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THE IMPACT OF ADAPTATION POLICIES ON CHANNEL CAPACITY OVER RAYLEIGH FADING WITH EGC DIVERSITY

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ABSTRACT

In this paper, we study the basic diversity combining techniques and investigate analytically-derived closed-form expressions for the capacities per unit bandwidth for Rayleigh fading channels with equal gain combining (EGC) diversity. We consider different channel performance adaptation policies such as: power and rate adaptation with constant transmit power, channel inversion with fixed rate, and truncated channel inversion. A simulation of these schemes was carried out under ideal communication conditions and their performance compared. Results obtained show that channel inversion policies gave the highest capacity over other adaptation policies (with EGC diversity) while the constant transmit power policy yielded the lowest capacity. Furthermore, the truncated channel inversion policy outperformed other policies, while the constant power policy had the lowest capacity, compared to other policies.

KEYWORDS

Rayleigh fading, channel capacity, channel gain, multi-path fading

1. INTRODUCTION

The astronomical growth in the capacity of wireless communication services in recent times is not unconnected with the high-tech communication infrastructure which has simplified the communication process. On the other hand, this growth has generally affected the allocation of the scarce radio spectrum, due to the fact that more users now join the network. This therefore calls to question how the expected quality of service (QoS) will be sustained or guaranteed in the presence of these challenges. Some network operators attempt to confront these challenges by conserving the sharable bandwidth, but lack the required optimization skills. Thus, channel capacity is most vital in the design of wireless communication systems, as it determines the maximum attainable throughput of the system. An important concept is the coherence time [1], which is a measure of the time duration over which channel gain remains almost constant or highly correlated with a recommended correlation coefficient of above 0.5.

When a signal is transmitted over a radio channel, it is bound to experience delay, reflection, scattering and diffraction. This propagation defect also known as multi-path fading causes rapid changes in the communication environment, which introduces more complexities and uncertainties to the channel response and results in time-variation of the signal strength between the transmitter and the receiver. The urban and suburban areas where cellular phones are most

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often used are mostly affected by this phenomenon. A simulator offers a better understanding of this phenomenon.

Multi-path fading channel modelling traditionally focuses on physical-level dynamics such as signal strength and bit error rate (BER). The end-to-end modelling and design of systems that mitigates the effect of fading are usually more challenging than those whose sole source of performance degradation is the Additive White Gaussian Noise (AWGN). Fading mitigation is important because wireless systems are prone to fading which is also known to cause degradation in the wireless link performance, and calls for efficient fading mitigation schemes. In this paper, an extended simulation is carried out to investigate the effect of diversity level on channel capacity. We proceed as follows: a review of related works is first presented, then a discussion on the basic diversity methods, with a simulation (of the performance) of each technique. Finally, a discussion of an extensive simulation of the effect of different diversity level on the channel capacity is presented.

2. REVIEW OF RELATED WORKS

Diversity techniques are becoming well known techniques for combating the notorious effect of channel fading. This is evident in the numerous research works available in the study of channel capacity over fading channels. Initial investigation in this area (use of diversity schemes) dates back to [2], who studied the use of maximum ratio diversity combination (MRDC) technique to provide maximum capacity improvement. In [3], the theoretical spectral efficiency limits of adaptive modulation in Nakagami multi-path fading (NMF) channels are investigated. They apply the general theory developed in [4] to obtain closed-form expressions for the capacity of *Rayliegh* fading channels under different adaptive transmission and diversity combining techniques. In [5], the capacity of a single-user flat fading channel with perfect channel measurement information at the transmitter and the receiver is derived for various adaptive transmission policies. The basic concept of adaptive transmission is the real-time balancing of the link budget through adaptive variation of the transmitted power level, symbol transmission rate, constellation size, coding rate or a combination of these parameters [6].

Mobile radio links are exposed to multi-path fading due to the combination of randomly delayed reflected, scattered and diffracted components. In [7], a novel closed-form expression for achieving average channel capacity of a generalized selection combining rake receiver in Rayleigh fading is derived. A performance comparison of the capacity achieved with maximum ratio combination and rake receivers is also presented. Perera, Pollock and Abhayapala [8] has investigated the limits of information transfer over a fast *Rayleigh* fading Multi Input and Multi Output (MIMO) channel, where neither the transmitter nor the receiver is aware of the channel state information (CSI), except the fading statistics. Their work develops a scalar channel model in the absence of phase information for non-coherent *Rayleigh* fading and derives a capacity supremum with the number of receive antennas at any SNR using La-grange optimization. In [9], a unified L-branch equal gain combining (EGC) over generalized fading channels, such as Nakagmi-m, Rician, Hoyt or Weibull is presented. For each of these models, an exact closed-form expression is derived for the moments of the EGC output and SNR. Ekpenyong, Isabona and Umoren [10] extends [9] by deriving closed-form expressions for spectral efficiency of *Raleigh* fading channels, with EGC diversity for various adaptation policies. A methodology for computing the optimal cutoff SNR required for successful data transmission is also presented.

This paper is an extended version of [10]. The research improves on the bit error rate (BER) in the presence of SNR at various diversity levels using EGC and explores useful optimality conditions for achieving a robust system that minimizes degradation in the presence of fading.

3. BASIC DIVERSITY COMBINING METHODS

The collection of independently fading signal branches can be combined in a variety of ways to achieve a satisfactory (received) SNR. Since the chance of having two deep fades from two uncorrelated signals at any instant is rare, combining them can reduce the effect of the fades. The three most prevalent space diversity-combining techniques are selection diversity (SC), equal gain combination (EGC), and maximum radio combining (MRC). MRC co-phases the signal branches, weighs them according to their respective SNRs, and then computes their sum. MRC is the most complex combining technique, but this technique yields the highest SNR. A study of all of these diversity techniques is presented here.

3.1. Selection diversity

Selection diversity is the simplest of all the diversity schemes. It is based on the probability that the received signals rises above a threshold. An ideal selection combiner chooses the signal with the highest immediate SNR of all the branches, so the output SNR is identical to that of the best incoming signal and makes it available to the receiver at all times. However, multiple branches will increase the probability of having a better SNR at the receiver [11]. The algorithm for selective diversity combining is based on the principle of selecting the best signal among all of the signals received from different branches, at the receiver end. In the SC method for two antennas, as shown in Figure 1, the branch with the maximum voltage SNR is selected as the contributing received signal. For instance, branch one (1) *SNR* is chosen if it is larger than branch two (2) *SNR.* The weaker branch is not used.

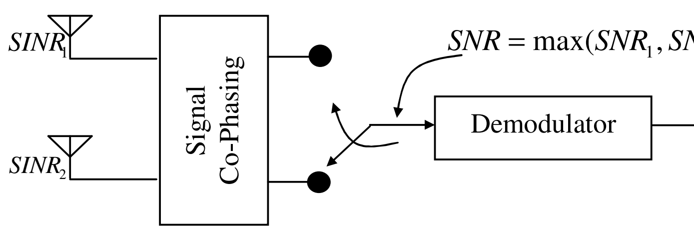

Figure 1. Two branch selection combining (SC) with equal noise power

In this method, the mean SNR of the selected signal is [12]:

$$< SNR >= \rho \sum_{m=1}^{M} \frac{1}{m} \cong \rho (C + \ln m + \frac{1}{2M}) \qquad (1)$$

where ρ is the mean branch SNR. The mean SNR improves logarithmically with the *N* number of branches.

3.2. Maximum Ratio Combining (MRC)

Maximum ratio combining gathers the information from all received branches for a multiple antenna system in order to increase the SNR. It employs different gains to each antenna to improve the signal to noise ratio for the combined signals. Maximum ratio combining can provide the diversity gain and array gain but it does not help in spatial multiplexing scenario [11]. The MRC method is shown in Figure 2, where each branch signal is first weighted by its received instantaneous voltage SNR, r_1M and r_2M, respectively. Thus the branch with the higher voltage SNR is weighted more than the branch with lower voltage SNR. The weighted signals are then co-phased and coherently summed. This method yields the highest instantaneous SNR possible using any linear combining technique. However, the implementation of the MRC is computationally expensive, as the weights need both amplitude and phase tracking of the channel response.

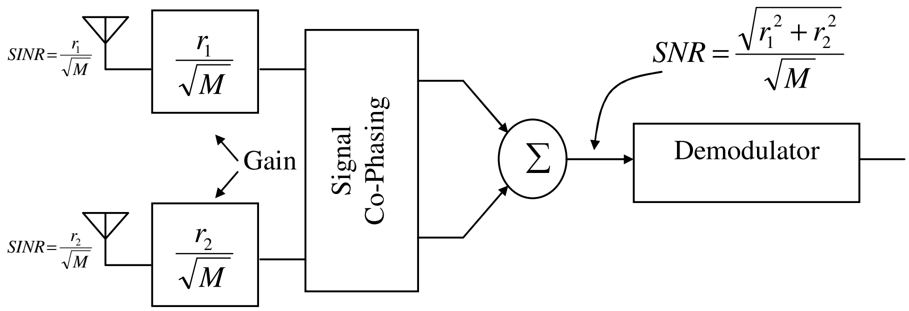

Figure 2. Two branch maximal-ratio combining (MRC) with equal noise power, source [13]

The mean SNR at the output of the combiner is [12]:

$$< SNR >= \sum_{m=1}^{M} \rho = M\rho \qquad (2)$$

where ρ is the mean branch SNR. The mean SNR improves with the number of branches, M.

3.3. Equal Gain Combining (EGC)

EGC diversity receiver is of practical interest because of its reduced complexity relative to optimum maximal ratio combining scheme, while achieving near-optimal performance [11]. It is the accumulation of all the signals received in order to increase the available SNR at the receiver. The gain of all of the branches is set to a particular value that does not change which is in contrast to MRC. In the EGC method, the weights possess same constant magnitude, G, unlike the MRC, where the weights are based on the instantaneous voltages. As shown in Figure 3, the weighted signals are then co-phased and coherently summed. The noise power for the output voltage SNR is doubled.

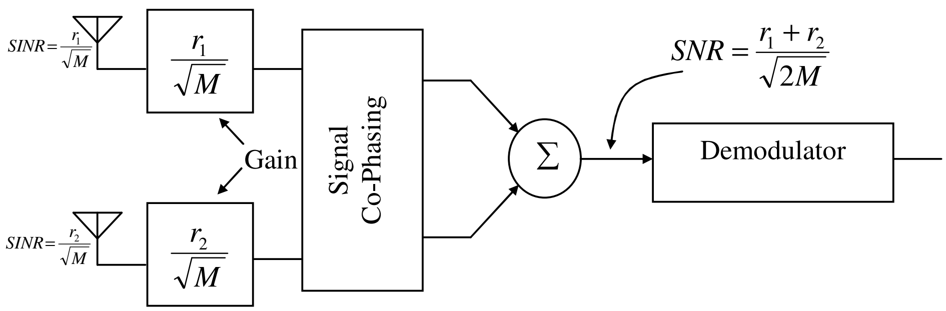

Figure 3. Two branch equal gain combining (EGC) with equal noise power, source [13].

The closed-form expression for the mean SNR at the output of the combiner is [12]:

$$< SNR >= \left[1 + (M-1)\frac{\pi}{4} \right] \rho \qquad (3)$$

Here, the various diversity techniques which include Selection Combining (SC), Equal Gain Combining (EGC), and Maximum Ratio Combining (MRC), were simulated in MATLAB to compare the performance of the three techniques in terms of the complexity and improvement in SNR Rayleigh fading channel. From Figure 4, the plots of improved mean SNR as a function of number of diversity levels, *M*, show that MRC and EGC yield better gain than the SC method. For larger *M*, the MRC is about 1 dB higher than the EGC method. Hence, an improvement in the case of equal gain combining is comparable to that of maximal ratio combining.

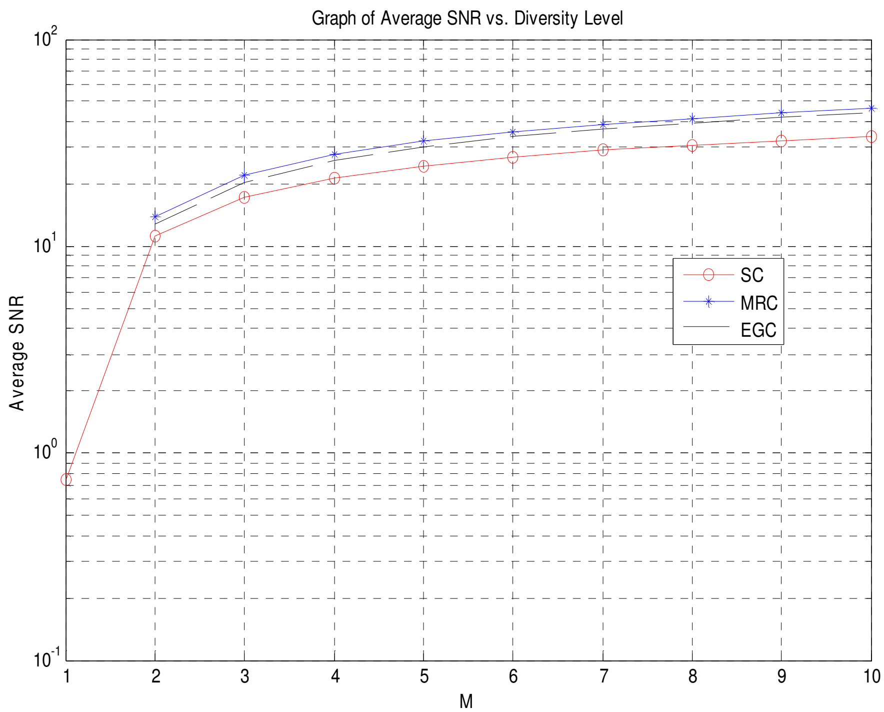

Figure 4. Graph of SNR vs. number of branches

In terms of the required processing, the selection combiner is the easiest – it requires only a measurement of SNR at each element and not the phase or the amplitude, i.e., the combiner need not be coherent. Both the maximal ratio and equal gain combiners, on the other hand, require phase information. The maximal ratio combiner requires accurate measurement of the gain too. But EGC is often used in practice because of its reduced complexity relative to the optimum MRC scheme. This is because the latter requires information on the fading amplitude in each signal branch while the former requires no such knowledge [14]. Thus, we focus more on the EGC performance in Rayleigh fading channel. We begin the investigation by exploring how the probability of error (BER) can be improved in the presence of interference with M = 4, 6, 8, 10 branches, using EGC. Three BER schemes: the Binary Phase shifts Keying (BPSK), Differential Phase shift Keying (DPSK) and Binary Frequency Phase shift Keying (BFSK) were used to specify different services in multimedia environment, i.e. data, voice and video channel. As can be seen from the plots in Figure 5-7, the three BERs improve as the diversity level increases.

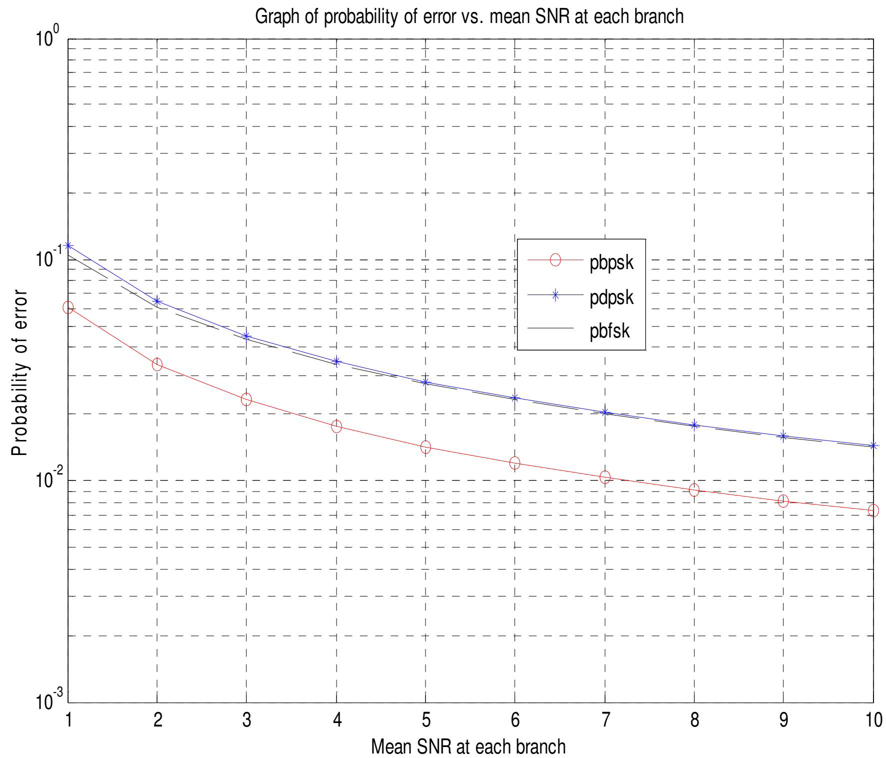

Figure 5. Graph of probability of error vs. SNR at each branch, for M=4

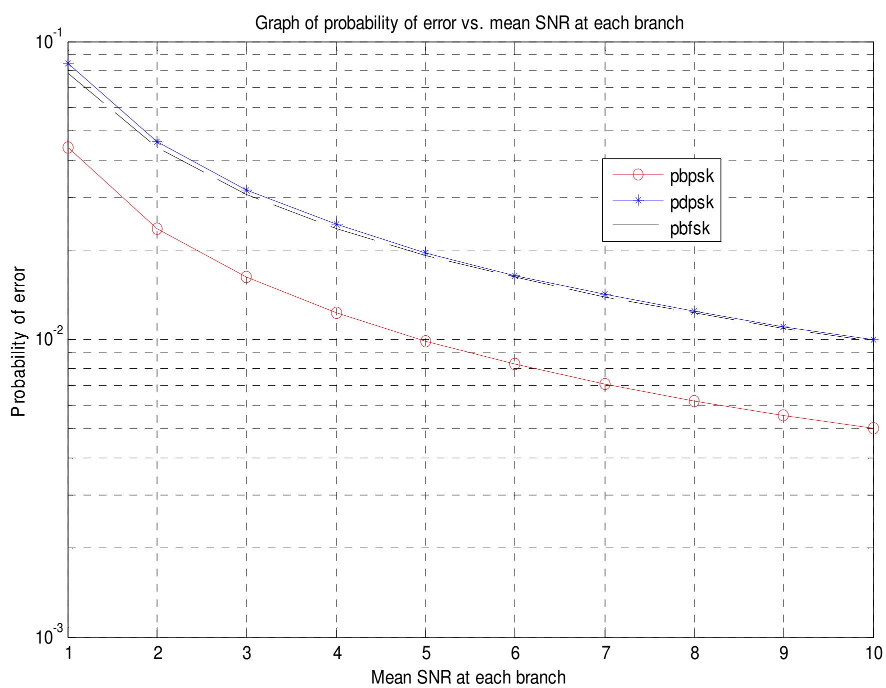

Figure 6. Graph of probability of error vs. SNR at each branch, for M=6

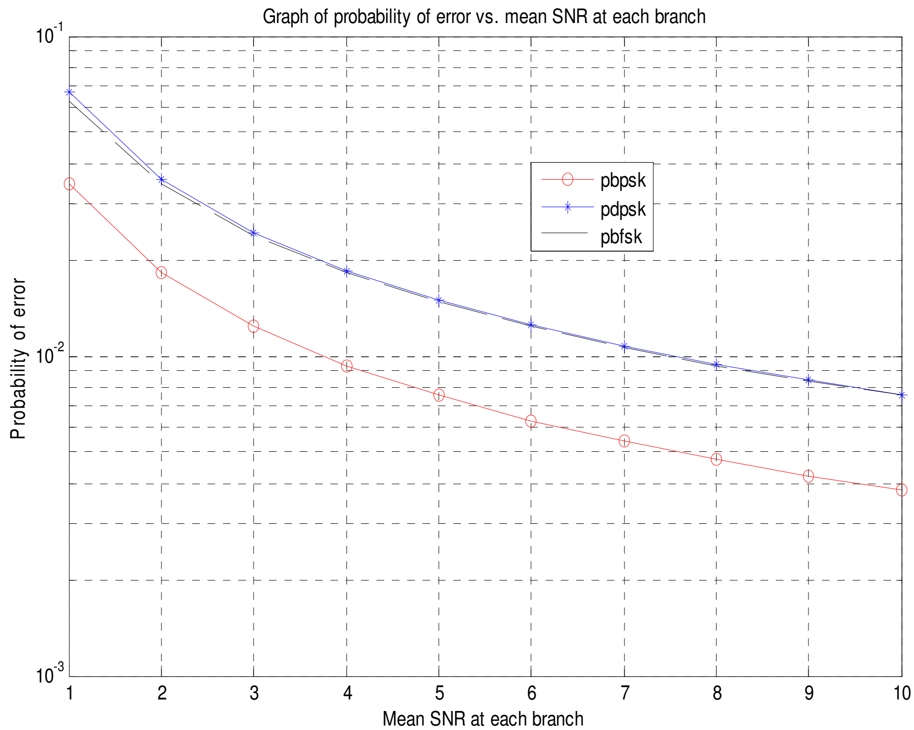

Figure 7. Graph of probability of error vs. SNR at each branch, for M=8

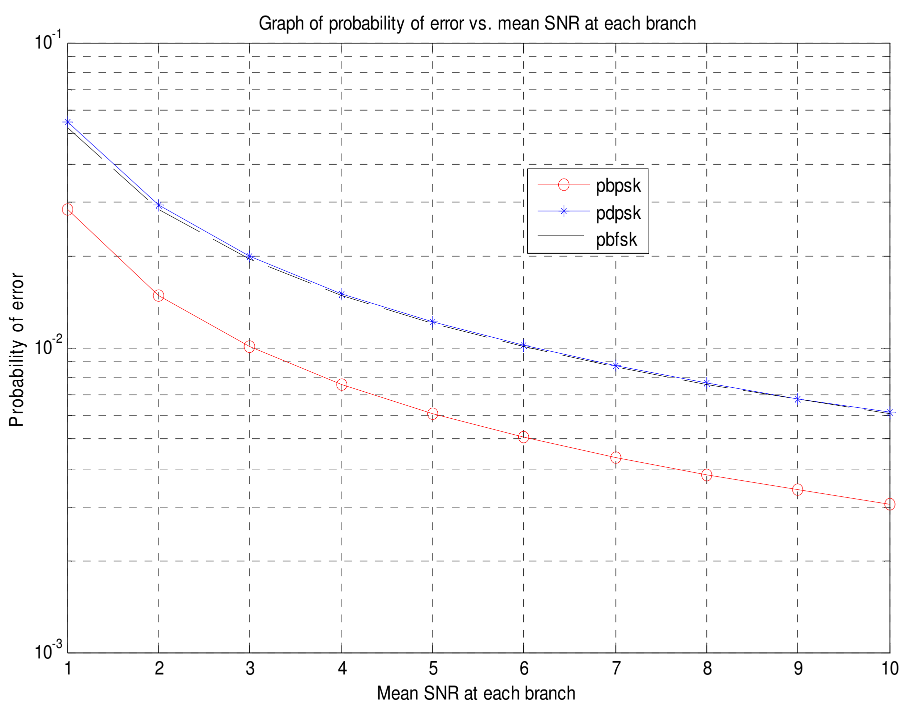

Figure 8. Graph of probability of error vs. SNR at each branch, for M=10

Next, we revisit the Shannon capacity efficiency of *Raleigh* fading channels, with EGC diversity under various adaptation policies. Though we have discussed these in [10], we repeat then here to enable readers follow the derivations of the system model and the purpose of our extension. The derivations as presented as follows:

3.3.1. Equal Gain Diversity Reception for Rayleigh Fading Channel

Given an average transmit power constraint, the channel capacity of fading channel with received SNR distribution, $P_{\gamma}(\gamma)$, and power and rate adaptation, C_p bits/s is given as [6]:

$$C_{\rho} = B\int_{\gamma_0}^{\infty} \log_2\left(\frac{\gamma}{\gamma_0}\right)\rho_{\gamma}(\gamma)\partial\gamma \tag{4}$$

where B(Hz) is the channel bandwidth and γ_0 is the cutoff level SNR below which data transmission is suspended. This cutoff must satisfy the following condition:

$$\int_{\gamma_0}^{\infty}\left(\frac{1}{\gamma_0}-\frac{1}{\gamma}\right)\rho_{\gamma}(\gamma)\,\partial\gamma = 1 \tag{5}$$

where $\rho_{\gamma}(\gamma)$ represents the *pdf* of the received signal amplitude for a *Rayleigh* fading channel with a *m*-branch EGC diversity and is given by

$$\rho_{\gamma}^{EGC}(y) = \frac{y^{m-1}e^{-y/\rho_x}}{\rho_x^m(m-1)!} \tag{6}$$

To achieve the capacity in equation (4), the channel fading level must be tracked both at the receiver and transmitter and the transmitter has to adapt its power and rates for excellent channel conditions (i.e., γ is large), by maintaining lower power levels and rates for unfavourable channel conditions (γ is small). Since no data is sent when $\gamma < \gamma_0$, the optimal policy suffers a probability of outage, P_{out}, equivalent to the probability of no transmission, given by:

$$P_{out} = \int_0^{\gamma}\rho_{\gamma}(\gamma)\,d\gamma = 1-\int_{\gamma_0}^{\infty}\rho_{\gamma}(\gamma)\,d\gamma \tag{7}$$

Substituting equation (6) into (5), and simplifying same, we observe that γ_0 must satisfy

$$\begin{aligned}\Lambda^{(C)}\left(m,\frac{\gamma}{\rho_x}\right)\frac{-\gamma_0}{\rho_x}\bullet\Lambda^{(C)}\left(m-1,\frac{\gamma_0}{\rho_x}\right)\\ =(m-1)!\,\frac{\gamma_0}{\rho_x^{m-1}}\end{aligned} \tag{8}$$

where $\Lambda^{(C)}(\alpha,x) = \int_x^{\infty} t^{\alpha-1}e^{-t}\,dt$ is the complementary incomplete gamma function [14].

Let $v = \gamma/\rho_x$, and $f(v)$ is defined as:

$$f(v) = \Lambda^{(C)}(m,v) - v\Lambda^{(C)}(m-1,v) - \frac{v}{\rho_x^{m-2}}(m-1)! \tag{9}$$

Substituting equation (6) into (4), we have

$$\frac{C_p^{EGC}}{B} = \frac{1}{\rho_x^m (m-1)} \int_{\gamma_0}^{\infty} \log_2 \left(\frac{\gamma}{\gamma_0}\right) \gamma^{m-1} e^{-\gamma / \rho_x} \, d\gamma \tag{10}$$

3.3.2. Flat Fading and Frequency Selective Fading

As the carrier frequency of a signal is varied, the magnitude of change in amplitude also varies. The coherence bandwidth measures the minimum separation in frequency after which both signals experience uncorrelated fading [16]. In flat fading, the coherence bandwidth of the channel is usually higher than the bandwidth of the signal. Therefore, all frequency components of the signal will experience the same magnitude of fading.

In frequency selective fading, the coherence bandwidth of the channel is lower than the bandwidth of the signal. Different frequency components of the signal therefore experience de-correlated fading, since different frequency components of the signal are independently affected.

3.3.3. Optimal Rate Adaptation to Channel Fading with Constant Transmit Power Policy

With optimal rate adaptation to channel fading at a constant transmit power, the channel capacity, C_0 (bits/s) becomes [4]:

$$C_o = \beta \int_0^{\infty} \log_2 (1+\gamma) \, P_\gamma(\gamma) \, d\gamma \tag{11}$$

Substituting equation (6) into (11), we obtain

$$\frac{C_o^{EGC}}{B} = \log_2(e) \frac{1}{\rho_x^m (m-1)!} \times \int_0^{\infty} \log_e (1+\gamma) e^{-\xi\gamma} \gamma^{m-1} d\gamma$$

$$= \log_2(e) \frac{1}{\rho_x^m (m-1)!} I_m(\xi) \tag{12}$$

where

$$I_m(\xi) = \int_0^{\infty} t^{n-1} \log_e (1+t) e^{-\xi t} dt, \;\; \xi > 0$$

m represents the diversity levels

ρ_m^x is the average SNR

Using the result of $I_m(\xi)$, we can rewrite equation (11) as:

$$\frac{C_o^{EGC}}{B} = \log_2(e) e^{\xi} \Lambda^C(-k, \xi) \tag{13}$$

and equally express in the form of a Poisson distribution as [17]:

$$\frac{C_o^{EGC}}{B} = \log_2(e)(P_M(-\xi)E_1(\xi)) + \sum_{k=1}^{M-1} \frac{P_k(\xi)P_{M-k}(-\xi)}{k} \tag{14}$$

where $P_k(\xi)$ is given by $P_k(\xi) = e^{-\xi}\sum_{j=0}^{k-1}\frac{\xi_j}{j!}$ and $E_1(\xi) = \int_1^{\infty}\frac{e^{-\xi t}}{t}dt$.

3.3.4. Channel Capacity with Fixed Rate Policy

The channel capacity when the transmitter adapts its power to maintain a constant SNR at the receiver or inverts the channel fading is also investigated in [4]. This technique uses fixed rate modulation and a fixed code sign, since the channel after channel inversion appears as a time invariant AWGN channel. As a result, channel inversion with fixed rate is the least complex technique to implement, assuming good channel estimates are available at the transmitter and receiver. With this technique, the channel capacity of an AWGN channel is given as [4]:

$$C_c = B\log_2\left(1 + \frac{1}{\int_0^{\infty}\left(\rho_\gamma(\gamma)/\gamma)\,d\gamma\right)}\right) \tag{15}$$

Inverting channels with fixed rate suffers large capacity penalty relative to other techniques, since a large amount of the transmitted power is required to compensate for the deep channel fades.

The capacity with truncated channel in varied and fixed rate policies $C_t(bits/s)$ becomes:

$$C_t = B\log_2\left(1 + \frac{1}{\int_{\gamma_0}^{\infty}\left(\rho_\gamma(\gamma)/\gamma)\,d\gamma\right)(1-P_{out})}\right) \tag{16}$$

where P_{out} is given in equation (7). We then obtain the capacity per unit bandwidth with EGC diversity for channel inversion with fixed rate policy (total channel inversion) as C_c/B , by substituting equation (6) into equation (16) giving:

$$\frac{C_c}{B} = \log_2\left[1 + \frac{\rho_x^m\Gamma(m)}{\int_0^{\infty}\gamma^{m-2}e^{\gamma/\rho_x}\,d\gamma}\right] \tag{17}$$

Now, substituting $t = \gamma/\rho_x^m \; and \; dt = d\gamma/\rho_x^m$ into equation (15), yields,

$$\frac{C_c^{EGC}}{B} = \log_2\left[1 + \frac{\rho_x\Gamma(m)}{\int_0^{\infty}t^{m-2}e^{-t}dt}\right] = \log_2\left[1+(m-1)\rho_x\right] \tag{18}$$

The capacity of this policy for a *Rayleigh* fading channel is the same as the capacity of an AWGN channel with equivalent $SNR = (m-1)\,\rho_x$. Truncated channel inversion improves the capacity in equation (16) at the expense of the outage probability, P_{out}^{EGC} . The capacity per unit bandwidth of truncated channel inversion with EGC diversity C_t^{EGC}/B, is obtained by substituting equation (6) into equation (14). Thus,

$$\frac{C_t^{EGC}}{B} = \log_2\left[\frac{1+\rho_x^m(m-1)!}{\int_{\gamma_0}^{\infty}\gamma^{m-2}e^{-\gamma/\rho_x}}\partial\gamma\right]\times\left(1-P_{out}^{EGC}\right) \tag{19}$$

where P_{out}^{EGC} is given in equation (6). Substituting $t = \gamma/\rho_x$ and $dt = d\gamma/\rho_x$ into equation (17), gives:

$$\frac{C_t^{EGC}}{B} = \log_2\left[1+\frac{\rho_x(m-1)}{\int_{\gamma_0/\rho_x}^{\infty} t^{m-2}e^{-t}dt}\right]\bullet\int_{\gamma_0}^{\infty}P_{\gamma}^{EGC}(\gamma)\partial\gamma \tag{20}$$

Substituting $t = \gamma/\rho_x$ and $dt = d\gamma/\rho_x$ into equation (18), we arrive at:

$$\frac{C_t^{EGC}}{B} = \frac{1}{\Gamma(m)}\log_2\left[1+\frac{\rho_x\Gamma(m)}{\Lambda^{(C)}(m-Q,\mu)}\right]\times\int_{\gamma_0/\rho_x}^{\infty}t^{m-1}e^{-t}dt$$

$$= \frac{\Lambda^{(c)}(m,\gamma_0/\rho_x)}{(m-1)!}\log_2\left[1+\frac{\rho_x(m-1)!}{\Lambda^{(c)}(m-Q,\mu)}\right] \tag{21}$$

4. DISCUSSION OF RESULTS

Using the three channel capacity schemes we established relationships between the model parameters through extensive computer simulation. We continuously fine-tuned the parameters/characteristics behaviour of the system until an optimum solution was achieved. Table 1 shows the sample input used during the simulation:

Table 1. Sample input parameters and values

Parameter	Value
SNR (dB) (P_x)	5, 10, 15
Diversity level (M)	1-10

Figures 9-11 show the effect of diversity level on channel capacity at different average SNR values (SNR= 5, 10, 15), for the various transmission policies. We observe that channel capacity increases with the diversity level and improves for all the policies. This upper bound on the amount of information that can be reliably transmitted over communication channel is well maximized based on the input distribution, for channel inversion with fixed rate policy and truncated channel inversion, respectively, as can be seen from the plots. Also, the bits are satisfactorily controlled and do not exceed the Shannon bound, thus reducing the number of errors. This confirms the notion that if we attempt to send bits faster than this rate, the error rate will rise beyond a negligible value, thus causing large negative effects on the communication system.

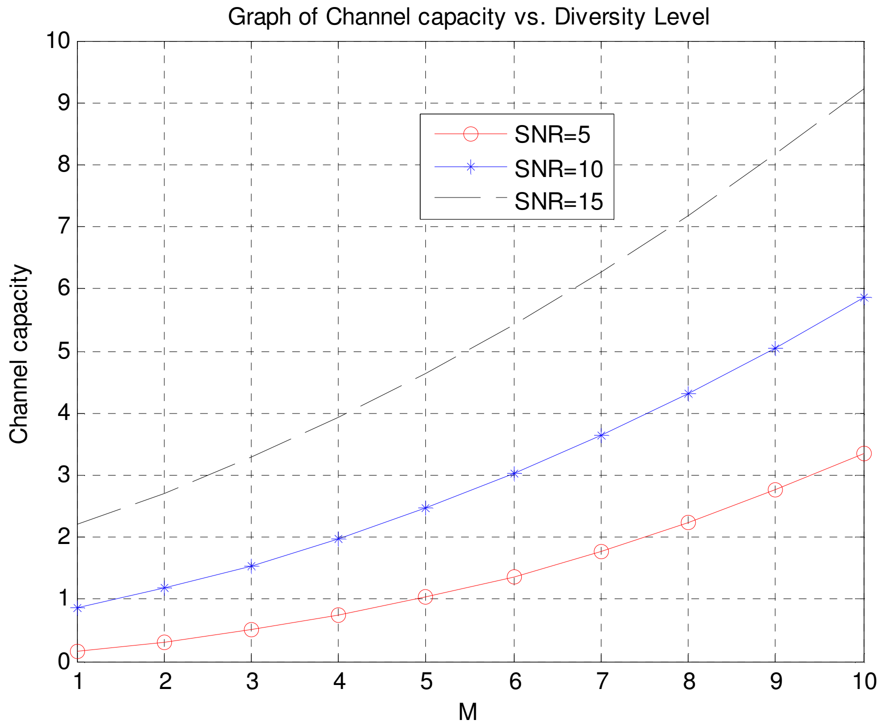

Figure 9. Graph of channel capacity vs. diversity level, for Channel capacity with optimal rate adaptation policy, at constant transmit power

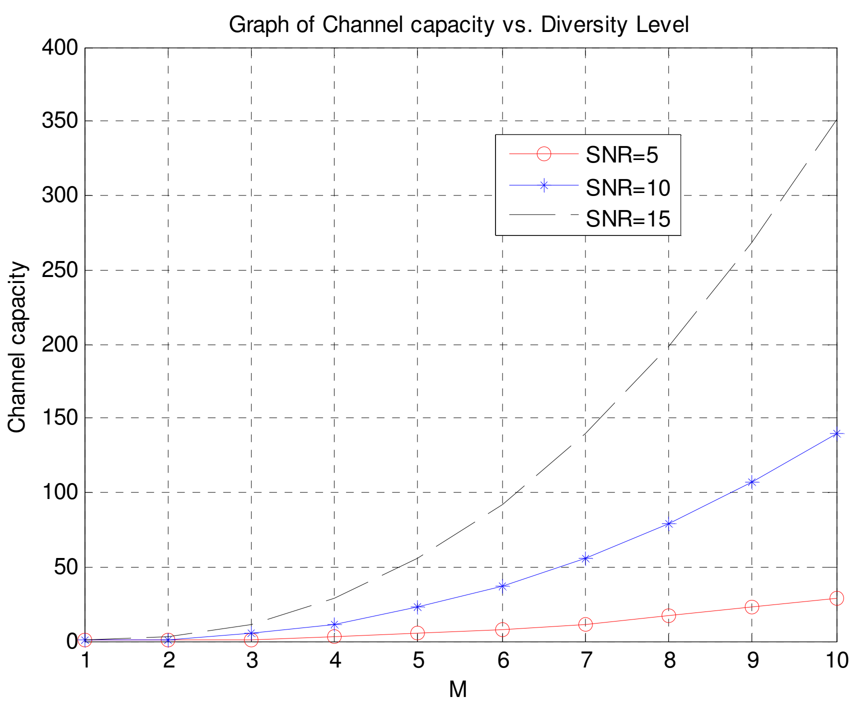

Figure 10. Graph of channel capacity vs. diversity level, for channel capacity with EGC diversity and channel inversion with fixed rate policy

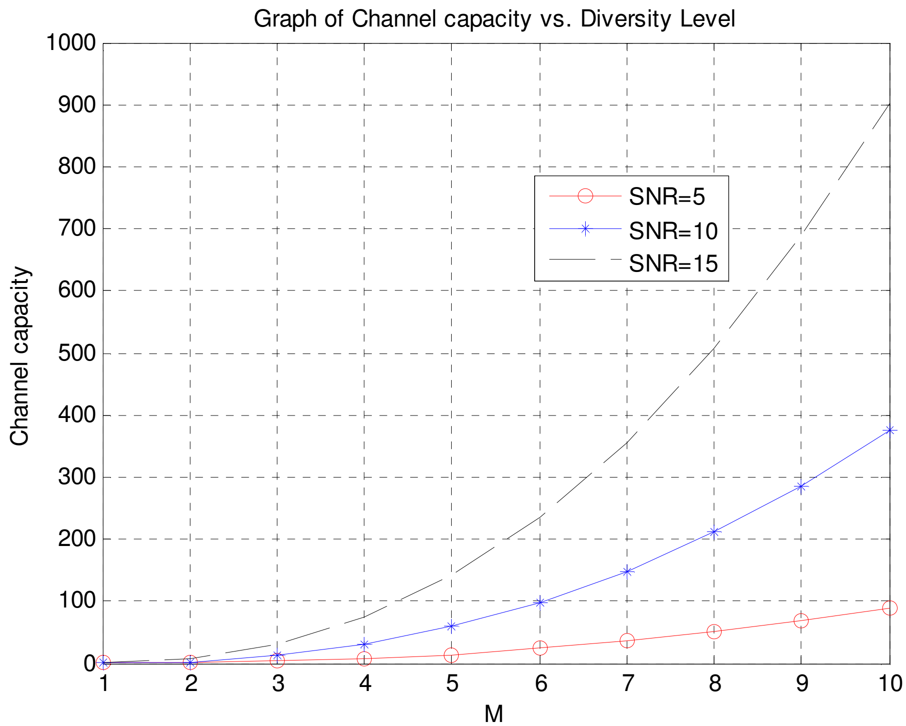

Figure 11. Graph of channel capacity vs. diversity level, for channel capacity with EGC diversity and truncated channel inversion

5. CONCLUSION

We have studied the different diversity combining techniques, with special interest on the estimation of the capacity of equal gain combining (EGC) under a multi-path fading channel. In particular, we obtained closed-form expressions for the channel capacities of the various adaptation policies used in conjunction with diversity combining. In order to evaluate the impact of the three adaptation policies on the diversity schemes, we simulated the schemes under ideal communication conditions using a robust simulation software. From the simulation results, channel inversion yields the best system performance compared to other diversity schemes. Hence, to maintain the desired level of productivity and contend with the ever increasing users' capacity, mobile network operators must conserve, share and manage available bandwidth efficiently.

Optimal power and rate adaptation yields a small increase in capacity over just optimal rate adaptation, and this small increase in capacity diminishes as the average received SNR and/or the number of diversity branches increases. In addition, channel inversion suffers the largest capacity penalty relative to the two other policies. However, this capacity penalty diminishes with increasing diversity.

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