\sum_{k=-\infty}^{\infty}[b_k.h_i^R(t-KT)+a_k.h_i^I(t-KT)]+\\&+n_x(t)+j\,n_y(t)\end{aligned}$$

where, in general

$$\begin{aligned}h_i(t)=&\,h_i^R+j\,h_i^I=\\&=[F^{-1}[H_T(f).H_R(f)]\,*\,h_{c,i}(t)].G_i.e^{-j\theta}\end{aligned}$$

with i=1,2 . F^{-1} denotes the inverse Fourier transform, * is the convolution operator, and G_i is a gain factor introduced to considered the presence of automatic gain control (AGC). We have taken into account a carrier recovery circuit that minimizes the output mean square error,[6]. Assuming that the bandwidth of the carrier recovery circuit is much higher than the fading rate, it could be considered that the carrier phase can be tracked as if the global impulse response, $h_i(t)$, is time-invariant. As we focus on the effects of the delay spread, the phase jitter on the recovered carrier caused by the gaussian noise will not be taken into account. The optimum sampling instant is obtained from a classical squaring timing recovery loop,[7]. Two baseband equalizer structures are analyzed. Linear and Non-Linear equalizers both with baud period T spacing between stages. In all the cases, the minimum mean-square error (MMSE) technique has been adopted to calculate the tap values.

RESULTS

We have examined the effectiveness of the joint adaptive equalization and diversity techniques in fighting the multipath and fading introduced by the indoor radio channel. The objective is to determine the data rate limitation for indoor communication systems. The criterium used to evaluate the system quality is the outage probability, defined as :

$$P_0=Prob.(P_e>10^{-\gamma})$$

where P_e is the error probability and γ is a constant that we have taken equal to 2 or 6. To compute the error probability integral we have considered the LEVI's method,[8].

In figures 2 and 3 we show the evolution of the outage probability, against the normalized delay spread of the Power Delay Profile, τ/T. We can see that a system without any protection has a very limited performances since for $\tau/T > 0.1$ the outage probability is greater than 0.1 (10%). Moreover, for smaller values of τ/T, the outage probability goes to an asymptotic value (marked by the letter A on the figures) that is greater than 0.01 (1%). It is important to emphasize that this value shows the behavior of the system performances when a flat fading channel is considered. If the diversity technique is considered we can see that for high values of the ratio τ/T the system performances are only slightly better than the obtained for a system without protection, but when smaller values are taken into account the values of the outage probability converge on the value for a flat fading channel. On the other hand, for small values of the normalized delay spread, the system performances increase by a factor of ten approximately. In conclusion, the diversity technique could be used in an effective way if a flat channels or channels with low distortion are considered. When joint equalizer and diversity techniques are taken into account, the performance of the system increases quickly. For a BER of 10^{-2} and a linear equalizer of 5 taps in each branch (marked as 2+2 in the figure) the system is able to guarantee an outage probability lower than 0.001 (0.1%) for values of the normalized delay spread smaller than 0.8. However if a BER of 10^{-6} is considered the system is not able to give an outage probability lower than 0.01 (1%).

In order to obtain an outage probability lower than 10^{-3} for both BER values of 10^{-2} and 10^{-6} a higher signal to noise ratio must be considered. In particular we have chosen a signal to noise ratio of 30 dB. Figures 4 and 5 show the system performances in this case. Considering a non-linear equalizer with 3 taps (1 tap in the non-linear part) and for a BER equal to 10^{-2} the outage probability is lower than 10^{-4} (0.01%) for values of $\tau/T< 0.5$. It is important to emphasize that, when joint equalization and diversity techniques are considered, the system performances are better than the obtained for a flat fading channel for values of τ/T ranging from 0.01 to 0.5 . This could be explained because the system uses the multipath as a additional redundant channels to increase the diversity gain. However, for large values of τ/T the induced intersymbol interference ,due to the multipath, increases considerably and the equalizer can not cope completely with it , and as the result the system performances degrades quickly. For a BER of 10^{-6} an outage probability smaller than 10^{-3} could be obtained for values of τ/T lower than 0.3 . It could also be noticed that for great values of τ/T the system performances are limited by the intersymbol interference due to the limited number of equalizer taps (3 taps are only considered in each branch). For higher values of the τ/T ratio, better system performances could be obtained increasing the number of taps.

Figures 6 and 7 show the system performances when 16 QAM modulation is considered. Again a signal to noise ratio of 30 dB is taken into account. The behavior of the linear and non linear equalizer is shown considering 3 and 5 taps in each diversity branch (marked in the figure by 1+1 and 2+2 respectively). For a BER of 10^{-2} a linear equalizer could guarantee an outage probability lower than 0.01 (1%) for values of $\tau/T < 0.3$ if 3 taps are taken into account, and $\tau/T < 0.5$ when 5 taps are used. An outage probability lower than 10^{-3} could only be guaranteed for $\tau/T \cong 0.1$. However if a nonlinear equalizer with 5 taps (marked by 2+2) is considered the outage probability could be lower than 10^{-3} if $\tau/T<0.55$ and lower than 10^{-2} if $\tau/T< 0.7$. For a BER of 10^{-6} a non linear equalizer with 5 taps is necessary in order to obtain an outage probability lower than 10^{-2} for $\tau/T<0.4$

Finally, figures 8 and 9 show the system performances when 64 QAM modulation is considered. In this case a signal to noise ratio of 40 dB is taken into account. Again, the behavior of the linear and non linear equalizer considering 3 and 5 taps in each diversity branch (marked in the figure by 1+1 and 2+2 respectively) is also analyzed. For a BER of 10^{-2} a linear equalizer could guarantee an outage probability lower than 0.01 (1%) for values of $\tau/T < 0.2$ if 3 taps are taken into account, and $\tau/T< 0.5$ when 5 taps are used. If a nonlinear equalizer with 5 taps (marked by 2+2) is considered the outage probability could be lower than 10-3 if $\tau/T<0.4$ and lower than 10^{-2} if $\tau/T< 0.55$.

For a BER of 10^{-6} a non linear equalizer with 5 taps is necessary in order to obtain an outage probability lower than 10^{-2} for $\tau/T<0.4$

CORRELATED CHANNELS

We have also considered the influence on the system performances of the impulse response correlation between both diversity channels.

Given a value of the correlation coefficient,ρ, defined as:

$$\rho=\frac{E[(X-\overline{X}).(Y-\overline{Y})]}{\sqrt{E[(X-\overline{X})^2].E[(Y-\overline{Y})^2]}}=\frac{\mu_{xy}}{\sqrt{m_{xx}.m_{yy}}},$$

where X and Y are zero mean variables and:

$$\mu_{xy}=m_{xy}$$
$$m_{xx}=m_{yy}=\sigma^2$$

with σ^2 the variance, the two complex impulse response of the system are obtained by means of the following procedure:

a.- Two uncorrelated complex gaussian impulse response, h(t) and b(t), are generated, with :

$$h(t)=\sqrt{t_n}\,.\sum_{n=1}^{L}(h_{in}+jh_{qn}).\delta(t-nt_n)$$

$$b(t)=\sqrt{t_n}\,.\sum_{n=1}^{L}(b_{in}+jb_{qn}).\delta(t-nt_n)$$

b.- For each couple of random variables, h_{in} and b_{in}, (resp. b_{qn} and b_{qn}) two new correlated random variables are obtained using the following expressions:

$$u_{in}=a_{11}.h_{in} \qquad u_{qn}=a_{11}.h_{qn}$$
$$v_{in}=a_{21}.h_{in}+a_{22}.b_{in} \qquad v_{qn}=a_{21}.h_{qn}+a_{22}.b_{qn}$$

with:

$$a_{11}=\sqrt{m_{xx}} \qquad a_{22}=\sqrt{\frac{m_{yy}.m_{xx}-m^2{}_{xy}}{m_{xx}}}$$

$$a_{21}=\frac{m_{xy}}{\sqrt{m_{xx}}}$$

where:

$$m_{xx}=m_{yy}=\sigma^2=P(nt_n)/2$$
$$m_{xy}=\mu_{xy}=\rho.m_{xx}.m_{yy}$$

c.- The impulse response of the two new correlated channels are obtained as :

$$u(t)=\sqrt{T_n}\,.\sum_{n=1}^{L}(u_{in}+ju_{qn}).\delta(t-nt_n)$$

$$v(t)=\sqrt{T_n}\,.\sum_{n=1}^{L}(v_{in}+jv_{qn}).\delta(t-nt_n)$$

In figure 10 we show the evolution of the outage probability, for a BER of 10^{-2}, against the correlation coefficient ρ for a 4-QAM modulation and a signal to noise ratio at I.F. of 20 dB. Three different ratio τ/T, related to channels with small, medium and high level of the intersymbol interference, have been considered.

From the figure we can conclude that for correlation coefficients, ρ, lower than 0.7 the system performances remain almost unchanged. However when the correlation coefficient increases its value the system performances degrades quickly. Similar results were obtained for higher signal to noise ratios and high level M-QAM modulation.

Furthermore, in each figure we are able to compare the behavior of three different systems. The point denoted by **A** in the upper curve gives the system performance when an unprotected system is considered. The reason is that if we consider a system with only diversity technique when the correlation coefficient is equal to one, both diversity channels have the same impulse response and as a result the system performances are corresponding to an unprotected system. Over the same curve, the point **B** indicates the system performance when ideal diversity technique is considered. In a similar form, on the lower curve we can distinguish two points. The point denoted by **C** represents the system performances when joint equalization and diversity techniques are considered. Finally the point **D** denotes the system performances for an equalized system, because as the correlation coefficient is equal to one both diversity channels have the same impulse response and as a result only the equalization technique becomes operative. Comparing the three figures it can be concluded:

a.- When the impulse responses present low level of distortion with, e.g. for τ/T=0.05, the diversity technique produces better performances than the equalizer techniques.

b.- When the impulse responses show a high degree of intersymbol interference, e.g. for τ/T=0.5, the equalizer techniques are slightly better than the diversity techniques.

c.- The improvement on the system performances due to use jointly diversity and equalization techniques, with respect to an unprotected system, ranges between 10 to 100.

CONCLUSIONS

In this paper we have analyzed the performances of the joint diversity and equalization techniques in an indoor radio environment. 4, 16 and 64 QAM modulation have been considered. From the obtained results we can conclude that a system without protection has very limited performances. When the channel introduces low level of distortion, the diversity technique produces better performances than the equalizer technique, but if the channel introduces a high degree of intersymbol interference, then the equalizer techniques are slightly better than the diversity techniques.

On the other hand the joint equalization and diversity techniques are very effective tools to combat the degrading effect introduced by the indoor channel. Improvement in the system performances , with respect to a system without any protection, ranging from 10 to 100 have been obtained. Moreover the system performances remain almost unchanged if the value of the correlation coefficient between diversity branches is lower than 0.6 ,0.7 approximately.

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AGREEMENTS

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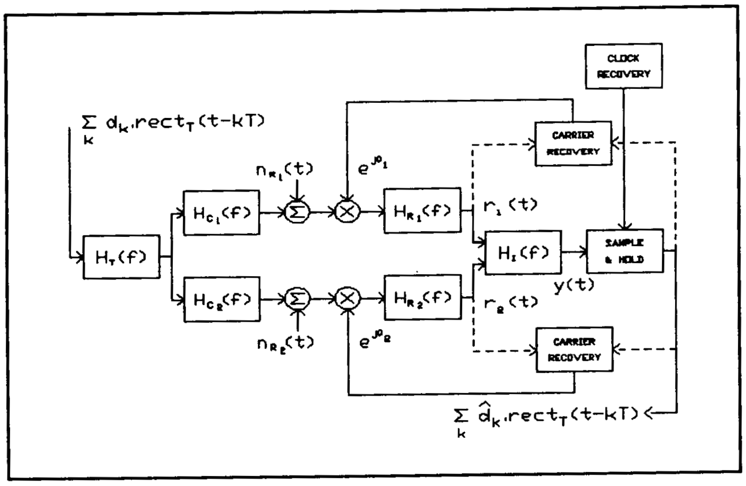


Figure 1.- LOW PASS EQUIVALENT MODEL OF THE TRANSMISSION SYSTEM

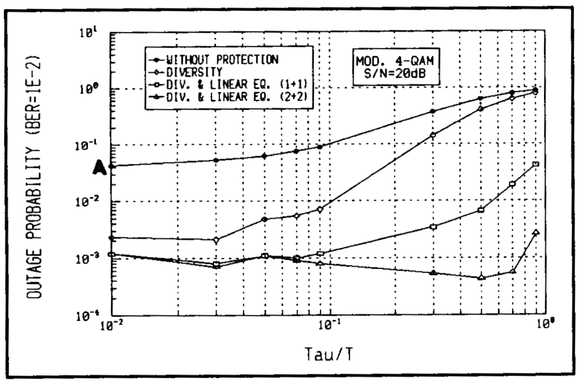


Figure 2.- OUTAGE PROBABILITY VERSUS NORMALIZED DELAY SPREAD. 4-QAM, SNR=20dB, BER= 10^{-2}

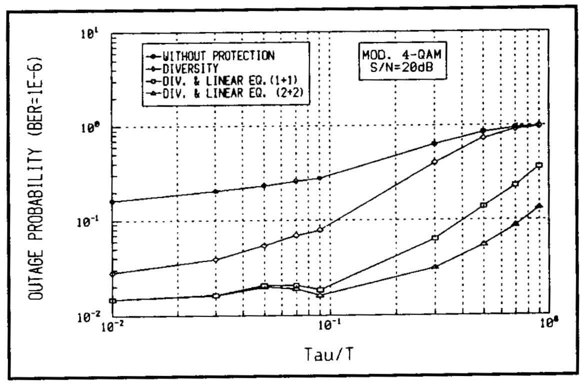


Figure 3.- OUTAGE PROBABILITY VERSUS NORMALIZED DELAY SPREAD. 4-QAM, SNR=20dB, BER=10^{-6}

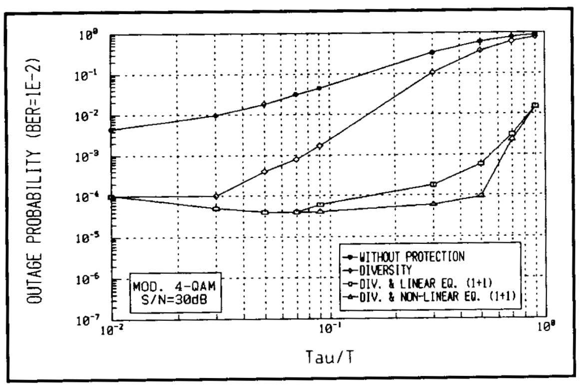


Figure 4.- OUTAGE PROBABILITY VERSUS NORMALIZED DELAY SPREAD. 4-QAM, SNR=30dB, BER=10^{-2}.

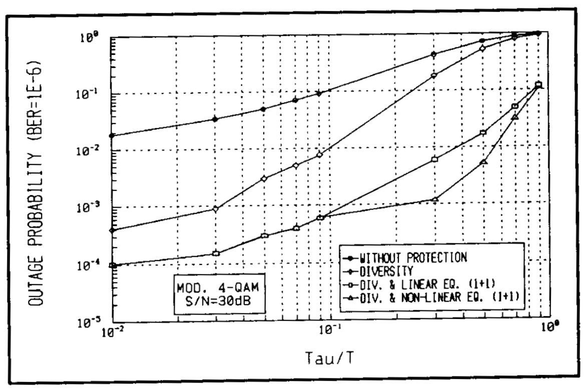


Figure 5.- OUTAGE PROBABILITY VERSUS NORMALIZED DELAY SPREAD. 4-QAM, SNR=30dB, BER=10^{-6}.

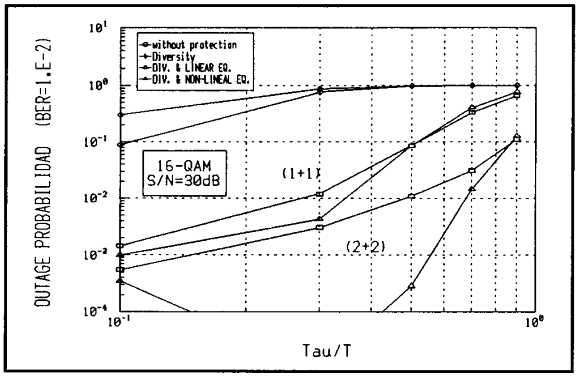


Figure 6.- OUTAGE PROBABILITY VERSUS NORMALIZED DELAY SPREAD. 16-QAM, SNR=30dB, BER=10^{-2}

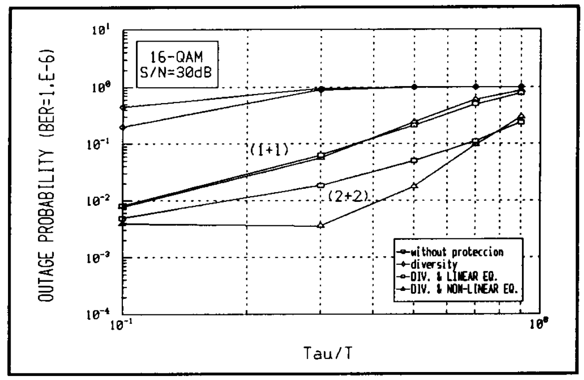


Figure 7.- OUTAGE PROBABILITY VERSUS NORMALIZED DELAY SPREAD. 16-QAM, SNR=30dB, BER=10^{-6}

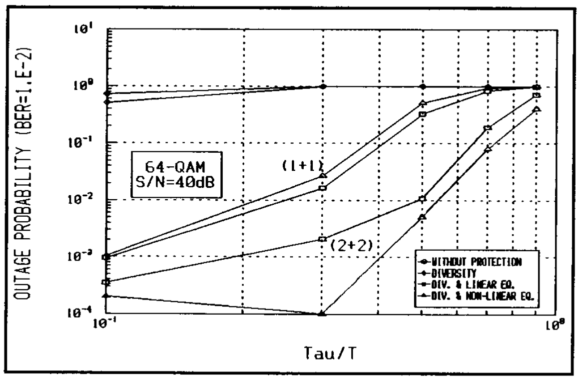


Figure 8.- OUTAGE PROBABILITY VERSUS NORMALIZED DELAY SPREAD. 64-QAM, SNR=40dB, BER=10^{-2}

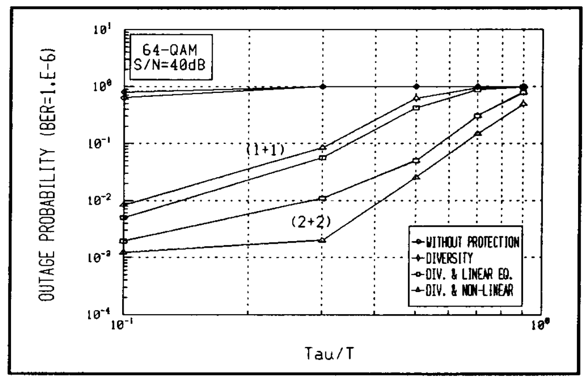
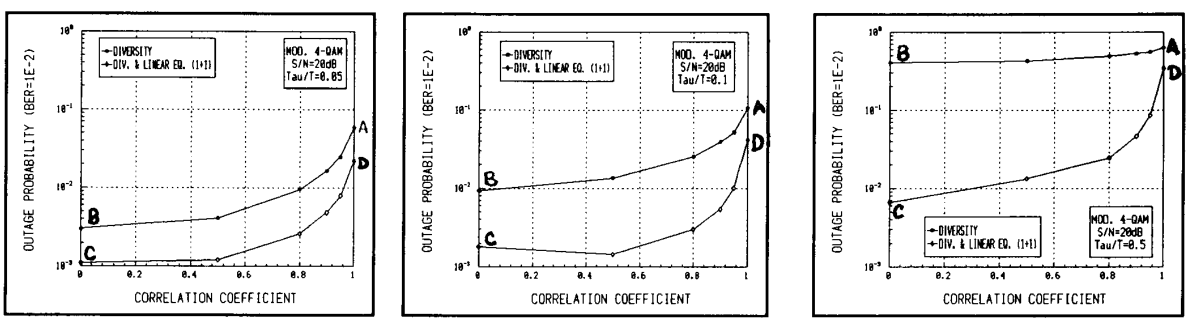


Figure 9.- OUTAGE PROBABILITY VERSUS NORMALIZED DELAY SPREAD. 64-QAM, SNR=40dB, BER=10^{-6}.



(a) (b) (c)

Figure 10.-OUTAGE PROBABILITY VERSUS CORRELATION COEFFICIENT. SNR=20 dB, 4-QAM, τ/T = 0.05, 0.1, 0.01