Channel Capacity of Adaptive Transmission Schemes Using Equal Gain Combining Receiver Over Hoyt Fading Channels

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***Abstract*—Closed-form expressions for the channel capacity of an L-branch equal gain combining diversity receiver over Hoyt (Nakagami-q) fading channels is derived for adaptive transmission schemes. To obtain capacity expressions, probability density function of the combiner out put signal-to-noise ratio (SNR) is used. The capacity expressions are given in terms of Yacoub's integral, a general solution for which is presented in the literature recently. Further, an expression is derived for optimal cutoff SNR for the optimal power and rate adaptation scheme. A study on the effects of fading parameters and diversity order on the channel capacity of the systems for different techniques have been presented.**

***Index Terms*—Equal gain combining, Hoyt (Nakagami-q) fading, channel capacity, adaptive transmission.**

I. Introduction

To offer a better quality of service, capacity analysis of communication systems along with outage and bit error probability is necessary. In wireless channels, performance of a communication system degrades mainly due to fading, among other known factors, which occurs because of multipath propagation of signals. Diversity combining is widely used to reduce the effect of fading in a wireless communication system. Among different diversity combining techniques available in literature, the maximal ratio combining (MRC) gives an optimum performance. The equal gain combining (EGC) diversity technique can provide a performance very close to the MRC with less implementation complexity [1]. Therefore, an EGC system is practically more important compared to a MRC system. The capacity analysis of EGC systems are available in [2]-[8]. In [2]-[5], study of statistical properties of the capacity of EGC and MRC systems over Nakagami-m, Rice, double Rayleigh and Rayleigh fading channels have been presented. Simple mathematical expressions for capacity for Nakagami channels has been presented in [6]. Capacity of EGC systems over Rayleigh fading channels for both independent and correlated fadings are presented in [7] and [8], respectively. Hoyt (Nakagami-q) fading channels is normally observed in satellite links subject to strong ionospheric scintillation and heavily shadowed environment [1], [9]. This model, originally introduced by Nakagami [10] as an approximation to the Nakagami-m model over the range of $m = 0.5$ to 1, models fading conditions severe than the Rayleigh fading. It includes the one sided Gaussian and Rayleigh models as special cases. In literature, although the channel capacity of a MRC receiver is available for Hoyt fading channels [11], [12], it is not available for EGC systems. In this paper, we analyze the capacity of an EGC system over Hoyt fading channels. We use the available probability density function (PDF) expression for the EGC combiner output signal-to-noise ratio (SNR) in [13] to derive expressions for the channel capacity for different adaptive transmission schemes.

The rest of this paper is organized as follows. In Section II, we introduce the channel and diversity systems and in Section III we discuss the capacity formulas available in literature for different adaptive transmission schemes. In Section IV, capacity of EGC diversity systems have been obtained. In Section V, numerical results are given. Finally, we conclude the paper in Section VI.

II. Channel and Diversity Systems

The channel is assumed to be slow, frequency nonselective, with Hoyt fading statistics. The receiver is provided with L antennas for spatial diversity reception of fading signals. The system is as shown in the Figure 1, where the EGC combiner receives L faded copies of the transmitted signal $s(t)$ with energy E_b. The channel introduces an attenuation and time delay of the signals received at the combiner. The complex low pass equivalent of the signal received by the l^{th} antenna, $l = 1, 2, \ldots, L$, over one symbol duration T_s can be expressed as

$$r_l(t) = \alpha_l e^{j\phi_l} s(t) + n_l(t), \qquad (1)$$

where $n_l(t)$ is the complex Gaussian noise having zero mean and two sided power spectral density $2N_0$. Random variable (RV) ϕ_l represents the phase and α_l is the Hoyt distributed fading amplitude having PDF given by [1]

$$p(\alpha_l) = \frac{(1+q^2)\alpha_l}{q\Omega_l} e^{-\frac{(1+q^2)^2\alpha_l^2}{4q^2\Omega_l}} I_0\left[\frac{(1-q^4)\alpha_l^2}{4q^2\Omega_l}\right], \alpha_l \geq 0, \qquad (2)$$

where $\Omega_l = E\left[\alpha_l^2\right]$, $q \in [0,1]$ is the Hoyt fading parameter and $I_0(\cdot)$ is the modified Bessel function of the first kind and

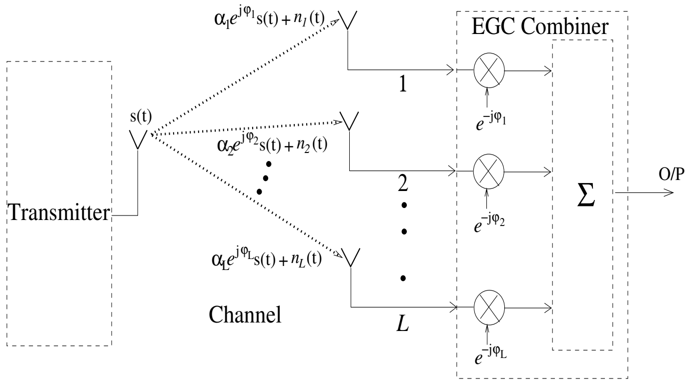

Fig. 1. EGC receiver

zeroth order. The PDF in (2) can be expressed as a function of another Hoyt fading parameter b by substituting $q=\sqrt{\frac{1-b}{1+b}}$ [14]. In this paper we consider identical fading statistics in all the branches i. e. $b_l=b$ and average input SNR $\bar{\gamma}_l=\bar{\gamma}$ for all l.

In the EGC combiner, signals from all receiving antennas are co-phased before combining with unity gain each. The output SNR of a L-EGC diversity system can be written as [14]

$$\gamma=\frac{E_b}{LN_0}(\alpha_1+\alpha_2+\ldots+\alpha_L)^2, \tag{3}$$

where the parameters α_l, E_b, L and N_0 are defined in (1).

III. Capacity of Adaptive Transmission Systems

A. Capacity Formulas

In literature, channel capacity of different communication systems have been analyzed and various schemes based on power and rate adaptation techniques have been suggested. For fading channels, analytical expressions for the capacity based on these techniques have been presented in [15] and [11]. In our analysis, we use these formulas to obtain mathematical expressions for the capacity of EGC receiver over Nakagami-m fading channels. These formulas are introduced below:

1) Optimal Power and Rate Adaptation at the Transmitter: For a system with a constraint on the average transmitting power using optimal power and rate adaptation (OPRA) technique at the transmitter, the channel capacity (bits/sec) is given by [15]

$$C_{opra}=B\int_{\gamma_0}^{\infty} log_2\left(\frac{\gamma}{\gamma_0}\right)f_\gamma(\gamma)d\gamma, \tag{4}$$

where B is the channel bandwidth, $f_\gamma(\gamma)$ is the PDF of the combiner output SNR and γ_0 is the optimal cutoff SNR, below which no transmission is allowed. The optimal cutoff SNR γ_0 has to satisfy the condition

$$\int_{\gamma_0}^{\infty}\left(\frac{1}{\gamma_0}-\frac{1}{\gamma}\right)f_\gamma(\gamma)d\gamma=1. \tag{5}$$

2) Constant Transmitting Power: When the transmitting power of the system is constant and optimal rate adaptation (ORA) technique is used at the transmitter, the channel capacity (bits/sec) can be given as [15]

$$C_{ora}=B\int_0^{\infty} log_2(1+\gamma)f_\gamma(\gamma)d\gamma. \tag{6}$$

3) Channel Inversion with Fixed Rate: When the transmitter adapts its power to maintain a constant received SNR so that inversion of the channel fading effects are possible, the system is said to be adopting channel inversion with fixed rate (CIFR) techniques. The channel capacity (bits/sec) for this case is given by [15]

$$C_{cifr}=B\log_2\left(1+\frac{1}{R_{cifr},}\right), \tag{7}$$

where $R_{cifr}\triangleq\int_0^{\infty}\left(\frac{1}{\gamma}\right)f_\gamma(\gamma)d\gamma$.

4) Truncated Channel Inversion with Fixed Rate: This is a modified CIFR scheme. When the channel goes into deep fades, to maintain constant receiver SNR a large amount of power is required at the transmitter. So, to overcome this problem truncated channel inversion with fixed rate (TIFR) method is employed. In this case, the channel inversion is done when the receiver SNR is above a threshold value γ_0. The capacity formula for TIFR can be given by [11]

$$C_{tifr}=B\log_2\left(1+\frac{1}{R_{tifr}}\right)[1-P_{out}(\gamma_0)], \tag{8}$$

where $R_{tifr}\triangleq\int_{\gamma_0}^{\infty}\left(\frac{1}{\gamma}\right)f_\gamma(\gamma)d\gamma$ and $P_{out}(\gamma_0)=\int_0^{\gamma_0}p_\gamma(\gamma)d\gamma$ is the probability of the outage for a threshold value γ_0.

From (4)-(8), it is clear that to know the capacity of a communication system for different adaptive schemes, we require the knowledge of the PDF of the system output SNR i.e., $f_\gamma(\gamma)$. A moment based accurate approximation of sum of Hoyt distribution is presented in [16]. Using this result an expression of $f_\gamma(\gamma)$ is presented in [13]. In this paper, we use this result to obtain the capacity of the L-EGC diversity system.

IV. Capacity of Equal Gain Combining System

The PDF of the output SNR of a L-EGC diversity system can be given as [13]

$$f_\gamma(\gamma)=\frac{2\sqrt{\pi}}{\Gamma(\mu)}\left(\frac{\mu}{\bar{\gamma}}\right)^{\mu+\frac{1}{2}}\left(\frac{\gamma}{H}\right)^{\mu-\frac{1}{2}}e^{-\frac{2\mu h\gamma}{\bar{\gamma}}}I_{\mu-\frac{1}{2}}\left(\frac{2\mu H}{\bar{\gamma}}\gamma\right), \tag{9}$$

where $h\triangleq\left(2+\eta^{-1}+\eta\right)/4$ and $H\triangleq\left(\eta^{-1}-\eta\right)/4$. Parameters η and μ can be numerically obtained from [16, (4)-(8)] in terms of Hoyt fading parameter b. Thus, using (9) we obtain the capacity of EGC diversity for various techniques as discussed in subsections below.

A. Optimal power and rate adaptation at the transmitter

Putting (9) into (4), expressing the Modified Bessel function in infinite series form [17] and arranging the integral, the capacity of OPRA scheme implemented system can be given as

$$C_{opra} = \frac{B\log_2 e\sqrt{\pi}\mu\gamma_0^{2\mu}}{2^{2\mu}\Gamma(\mu)\bar{\gamma}(h+H)^{2\mu-1}\Gamma(\mu+\frac{1}{2})}\sum_{k=0}^{\infty}\frac{(\mu)_k}{k!\,(2\mu)_k} \times\left(\frac{2H\gamma_0}{h+H}\right)^k J_{2\mu+k}\left(\frac{2\mu(h+H)\gamma_o}{\bar{\gamma}}\right), \quad (10)$$

where $(x)_n$ is the Pochhammer's symbol and $J_n(\mu) = \int_1^{\infty} t^{n-1}\ln(t)e^{-\mu t}dt$ [18]. For integer n, $J_n(\mu) = \frac{(n-1)!}{\mu^n}\sum_{k=0}^{n-1}\frac{\Gamma(k,\mu)}{k!}$ [19] with $\Gamma(a,x) = \int_x^{\infty} e^{-t}t^{a-1}dt$ is incomplete gamma function. In the above expression the optimal cutoff SNR, γ_0 should satisfy

$$\int_{\gamma_0}^{\infty}\left(\frac{1}{\gamma_0}-\frac{1}{\gamma}\right)f_\gamma(\gamma)d\gamma = 1. \quad (11)$$

Substituting $f_\gamma(\gamma)$ from (9) into (10) and solving the involved integral, the final expression can be written as

$$\frac{Y_\mu\left(\frac{H}{h},\sqrt{\frac{2\mu h}{\bar{\gamma}}\gamma_o}\right)}{\gamma_0\,(h^2-H^2)^{\mu}} - \frac{\mu\Gamma(\mu-1)\,Y_{\mu-1}\left(\frac{H}{h},\sqrt{\frac{2\mu h}{\bar{\gamma}}\gamma_o}\right)}{\Gamma(\mu)\bar{\gamma}H\,(h^2-H^2)^{\mu-1}} = 1, \quad (12)$$

where $Y_v(a,b) = \frac{2^{\frac{3}{2}-v}\sqrt{\pi}(1-a^2)^v}{a^{v-\frac{1}{2}}\Gamma(v)}\int_b^{\infty} x^{2v}\exp(-x^2)I_{v-\frac{1}{2}}\left(ax^2\right)dx$ is the Yacoub's integral [20]. Recently a general solution of this integral is given in [21] as

$$Y_v(a,b) = 1-\frac{(1-a^2)^v b^{4v}}{\Gamma(1+2v)} \times\Phi_2(v,v;1+2v;-(1+a)b^2,-(1-a)b^2), \quad (13)$$

where $\Phi_2(\cdot;\cdot;\cdot,\cdot)$ is the confluent Lauricella function. The expression of $Y_v(a,b)$ is further simplified in [21] for integer value of $2v$. For odd value of $2v$, a solution to Yacoub's integral is given as

$$Y_v(a,b) = 1-\frac{2^{\frac{1}{2}-v}\sqrt{\pi}(1-a^2)^v}{|a|^{2v}\Gamma(v)}I_{e_{v-\frac{1}{2}}}\left(|a|b^2,\frac{1}{|a|}\right), \quad (14)$$

where $I_{e_m}(x,\alpha) \triangleq \int_0^x t^m e^{-\alpha t}I_m(t)dt$ is the incomplete Lipschitz-Hankel integral. For even $2v$ i.e integer v, expression for Yacoub's integral is given as

$$Y_v(a,b) = 1-(1-a^2)^v\left\{\frac{1}{(1+a)^v(1-a)^v}+ \sum_{k=0}^{v-1}\frac{(-1)^{v-1}(1-a)^k 2^{-v-k}}{\Gamma(v-k)(1+a)^{k+1}}a^{-v-k}b^{2v-2-2k} \times e^{-b^2(1+a)}P_k^{(-1-k,-v-k)}\left(\frac{3a+1}{a-1}\right)+ \sum_{k=0}^{v-1}\frac{(-1)^{k+1}(1+a)^k 2^{-v-k}}{\Gamma(v-k)(1-a)^{k+1}}a^{-v-k}b^{2v-2-2k} \times e^{-b^2(1-a)}P_k^{(-1-k,-v-k)}\left(\frac{3a-1}{a+1}\right)\right\}, \quad (15)$$

where $P_k^{(a,b)}(\cdot)$ is the Jacobi polynomial [18].

B. Constant transmitting power

Putting (9) into (6) and solving the integral following an approach similar to OPRA scheme, the capacity for constant transmitting power techniques can be obtained as

$$C_{ora} = \frac{B\log_2 e\mu\sqrt{\pi}}{4^{\mu-1}\bar{\gamma}(h+H)^{2\mu-1}\Gamma(\mu)\Gamma(\mu+\frac{1}{2})}\sum_{k=0}^{\infty}\frac{(\mu)_k}{k!\,(2\mu)_k} \times\left(\frac{2H}{h+H}\right)^k I_{2\mu+k}\left(\frac{2\mu(h+H)}{\bar{\gamma}}\right), \quad (16)$$

where $I_n(\mu) = \int_0^{\infty} t^{n-1}\ln(1+t)e^{-\mu t}dt$. For integer n, $I_n(\mu)$ can be given as $I_n(\mu) = (n-1)!e^{\mu}\sum_{k=1}^{n}\frac{\Gamma(-n+k,\mu)}{\mu^k}$ [19].

C. Channel inversion with fixed rate

The capacity for this scheme requires a solution to the integral in R_{cifr} in (7). Putting (9) in (7), the integration can be rearranged by expressing the modified Bessel function in confluent hypergeometric function [22]. The resulting integral can be solved using [18, (7.621.4)] and the final expression after algebraic manipulation and simplification can be given as

$$R_{cifr} = \frac{\sqrt{\pi}\mu\Gamma(2\mu-1)}{4^{\mu-1}\bar{\gamma}(h+H)^{2\mu-2}\Gamma(\mu)\Gamma(\mu+\frac{1}{2})} \times{}_2F_1\left(\mu,2\mu-1;2\mu;\frac{2H}{h+H}\right). \quad (17)$$

Thus, an expression for the capacity of this scheme can be obtained by putting (17) into (7).

D. Truncated channel inversion with fixed rate

The capacity for this scheme requires a solution to the integral in R_{tifr} and $P_{out}(\gamma_0)$ in (8). Using (9), R_{tifr} can be obtained by solving the resulting integral using [20, (20)]. The final expression after simplification can be given as

$$R_{tifr} = \frac{\mu\Gamma(\mu-1)\,Y_{\mu-1}\left(\frac{H}{h},\sqrt{\frac{2\mu h}{\bar{\gamma}}\gamma_o}\right)}{\bar{\gamma}H\Gamma(\mu)\,(h^2-H^2)^{\mu-1}}. \quad (18)$$

An expression for $P_{out}(\gamma_0)$ has been given in [23, (7)] as

$$P_{out}(\gamma_0) = \frac{2^{1-2\mu}\sqrt{\pi}}{h^{\mu}\Gamma(\mu)} \sum_{k=0}^{\infty} \frac{\left(\frac{H}{2h}\right)^{2k} g\left(2\mu+2k, \frac{2\mu h \gamma_t}{\bar{\gamma}}\right)}{k!\Gamma\left(\mu+k+\frac{1}{2}\right)}, (19)$$

where $g(a,x) = \int_0^x e^{-t}t^{a-1}dt$ is the lower incomplete gamma function. Thus, a final expression for the capacity of this scheme can be obtained by putting (18) and (19) into (8).

V. Numerical Results and Discussion

The obtained capacity expressions (10)-(18) are numerically evaluated and plotted for different parameters of interest. The important parameters of interest are the Hoyt fading parameter b and the diversity order L. The numerical evaluation requires the values of η and μ (hence h and H). These two parameters can be obtained from [16, (4)-(8)], for a given b and L. The obtained values of η and μ are to be put in (10)-(18) to evaluate the capacity. Numerical results have been plotted for $L = 2,5$ and $b = 0.5, 0.6$ for comparison.

Capacity (per unit bandwidth) vs. $\bar{\gamma}_1$ of CIFR scheme has been plotted in Fig. 2. It can be observed from the figure that for a given fading parameter b the capacity increases with an increase in L. Again, increase in b for a given L reduces the capacity of the channel, as expected. This is because the increase in fading parameter b increases the severity of fading in the channel which is responsible for the decrease in capacity. The CIFR system is impractical during severe fading conditions and a modified version known as TIFR scheme is developed. In TIFR scheme, the transmission is suspended if the SNR of the received signal falls below a threshold. The value of threshold may vary in different scenarios. For the purpose of illustration, in the numerical evaluation of (8), we assume $\gamma_0 = 2$ dB. The plots for the TIFR scheme are given in Fig. 3. As expected, the figure shows that the TIFR scheme provides a better capacity compared to CIFR scheme. For example, for a capacity of 6 bits/sec/Hz and $L = 5$, the CIFR scheme requires a SNR of 6.94 dB whereas the TIFR scheme requires 6.41 dB, a 0.5 dB (approx.) less. Comparison for other values of L and b have been shown in figures. Numerical evaluation of the expression for OPRA scheme (10) requires the values of γ_0 from the solution of (12), a numerical solution of which is tedious to obtain because of the involved confluent Lauricella function. Hence, numerical results for OPRA scheme are not provided here. For ORA scheme, related expression has been numerically evaluated for an integer value 2μ, and curves are given in Fig.4. The ORA scheme follows similar capacity trends as CIFR and TIFR schemes. It is a poor scheme as can be observed by comparing the plots with other figures. The capacity results obtained for the EGC diversity systems have been compared with the results for MRC diversity in [12] and found to be poor within a fraction of a dB, as expected.

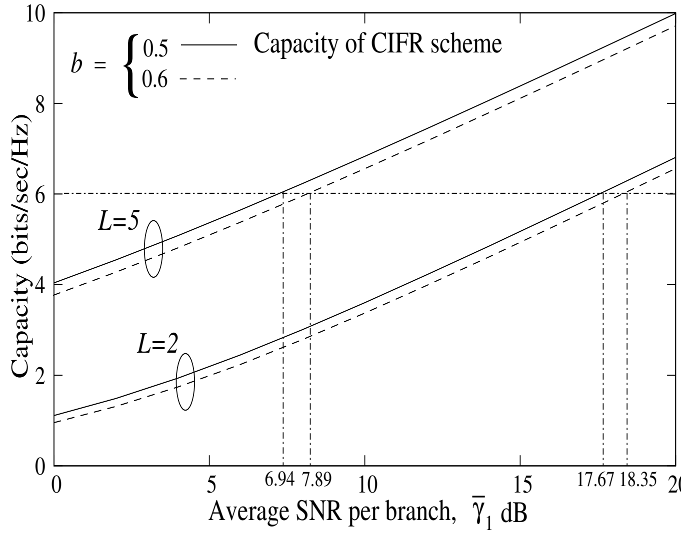

Fig. 2. Capacity of EGC receiver for CIFR scheme

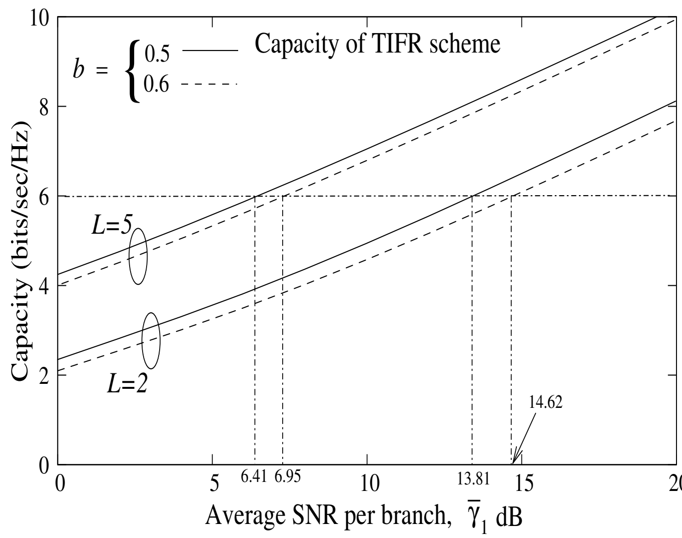

Fig. 3. Capacity of EGC receiver for TIFR scheme

VI. Conclusions

In this paper, we analyze the channel capacity of EGC diversity systems over slow varying Hoyt fading channels for different adaptive transmission techniques available in the literature. For the channel capacity of CIFR and TIFR schemes, the mathematical expressions are presented in terms of Yacoub's integral. Expressions for the capacity of OPRA and ORA schemes are also obtained. Numerically evaluated results have been plotted for different parameters of interest and compared among the transmission schemes under analysis.

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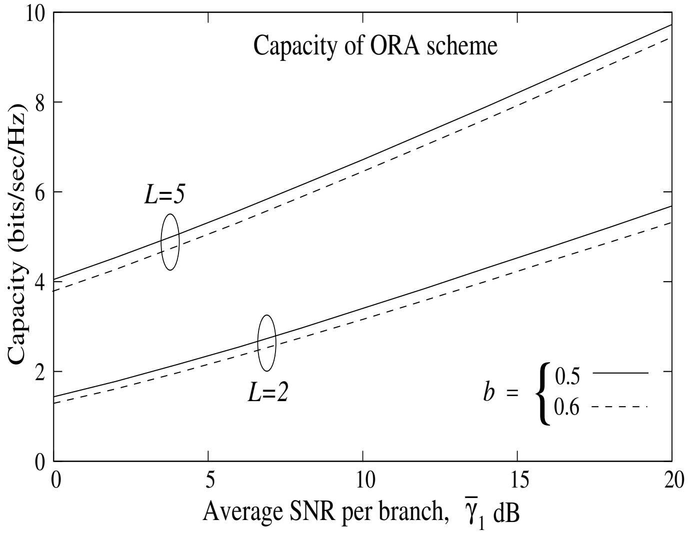

Fig. 4. Capacity of EGC receiver for ora scheme

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