Adaptive Transmission with Multiuser TAS/MRC Systems over Exponentially Correlated Rayleigh Fading Channels

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***Abstract*—This paper analyzes the channel capacity for multiuser Transmit antenna selection (TAS) / Maximal ratio combining (MRC) system over exponentially correlated Rayleigh fading channels. TAS scheme reduces the hardware complexity and the number of RF chains in MIMO systems and MRC is a diversity technique which provides optimal performance. The correlation is almost unavoidable in spatial diversity combining scheme due to reduced size of the wireless portable receivers. Different types of correlations exist based on their antenna placing. Exponential correlation is observed when antennas are put in a linear array in a communication receiver. Expressions for channel capacities with different power and rate adaptation techniques have been found. The influence of diversity order and correlation on the channel capacity has been examined for different adaptive transmission techniques.**

Keyword- Channel capacity, Multi-user MIMO, TAS/MRC, Rayleigh fading, Exponential correlation

I. INTRODUCTION

To remove the issue of rapid fluctuations of receiving signals in wireless environment multi-antenna systems are accepted worldwide for the modern communication systems. Multiple input multiple output (MIMO) is the best techniques among all which can provide multiplexing gain along with the diversity gain [1]. However, with an increase in the number of antennas and the number of users in the multiuser environment the computational complexity of a MIMO system increases exponentially. To reduce the computational complexity of a MIMO system without affecting the performance of the MIMO system, TAS/ MRC is a well-accepted method [2, 3]. TAS techniques reduce the number of RF links considerably without affecting the performance of the system. In TAS/MRC scheme, the channel state information (CSI) of all link has been sent back to the transmitter and based on CSI information the best antenna which maximizes the instantaneous signal-to-noise ratio (SNR) at the output of the maximal-ratio combiner is chosen for transmission [3-5].

The information of maximum channel capacities provides vital information to the design personnel to plan their communication system optimally. Analysis of the channel capacities have been taken up by the research communities worldwide and reported in the literature for last few decades over varieties of fading channels considering different communication model [6-14]. The power and rate adaptation techniques provide maximum channel capacity using optimized system resource. For a multiuser TAS/MRC system, it will be easy to implement the adaptive transmission schemes since the sender is already receiving CSI. Considering TAS/ MRC, channel capacities have been analyzed recently in [15] including the channel estimation errors.

Maximal ratio combining uses multiple diversity path to receive the transmitted signal. At maximum theoretical analysis, antenna correlations have been avoided to reduce the analytical complexity. Practically the antenna correlation is unavoidable due to the space limit of the wireless devices [16]. In this paper, we have studied the behaviour of the adaptive transmission scheme in terms of capacities for TAS/MRC system considering exponential correlation over Rayleigh fading channels. It has been noted that the increase in correlation coefficients improves the maximum possible channel capacity. The analysis of the obtained results is documented in result and discussion sections.

The remainder of this paper is structured as follows. In Section II we introduce the system and channel model description. The PDF of the output SNR of the TAS/MRC system is presented in Section III. Capacity analysis of adaptive transmission schemes are derived in Section IV. In Section V the results and discussions are cited. At long last, concluding remarks are given in Section VI.

II. SYSTEM AND CHANNEL MODEL DESCRIPTION

We consider a multi user, multiple input and multiple output (MIMO) wireless communication system with a base station communicating with K users. A block diagram of the system is shown in Fig. 1 for analysis of downlink data transmission. The base station has N transmit antennas and each user has L receive antennas. The base station is serving K users. Each user is served by a single antenna of base station. In Fig. 1, the transmit antennas are defined by N_t where $t=1,2,....,N$ and received antennas are expressed as $R_{k,l}$ where k represents the user number (from $k=1,2,....,K$) and l represents the antenna number ($l=1,2,....,L$). The channels between the transmit antennas and the users are modelled as a slow flat fading Rayleigh channel. Using channel state information (CSI) received through an error free feedback path, the base station selects the best transmit antenna to transmit data for each user. The complex low pass equivalent of the signal received at the $R_{k,l}$ antenna over one bit duration T_b can be expressed as

$$r_{k,l}(t)=\alpha_{k,l}e^{j\varphi_{k,l}}s(t)+n_{k,l}(t), 0\le t\le T_b \tag{1}$$

where $s(t)$ is the transmitted bit signal with energy E_b and $n_{k,l}(t)$ is the complex Gaussian noise having zero mean and two sided power spectral density $2N_0$. Random variable (RV) $\varphi_{k,l}$ represents the phase, which is uniformly distributed over the range $[0,2\pi]$ and $\alpha_{k,l}$ is the Rayleigh distributed fading amplitude with PDF given by [17].

$$f_{\alpha_{k,l}}(\alpha_{k,l})=\frac{2\alpha_{k,l}}{\Omega_{k,l}}\exp\left(-\frac{\alpha_{k,l}^2}{\Omega_{k,l}}\right), \alpha_{k,l}\ge 0 \tag{2}$$

where $\Omega_{k,l}=E[\alpha_{k,l}^2]$, E is the expectation operator. We assume $\alpha_{k,l}$ is independent of $\varphi_{k,l}$ and $\Omega_{k,l}=\Omega\forall k,l$. The receiving antennas of each user are placed in a linear array, thus they are affected by exponential correlation. The correlation coefficient between i^{th} and j^{th} received fading signals is defined as [17, 18].

$$\rho_{i,j}=\rho^{|i-j|};(i,j=1,2,.,L) \tag{3}$$

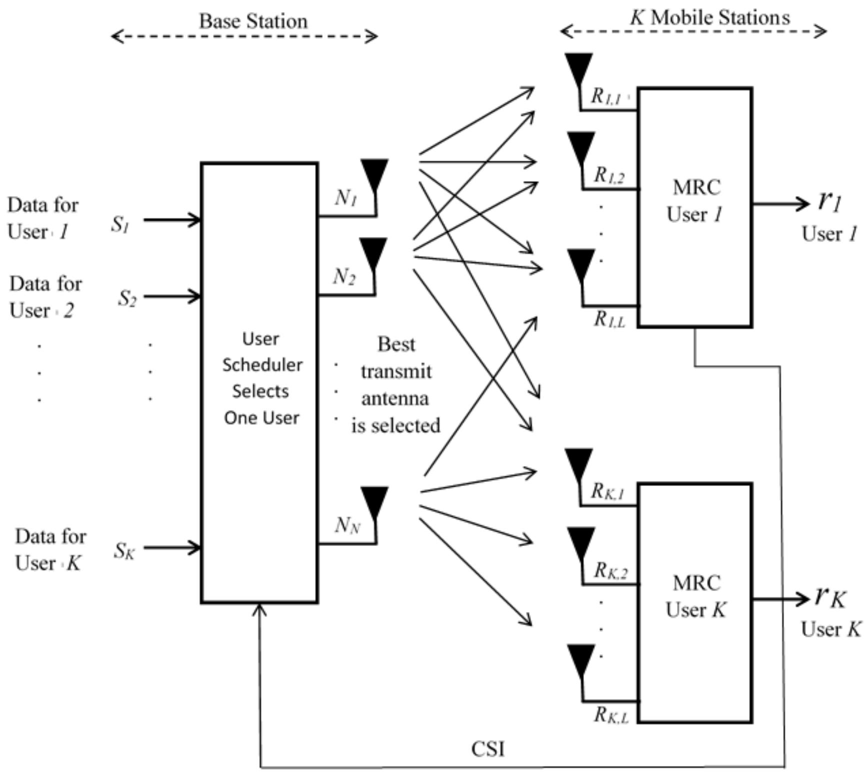

Fig. 1. The TAS/MRC System

In the system, MRC is performed by each user to improve the quality of the downlink information. In the MRC receiver, the received signals are obtained by summing the signal of all branches after performing co-phased and scaling by a component proportional to the branch SNR. The instantaneous output SNR of the MRC receiver is given by [17]

$$\gamma = \sum_{l=1}^{L} \gamma_l \tag{4}$$

where $\gamma_l = \frac{{\alpha_l}^2 E_b}{N_0}$, is the instantaneous SNR of l^{th} branch and L is the total number of diversity branches in the combiner. By using the channel state information (CSI) of each user, the best transmit antennas out of all N transmit candidates, which maximizes the SNR at the MRC output of L receive antennas, are selected to transmit data.

III.PDF OF OUTPUT SNR

From the formula given for the exponentially correlated sum of gamma RVs in [19], sum of the Rayleigh square distribution can be very closely approximated. From which performing RV transformation the PDF of SNR between t^{th} transmitting antenna and k^{th} user can be given as

$$f_{\gamma_{t,k}}\left(\gamma_{t,k}\right) = \frac{1}{\Gamma\left(\frac{L^2}{r}\right)\left(\frac{r\bar{\gamma}}{L}\right)^{\frac{L^2}{r}}} {\gamma_{t,k}}^{\frac{L^2}{r}-1} \exp\left(\frac{-L\gamma_{t,k}}{r\bar{\gamma}}\right) \tag{5}$$

where $r = L + \frac{2\rho}{1-\rho}\left(L - \frac{1-\rho^L}{1-\rho}\right)$ and $\bar{\gamma}$ is the average input SNR in each branch of an MRC receiver. We assume equal average SNR in each branch i.e $\bar{\gamma}_{t,k} = \bar{\gamma}\forall(t,k)$ and ρ is the correlation coefficient among the input branches of MRC receiver. The CDF of the RV $\gamma_{t,k}$ can be given as

$$F_{\gamma_{t,k}}\left(\gamma_{t,k}\right) = \frac{1}{\Gamma\left(\frac{L^2}{r}\right)\left(\frac{r\bar{\gamma}}{L}\right)^{\frac{L^2}{r}}} \int_0^{\gamma_{t,k}} {\gamma_{t,k}}^{\frac{L^2}{r}-1} \exp\left(\frac{-L\gamma_{t,k}}{r\bar{\gamma}}\right) d\gamma_{t,k} \tag{6}$$

Simplifying using [20, (3.381.1)],

$$F_{\gamma_{t,k}}\left(\gamma_{t,k}\right) = \frac{1}{\Gamma\left(\frac{L^2}{r}\right)} g\left(\frac{L^2}{r}, \frac{L\gamma_{t,k}}{r\bar{\gamma}}\right) \tag{7}$$

where $g(a,x) = \int_0^x t^{a-1} e^{-t} dt$ is the lower incomplete gamma function. For N number of transmit antennas and K number of users the total number of communication link will be NK. Each of link will have PDF and CDF as given in (5) and (7) respectively. The joint CDF of all links can be expressed as

$$F_{\gamma_{1,1},\gamma_{1,2},..,\gamma_{N,K}}\left(\gamma_{1,1},\gamma_{1,2},..,\gamma_{N,K}\right) = \prod_{t=1}^{N}\prod_{k=1}^{K} F_{\gamma_{t,k}}\left(\gamma_{t,k}\right) \tag{8}$$

Now in TAS/MRC system best $\gamma_{t,k}$ have been selected from NK number of RV. The CDF of output SNR for a TAS/MRC system can be calculated from the expression of joint CDF (8) by putting $\gamma_{t,k} = \gamma\forall(t,k)$ as

$$F_{\gamma}(\gamma)=\left(\frac{1}{\Gamma\left(\frac{L^2}{r}\right)}g\left(\frac{L^2}{r},\frac{L\gamma}{r\bar{\gamma}}\right)\right)^{NK} \tag{9}$$

Differentiating the expression (9), the PDF of SNR for the TAS/MRC system over Rayleigh Fading Channel can be expressed as:

$$f_{\gamma}(\gamma)=\left(\frac{1}{\Gamma\left(\frac{L^2}{r}\right)}\right)^{NK} NK\left(g\left(\frac{L^2}{r},\frac{L\gamma}{r\bar{\gamma}}\right)\right)^{NK-1}\left(\frac{L}{r\bar{\gamma}}\right)^{\frac{L^2}{r}}\gamma^{\frac{L^2}{r}-1}e^{-\frac{L\gamma}{r\bar{\gamma}}} \tag{10}$$

Writing the lower incomplete gamma function in infinite series from [21, (1.7], the PDF of output SNR for the TAS/MRC system over Rayleigh Fading Channel can be obtained as:

(11)

$$f_{\gamma}(\gamma)=NK\left(\frac{1}{\Gamma\left(\frac{L^2}{r}\right)}\right)^{NK}\sum_{n_1=0}^{\infty}\sum_{n_2=0}^{\infty}\cdots\sum_{n_{NK-1}=0}^{\infty}\frac{\left(\frac{L}{r\bar{\gamma}}\right)^{\frac{NKL^2}{r}+\sum_{i=1}^{NK-1}n_i}}{\prod_{i=1}^{NK-1}\left(\frac{L^2}{r}\right)_{n_i+1}}\gamma^{\left(\frac{NKL^2}{r}+\sum_{i=1}^{NK-1}n_i\right)-1}e^{-\frac{NKL\gamma}{r\bar{\gamma}}} \tag{11}$$

IV. CAPACITY ANALYSIS OF ADAPTIVE TRANSMISSION SCHEMES

The various adaptive transmission schemes are highlighted in [6] and [14] along with the general expression of channels capacities. We have considered the adaptive transmission system to analyze the capacities of the TAS/MRC scheme along with antenna correlation. For finding out the capacity expression the PDF of system SNR (11) has been used and is explained in the following subsections.

4.1 Optimal Power and Rate Adaptation at the Transmitter

This technique is suited for power limiting scenario. With a constraint on the average transmitting power this method adaptively optimizes the transmission rate to enhance the capacity of the system. The analytical expression of capacity with this technique is given as [6]

$$C_{opra}=B\int_{\gamma_0}^{\infty}\log_2\left(\frac{\gamma}{\gamma_0}\right)f_{\gamma}(\gamma)\,d\gamma \tag{12}$$

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

$$\int_{\gamma_0}^{\infty}\left(\frac{1}{\gamma_0}-\frac{1}{\gamma}\right)f_{\gamma}(\gamma)\,d\gamma=1 \tag{13}$$

Putting the expression of (11) into (12) and arranging the integral, the capacity for OPRA scheme can be given as

$$C_{opra} = BNK\left(\frac{1}{\Gamma\left(\frac{L^2}{r}\right)}\right)^{NK} \sum_{n_1=0}^{\infty}\sum_{n_2=0}^{\infty}\cdots\sum_{n_{NK-1}=0}^{\infty} \frac{\left(\frac{L}{r\overline{\gamma}}\right)^{\frac{NKL^2}{r}+\sum_{i=1}^{NK-1} n_i}}{\prod_{i=1}^{NK-1}\left(\frac{L^2}{r}\right)_{n_i+1}} \log_2(e) \times\left(\gamma_0\right)^{\left(\frac{NKL^2}{r}+\sum_{i=1}^{NK-1} n_i\right)} J_{\frac{NKL^2}{r}+\sum_{i=1}^{NK-1} n_i}\left(\frac{NKL\gamma_0}{r\overline{\gamma}}\right) \tag{14}$$

where $(x)_n$ is the Pochhammer's symbol and $J_n(\mu)=\int_1^{\infty} t^{n-1}\ln(t)e^{-\mu t}dt$ for $\mu>0$. For integer n, $J_n(\mu)=\frac{(n-1)!}{\mu^n}\sum_{k=0}^{n-1}\frac{\Gamma(k,\mu)}{k!}$ [13] with $\Gamma(a,x)=\int_x^{\infty} e^{-t}t^{a-1}dt$ is incomplete gamma function. In the expression (14), the optimal cutoff SNR, γ_0 should satisfy (13). Substituting $f_\gamma(\gamma)$ from (11) in (13) and solving the involved integral using [20, (3.381.3)], the expression can be written as

$$\left(\frac{1}{\Gamma\left(\frac{L^2}{r}\right)}\right)^{NK} \sum_{n_1=0}^{\infty}\sum_{n_2=0}^{\infty}\cdots\sum_{n_{NK-1}=0}^{\infty} \frac{\left(NK\right)^{-\left(\frac{NKL^2}{r}+\sum_{i=1}^{NK-1} n_i\right)+1}}{\prod_{i=1}^{NK-1}\left(\frac{L^2}{r}\right)_{n_i+1}} \times\left[\frac{1}{\gamma_0}\Gamma\left(\left(\frac{NKL^2}{r}+\sum_{i=1}^{NK-1} n_i\right),\frac{NKL\gamma_0}{r\overline{\gamma}}\right)-\left(\frac{NKL}{r\overline{\gamma}}\right)\Gamma\left(\left(\frac{NKL^2}{r}+\sum_{i=1}^{NK-1} n_i\right)-1,\frac{NKL\gamma_0}{r\overline{\gamma}}\right)\right]=1 \tag{15}$$

4.2 Constant Transmitting Power

In a scenario when power is sufficient a constant transmitting power can be maintained in the transmitter with variable rate to reduce the complexity of the system. The channel capacity for this technique (bits/sec) can be given as [6].

$$C_{ora} = B\int_0^{\infty}\log_2(1+\gamma)f_\gamma(\gamma)\,d\gamma \tag{16}$$

Substituting (11) into (16) and solving the integral following an approach similar to OPRA scheme, the capacity for constant transmitting power techniques can be obtained as

$$C_{ora} = B\log_2(e)NK\left(\frac{1}{\Gamma\left(\frac{L^2}{r}\right)}\right)^{NK} \sum_{n_1=0}^{\infty}\sum_{n_2=0}^{\infty}\cdots\sum_{n_{NK-1}=0}^{\infty} \frac{\left(\frac{L}{r\overline{\gamma}}\right)^{\frac{NKL^2}{r}+\sum_{i=1}^{NK-1} n_i}}{\prod_{i=1}^{NK-1}\left(\frac{L^2}{r}\right)_{n_i+1}} \times I_{\left(\frac{NKL^2}{r}+\sum_{i=1}^{NK-1} n_i\right)}\left(\frac{NKL}{r\overline{\gamma}}\right) \tag{17}$$

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 $I_n(\mu)=(n-1)!e^{\mu}\sum_{k=1}^{n}\frac{\Gamma(-n+k,\mu)}{\mu^k}$ [13].

4.3 Channel Inversion with Fixed Rate

Channel inversion is a technique in which the received SNR is maintained constant by changing the transmitting power. In channel inversion technique the same rate is maintained as the effect of channel is nullified by inverting the channel effect. The channel capacity formula for this scheme is given as [6]

$$C_{cifr} = B\log_2\left(1+\frac{1}{R_{cifr}}\right) \tag{18}$$

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

The capacity for this scheme requires initially a solution to the integral of R_{cifr} in (18). Putting (11) in the expression of R_{cifr} , the resulting integral can be solved using [20, (3.351.3)] and the final expression after simplification can be given as

$$R_{cifr} = \left(\frac{L}{r\bar{\gamma}}\right)\frac{1}{\left(\Gamma\left(\frac{L^2}{r}\right)\right)^{NK}}\sum_{n_1=0}^{\infty}\sum_{n_2=0}^{\infty}\cdots\sum_{n_{NK-1}=0}^{\infty}\frac{(NK)^{-\left(\frac{NKL^2}{r}+\sum_{i=1}^{NK-1}n_i\right)+2}}{\left\{\prod_{i=1}^{NK-1}\left(\frac{L^2}{r}\right)_{n_i+1}\right\}}\left\{\left(\frac{NKL^2}{r}+\sum_{i=1}^{NK-1}n_i\right)-2\right\}! \tag{19}$$

Thus, the capacity of this scheme can be calculated by substituting (19) into (18).

4.4 Truncated Channel Inversion with Fixed Rate

The major drawback of the channel inversion technique is that in case of worst channel to invert the effect of the channel it requires large amount power which is difficult to realize in real system. To avoid this problem truncated channel inversion with fixed rate (TIFR) is developed which is a modified version of CIFR. In TIFR the transmission is suspended when the received SNR is below a predefined threshold γ_0 . The capacity formula for TIFR can be given by [14]

$$C_{tifr} = B\log_2\left(1+\frac{1}{R_{tifr}}\right)\left[1-P_{out}(\gamma_0)\right] \tag{20}$$

where $R_{tifr} = \int_{\gamma_0}^\infty \left(\frac{1}{\gamma}\right) f_\gamma(\gamma)\, d\gamma$ and in the above (20), $P_{out}(\gamma_0) = \int_0^{\gamma_0} f_\gamma(\gamma) d\gamma$ is the probability of outage for a threshold value γ_0 .

It is observed from the expressions in (12)-(20) that an analysis of the capacity of a system requires an expression for the PDF of the system output SNR i.e. $f_\gamma(\gamma)$. For TAS/MRC diversity systems over exponentially correlated Rayleigh fading channels, we have presented this PDF in (11).

The capacity for this scheme requires a solution to the integral in R_{tifr} and $P_{out}(\gamma_0)$ in (20). Using (11), R_{tifr} can be obtained by solving the resulting integral using [20, (3.351.2)]. The final expression after simplification can be given as

$$\begin{aligned} R_{tifr} &= \left(\frac{L}{r\bar{\gamma}}\right)\frac{1}{\left(\Gamma\left(\frac{L^2}{r}\right)\right)^{NK}}\sum_{n_1=0}^{\infty}\sum_{n_2=0}^{\infty}\cdots\sum_{n_{NK-1}=0}^{\infty}\frac{1}{\left\{\prod_{i=1}^{NK-1}\left(\frac{L^2}{r}\right)_{n_i+1}\right\}} \\ &\times (NK)^{-\left(\frac{NKL^2}{r}+\sum_{i=1}^{NK-1}n_i\right)+2}\,\Gamma\left(\left(\frac{NKL^2}{r}+\sum_{i=1}^{NK-1}n_i\right)-1,\frac{NKL\gamma_0}{r\bar{\gamma}}\right) \end{aligned} \tag{21}$$

An expression for $P_{out}\left(\gamma_0\right)$ can be obtained from (9) by putting $\gamma = \gamma_0$ only. Thus a final expression for the capacity of this scheme can be obtained by placing (21) and $P_{out}\left(\gamma_0\right)$ into (20).

V. NUMERICAL RESULTS AND DISCUSSION

In this section we have discussed the results obtained from the derived expressions for capacity with different power and rate adaptation techniques assuming exponential correlation among received antennas. We consider a TAS/MRC system having a number of transmitting antennas $N = 2$ and the number of users $K = 2$ with different diversity order for the purpose of illustration.

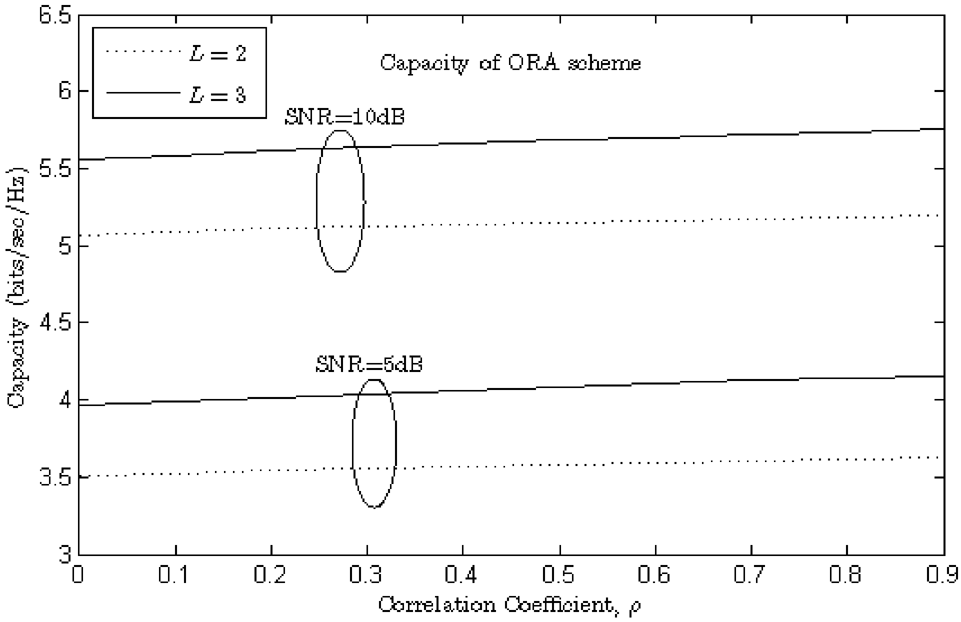

Fig. 2. Capacity of ORA scheme for $N = 2, K = 2$

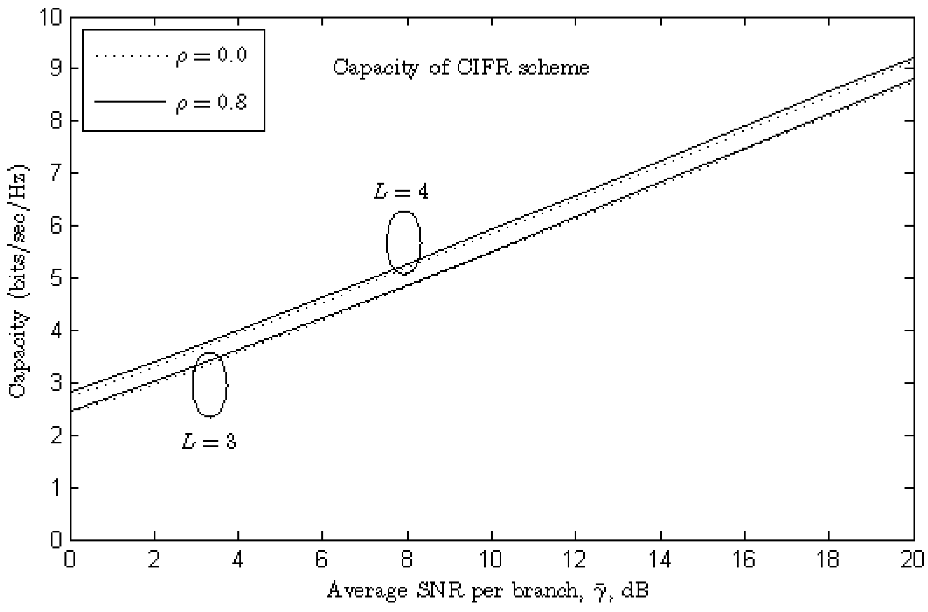

Fig. 3. Capacity of CIFR scheme for $N = 2, K = 2$

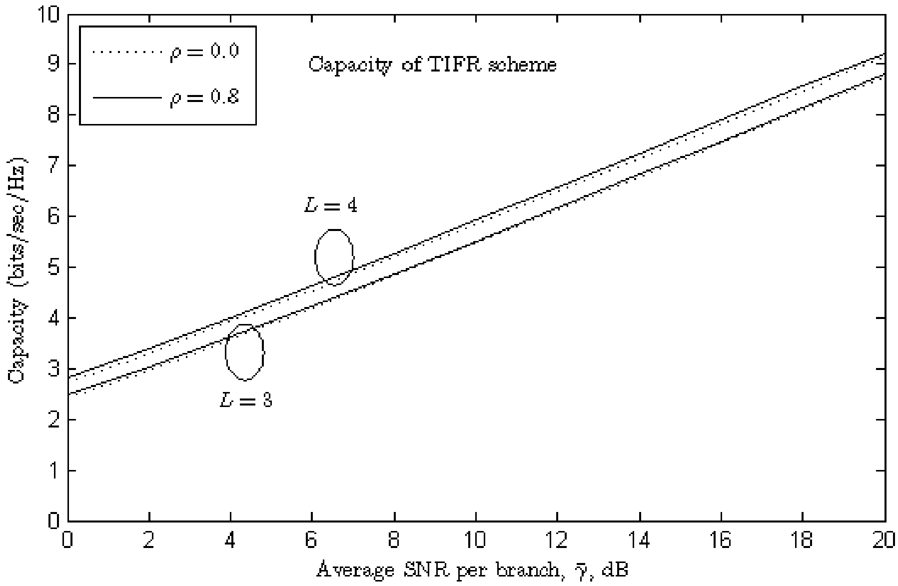

Fig. 4. Capacity of TIFR scheme for $N = 2, K = 2$

Fig. 2 shows the capacity (bits/sec/Hz) vs. correlation coefficient of the ORA scheme for different values of the average SNR per branch. Fig. 3 and 4 present the capacity vs. average SNR per branch in *dB* for CIFR and TIFR schemes respectively. It is seen that the increase in correlation coefficient results in an improvement of the capacity of the channels for all the schemes. This is due to the reason that these formulas give the maximum possible capacities through the channels. Therefore, when all the channels are good (means they are highly correlated) one can expect maximum capacity through the channels. The similar kind of result is also reported in [22]. It can also be observed that the larger the value of diversity order L, the capacity of the system increases considerably for a constant average SNR per branch. For TIFR scheme we have considered the threshold SNR, $\gamma_0 = 2dB$. The observations of CIFR and TIFR schemes are similar.

VI. CONCLUSIONS

In this work we have analyzed the channel capacity of multiuser TAS/MRC wireless systems under Rayleigh fading with exponentially correlated receive antennas. The channel capacity has been analyzed for different adaptive transmission techniques available in the literature. Expressions have been obtained for the capacity of OPRA, ORA, CIFR and TIFR schemes. The obtained expressions are in the form of infinite series and incomplete gamma function. The capacity expressions are numerically evaluated and plotted for different parameters of interest. It has been observed that the channel capacities increases with higher correlation and diversity order.

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