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The Performances of Complex SSC/MRC Combiner in the Presence of Rayleigh Fading

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Abstract

The complex SSC/MRC (Switch and Stay Combining/Maximal Ratio Combining) combiner is considered in this paper. The system in the presence of Rayleigh fading at the input, at two time instants, is observed. Both part of combiners, SSC as well as MRC, are dual-branches. The probability density function (PDF) at the output of the complex combiner is used for the bit error rate (BER), outage probability (P_{out}) and Amount of fading (AF) determination. Binary phase swift keying (BPSK) modulation is applied. Graphically presented results point out the gain of using this complex SSC/MRC combiner compared with classical MRC combiners and one channel receiver at one time instant.

Keywords: Bit error rate, Complex SSC/MRC combiner; Outage probability; Amount of fading; Probability density function; Rayleigh fading; two time instants.

1. Introduction

The phenomenon of the variation of an instantaneous value of the received signal envelope, called fading, is one of the most important factors of degradation of signal quality at the reception. It is due to multipath propagation. Rayleigh fading is a statistical model for the effect of a propagation environment on a radio signal, such as that used by wireless devices. Rayleigh fading models assume that the signal envelope, passed through such communications channel, is random and fade, according to a Rayleigh distribution. Rayleigh fading is viewed as a reasonable model for tropospheric and ionospheric signal propagation as well as the effect of heavily built-up urban environments on radio signals. [1], [2], i.e. when there is many objects in the environment that scatter the radio signal before it arrives at the receiver. Rayleigh fading is applicable when there is no dominant propagation along a line of sight between the transmitter and receiver.

The central limit theorem holds that, if there is sufficiently much scatter, the channel impulse response will be well-modeled as a Gaussian process irrespective of the distribution of the individual components. If there is no dominant component to the scatter, then such a process will have zero mean and phase evenly distributed between 0 and 2π radians. The envelope of the channel response will therefore be Rayleigh distributed.

There are several ways to reduce the impact of fading on system performances. The goal is to achieve this without increasing the signal power and channel capacity. The diversity combining technique is one of the best ways to do this. In this way the multiple copies of the same signal are sending. They are combined in different ways in order to obtain as larger as possible signal to noise ratio.

Maximal-Ratio Combining (MRC) is one of the most widely used diversity combining schemes [3], [4]. Maximal-ratio combining is a method of diversity combining in which: the signals from each channel are added together, the gain of each channel is made proportional to the root mean square signal level and inversely proportional to the mean square noise level in that channel and different proportionality constants are used for each channel. It is also known as ratio-squared combining and predetection combining. Maximal-ratio-combining is the optimum combiner for independent AWGN (additive white Gaussian noise) channels.

Since MRC requires cognition of all fading parameters of the channel, it has the highest cost and complexity. The next by performances is Equal Gain Combining (EGC) and then

Selection Combining (SC) and Switch and Stay Combining (SSC) with lower performance, but with simpler way to implement. Since the SC and SSC combining schemes do not require signal cophasing and fading envelope estimation, they are very often implemented in practice.

SSC is an attempt at simplifying the complexity of the system but with loss in performance. In this case, rather than continually connecting the antenna with the best fading conditions, the receiver selects a particular antenna until its quality drops below a predetermined threshold. When this happens, the receiver switches to another antenna and stays with it for the next time slot, regardless of whether or not the channel quality of that antenna is above or below the predetermined threshold. The consideration of SSC systems in the literature has been restricted to low-complexity mobile units where the number of diversity antennas is typically limited to two [5]-[7]. The switching of the receiver between the two receiving antennas is based on a comparison of the instantaneous SNR of the connected antenna with a predetermined threshold. This results in a reduction in complexity relative to SC in that the simultaneous and continuous monitoring of both branches SNRs is no longer necessary.

By the authors' knowledge in the new open literature, except from papers of this group of authors, there are no papers that treat these problems by sampling in the two time moments. But, these authors are derived the expression for the joint probability density function of the SSC combiner output signal in the presence of log-normal fading in two time instants in [6] and based on it they are made the performance analysis of SSC/SC combiner at two time instants in the presence of log-normal fading in [8]. The outage probability of the SSC/SC combiner at two time instants in the presence of Rayleigh fading is calculated in [9]. The bit error rates for SSC/MRC combiner at two time instants in the presence of log-normal and Hoyt fading are determined in [10] and [11], respectively.

In this paper the probability density function, the outage probability, the amount of fading and the bit error rate of the SSC/MRC combiner output signal at two time instants in the presence of Rayleigh fading will be determined.

This paper is organized as follows: the next, II Section, describes the system model and the probability density function, the outage probability, the amount of fading and the bit error rate of the SSC/MRC combiner output signal at two time instants are determined. Sections III presents numerical results obtained for performances introduced in Section II. Finally, the main results of the paper are presented in IV Section as conclusions.

2. System Model

The complex SSC/MRC combiner, considering in this paper, is presented in Fig. 1. The complex combiner is with two inputs, at two time instants. The SSC combiner output signals are the input signals for MRC combiner.

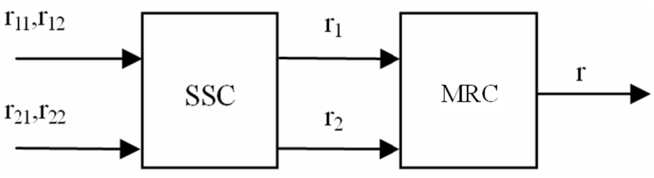

Figure 1. Model of complex dual SSC/MRC combiner

At the inputs of the first part of complex combiner the signals are r_{11} and r_{21} at first time moment and they are r_{12} and r_{22} at second time moment. The output signals from SSC part of complex combiner are r_1 and r_2. The first index represents the branch ordinal number and the other one signs the time instant observed. The indices at the output signal correspond to the time instants considered. The SSC combiner output signals r_1 and r_2, are the inputs for the MRC combiner. Finally, the overall output signal is r.

The joint probability density function of correlated signals r_1 and r_2 at the SSC combiner output, at two time instants, lognormal distributed and with same scale parameter σ_i, was designated in the closed form expression in [10, eq. (10)-(13)].

The outputs of SSC combiner are used as inputs for MRC combiner. The PDF at the output of SSC/MRC combiner with two branches is given by [11]:

$$p_r(r) = \int_0^r p_{r_1 r_2}(r_1, r - r_1) dr_1 \tag{1}$$

Substituting [10, eq. (10)] in (1), partials $p_i(r)$ for the signal at the output of SSC/MRC combiner can be obtained as:

For $r_1 < r_T, r - r_1 < r_T$:

$$\begin{aligned} p_1(r) = \int_0^r dr_1 \Bigg[& P_1 \frac{1}{\sqrt{2\pi}\sigma_1 (r - r_1)} e^{-\frac{(\ln(r - r_1) - \mu_1)^2}{2\sigma_1^2}} \left(\frac{1}{2} + erf\left(\frac{\ln r_t - (\mu_1 + \rho(\ln(r - r_1) - \mu_1))}{\sigma_1 \sqrt{1 - \rho^2}\sqrt{2}} \right) \right) \cdot \\ & \cdot \frac{1}{\sqrt{2\pi}\sigma_2 r_1} e^{-\frac{(\ln r_1 - \mu_2)^2}{2\sigma_2^2}} \left(\frac{1}{2} + erf\left(\frac{\ln r_t - (\mu_2 + \rho(\ln r_1 - \mu_2))}{\sigma_2 \sqrt{1 - \rho^2}\sqrt{2}} \right) \right) + \\ & + P_2 \frac{1}{\sqrt{2\pi}\sigma_2 (r - r_1)} e^{-\frac{(\ln(r - r_1) - \mu_2)^2}{2\sigma_2^2}} \left(\frac{1}{2} + erf\left(\frac{\ln r_t - (\mu_2 + \rho(\ln(r - r_1) - \mu_2))}{\sigma_2 \sqrt{1 - \rho^2}\sqrt{2}} \right) \right) \frac{1}{\sqrt{2\pi}\sigma_1 r_1} e^{-\frac{(\ln r_1 - \mu_1)^2}{2\sigma_1^2}} \left(\frac{1}{2} + erf\left(\frac{\ln r_t - (\mu_1 + \rho(\ln r_1 - \mu_1))}{\sigma_1 \sqrt{1 - \rho^2}\sqrt{2}} \right) \right) \Bigg] \end{aligned} \tag{2}$$

For $r_1 \geq r_T, r - r_1 < r_T$

$$\begin{aligned} p_2(r) = \int_{r_t}^r dr_1 \Bigg[& P_1 \frac{1}{\sqrt{2\pi}\sigma_2 (r - r_1)} e^{-\frac{(\ln(r - r_1) - \mu_2)^2}{2\sigma_2^2}} \frac{1}{\sqrt{2\pi}\sigma_1 r_1} e^{-\frac{(\ln r_1 - \mu_1)^2}{2\sigma_1^2}} \left(\frac{1}{2} + erf\left(\frac{\ln r_t - (\mu_1 + \rho(\ln r_1 - \mu_1))}{\sigma_1 \sqrt{1 - \rho^2}\sqrt{2}} \right) \right) + \\ & + P_1 \frac{1}{\sqrt{2\pi}\sigma_1 (r - r_1)} e^{-\frac{(\ln(r - r_1) - \mu_1)^2}{2\sigma_1^2}} \left(\frac{1}{2} + erf\left(\frac{\ln r_t - (\mu_1 + \rho(\ln(r - r_1) - \mu_1))}{\sigma_1 \sqrt{1 - \rho^2}\sqrt{2}} \right) \right) \cdot \end{aligned}$$

$$\cdot \frac{1}{\sqrt{2\pi}\sigma_2 r_1} e^{-\frac{(\ln r_1-\mu_2)^2}{2\sigma_2^2}} \left(\frac{1}{2}+erf\left(\frac{\ln r_t-(\mu_2+\rho(\ln r_1-\mu_2))}{\sigma_2\sqrt{1-\rho^2}\sqrt{2}}\right)\right)+\cdot$$

$$+P_2 \frac{1}{\sqrt{2\pi}\sigma_1(r-r_1)} e^{-\frac{(\ln(r-r_1)-\mu_1)^2}{2\sigma_1^2}} \frac{1}{\sqrt{2\pi}\sigma_2 r_1} e^{-\frac{(\ln r_1-\mu_2)^2}{2\sigma_2^2}} \left(\frac{1}{2}+erf\left(\frac{\ln r_t-(\mu_2+\rho(\ln r_1-\mu_2))}{\sigma_2\sqrt{1-\rho^2}\sqrt{2}}\right)\right)+$$

$$\left.+P_2 \frac{1}{\sqrt{2\pi}\sigma_2(r-r_1)} e^{-\frac{(\ln(r-r_1)-\mu_2)^2}{2\sigma_2^2}} \left(\frac{1}{2}+erf\left(\frac{\ln r_t-(\mu_2+\rho(\ln(r-r_1)-\mu_2))}{\sigma_2\sqrt{1-\rho^2}\sqrt{2}}\right)\right) \frac{1}{\sqrt{2\pi}\sigma_1 r_1} e^{-\frac{(\ln r_1-\mu_1)^2}{2\sigma_1^2}} \left(\frac{1}{2}+erf\left(\frac{\ln r_t-(\mu_1+\rho(\ln r_1-\mu_1))}{\sigma_1\sqrt{1-\rho^2}\sqrt{2}}\right)\right)\right] \tag{3}$$

For $r_1 < r_T, r-r_1 \geq r_T$:

$$p_3(r)=\int_0^{r_t} dr_1 \left[P_1\left(\frac{1}{2}+erf\left(\frac{\ln r_t-\mu_1}{\sigma_1\sqrt{2}}\right)\right) \frac{1}{2\pi\sigma_2^2\sqrt{1-\rho^2}\, r_1(r-r_1)} e^{-\frac{1}{2(1-\rho^2)}\left[\left(\frac{\ln r_1-\mu_2}{\sigma_2}\right)^2+\left(\frac{\ln(r-r_1)-\mu_2}{\sigma_2}\right)^2-2\rho\left(\frac{\ln r_1-\mu_2}{\sigma_2}\right)\left(\frac{\ln(r-r_1)-\mu_2}{\sigma_2}\right)\right]}+\right.$$

$$+P_1 \frac{1}{\sqrt{2\pi}\sigma_1(r-r_1)} e^{-\frac{(\ln(r-r_1)-\mu_1)^2}{2\sigma_1^2}} \left(\frac{1}{2}+erf\left(\frac{\ln r_t-(\mu_1+\rho(\ln(r-r_1)-\mu_1))}{\sigma_1\sqrt{1-\rho^2}\sqrt{2}}\right)\right)\cdot$$

$$\cdot \frac{1}{\sqrt{2\pi}\sigma_2 r_1} e^{-\frac{(\ln r_1-\mu_2)^2}{2\sigma_2^2}} \left(\frac{1}{2}+erf\left(\frac{\ln r_t-(\mu_2+\rho(\ln r_1-\mu_2))}{\sigma_2\sqrt{1-\rho^2}\sqrt{2}}\right)\right)+$$

$$+P_2\left(\frac{1}{2}+erf\left(\frac{\ln r_t-\mu_2}{\sigma_2\sqrt{2}}\right)\right) \frac{1}{2\pi\sigma_1^2\sqrt{1-\rho^2}\, r_1(r-r_1)} e^{-\frac{1}{2(1-\rho^2)}\left[\left(\frac{\ln r_1-\mu_1}{\sigma_1}\right)^2+\left(\frac{\ln(r-r_1)-\mu_1}{\sigma_1}\right)^2-2\rho\left(\frac{\ln r_1-\mu_1}{\sigma_1}\right)\left(\frac{\ln(r-r_1)-\mu_1}{\sigma_1}\right)\right]}+$$

$$\left.+P_2 \frac{1}{\sqrt{2\pi}\sigma_2(r-r_1)} e^{-\frac{(\ln(r-r_1)-\mu_2)^2}{2\sigma_2^2}} \left(\frac{1}{2}+erf\left(\frac{\ln r_t-(\mu_2+\rho(\ln(r-r_1)-\mu_2))}{\sigma_2\sqrt{1-\rho^2}\sqrt{2}}\right)\right) \frac{1}{\sqrt{2\pi}\sigma_1 r_1} e^{-\frac{(\ln r_1-\mu_1)^2}{2\sigma_1^2}} \left(\frac{1}{2}+erf\left(\frac{\ln r_t-(\mu_1+\rho(\ln r_1-\mu_1))}{\sigma_1\sqrt{1-\rho^2}\sqrt{2}}\right)\right)\right] \tag{4}$$

For $r_1 \geq r_T, r-r_1 \geq r_T$

$$p_4(r)=\int_0^{r_t} dr_1 \left[P_1 \cdot \frac{1}{2\pi\sigma_2^2\sqrt{1-\rho^2}\, r_1(r-r_1)} \frac{1}{2\pi\sigma_2^2\sqrt{1-\rho^2}\, r_1(r-r_1)} e^{-\frac{1}{2(1-\rho^2)}\left[\left(\frac{\ln r_1-\mu_2}{\sigma_2}\right)^2+\left(\frac{\ln(r-r_1)-\mu_2}{\sigma_2}\right)^2-2\rho\left(\frac{\ln r_1-\mu_2}{\sigma_2}\right)\left(\frac{\ln(r-r_1)-\mu_2}{\sigma_2}\right)\right]}+\right.$$

$$+P_1 \frac{1}{\sqrt{2\pi}\sigma_2(r-r_1)} e^{-\frac{(\ln(r-r_1)-\mu_2)^2}{2\sigma_2^2}} \frac{1}{\sqrt{2\pi}\sigma_1 r_1} e^{-\frac{(\ln r_1-\mu_1)^2}{2\sigma_1^2}} \left(\frac{1}{2}+erf\left(\frac{\ln r_t-(\mu_1+\rho(\ln r_1-\mu_1))}{\sigma_1\sqrt{1-\rho^2}\sqrt{2}}\right)\right)+$$

$$+P_1\left(\frac{1}{2}+erf\left(\frac{\ln r_t-\mu_1}{\sigma_1\sqrt{2}}\right)\right) \frac{1}{2\pi\sigma_2^2\sqrt{1-\rho^2}\, r_1(r-r_1)} e^{-\frac{1}{2(1-\rho^2)}\left[\left(\frac{\ln r_1-\mu_2}{\sigma_2}\right)^2+\left(\frac{\ln(r-r_1)-\mu_2}{\sigma_2}\right)^2-2\rho\left(\frac{\ln r_1-\mu_2}{\sigma_2}\right)\left(\frac{\ln(r-r_1)-\mu_2}{\sigma_2}\right)\right]}+$$

$$+P_1 \frac{1}{\sqrt{2\pi}\sigma_1(r-r_1)} e^{-\frac{(\ln(r-r_1)-\mu_1)^2}{2\sigma_1^2}} \left(\frac{1}{2}+erf\left(\frac{\ln r_t-(\mu_1+\rho(\ln(r-r_1)-\mu_1))}{\sigma_1\sqrt{1-\rho^2}\sqrt{2}}\right)\right)\cdot$$

$$\cdot \frac{1}{\sqrt{2\pi}\sigma_2 r_1} e^{-\frac{(\ln r_1-\mu_2)^2}{2\sigma_2^2}} \left(\frac{1}{2}+erf\left(\frac{\ln r_t-(\mu_2+\rho(\ln r_1-\mu_2))}{\sigma_2\sqrt{1-\rho^2}\sqrt{2}}\right)\right)+$$

Network Protocols and Algorithms
ISSN 1943-3581
2012, Vol. 4, No. 3

$$+P_2 \frac{1}{2\pi\sigma_2{}^2\sqrt{1-\rho^2}\,r_1(r-r_1)} e^{-\frac{1}{2(1-\rho^2)}\left[\left(\frac{\ln r_1-\mu_2}{\sigma_2}\right)^2+\left(\frac{\ln(r-r_1)-\mu_2}{\sigma_2}\right)^2-2\rho\left(\frac{\ln r_1-\mu_2}{\sigma_2}\right)\left(\frac{\ln(r-r_1)-\mu_2}{\sigma_2}\right)\right]}+$$

$$+P_2 \frac{1}{\sqrt{2\pi}\sigma_1(r-r_1)} e^{-\frac{(\ln(r-r_1)-\mu_1)^2}{2\sigma_1^2}} \frac{1}{\sqrt{2\pi}\sigma_2 r_1} e^{-\frac{(\ln r_1-\mu_2)^2}{2\sigma_2^2}} \left(\frac{1}{2}+erf\left(\frac{\ln r_t-(\mu_2+\rho(\ln r_1-\mu_2))}{\sigma_2\sqrt{1-\rho^2}\sqrt{2}}\right)\right)+$$

$$+P_2\left(\frac{1}{2}+erf\left(\frac{\ln r_t-\mu_2}{\sigma_2\sqrt{2}}\right)\right)\frac{1}{2\pi\sigma_1{}^2\sqrt{1-\rho^2}\,r_1(r-r_1)} e^{-\frac{1}{2(1-\rho^2)}\left[\left(\frac{\ln r_1-\mu_1}{\sigma_1}\right)^2+\left(\frac{\ln(r-r_1)-\mu_1}{\sigma_1}\right)^2-2\rho\left(\frac{\ln r_1-\mu_1}{\sigma_1}\right)\left(\frac{\ln(r-r_1)-\mu_1}{\sigma_1}\right)\right]}+$$

$$+P_2 \frac{1}{\sqrt{2\pi}\sigma_2(r-r_1)} e^{-\frac{(\ln(r-r_1)-\mu_2)^2}{2\sigma_2^2}} \left(\frac{1}{2}+erf\left(\frac{\ln r_t-(\mu_2+\rho(\ln(r-r_1)-\mu_2))}{\sigma_2\sqrt{1-\rho^2}\sqrt{2}}\right)\right)\frac{1}{\sqrt{2\pi}\sigma_1 r_1} e^{-\frac{(\ln r_1-\mu_1)^2}{2\sigma_1^2}} \left(\frac{1}{2}+erf\left(\frac{\ln r_t-(\mu_1+\rho(\ln r_1-\mu_1))}{\sigma_1\sqrt{1-\rho^2}\sqrt{2}}\right)\right)\Bigg] \tag{5}$$

The PDF at the output of MRC/SSC combiner is the sum of components $p_i(r)$:

$$p_r(r) = p_1(r) + p_1(r) + p_1(r) + p_1(r) \tag{6}$$

Relatively simple closed form expressions to represent $p_r(r)$ can not be derived, because Eq. (2) – (5) are too complex for tractable communication system analyses, but the PDF can be evaluated numerically using software tools.

The outage probability is very useful performance measure for diversity systems operating in fading environments defined as the probability that output signal value of the combiner falls below a given threshold r_{th} also known as a protection ratio. The outage probability $P_{out}(r_{th})$ is defined as [12]:

$$P_{out}(r_{th}) = \int_0^{r_{th}} p_r(r)dr \tag{7}$$

Substituting Eq. (6) in Eq. (7), $P_{out}(r_{th})$ can be written as:

$$P_{out}(r_{th}) = \int_0^{r_{th}} [p_1(r) + p_2(r) + p_3(r) + p_4(r)]dr \tag{8}$$

Amount of fading (AF) is a unified measure of the severity of fading for particular channel model and is typically independent of the average fading power, but is dependent of the instantaneous SNR. Amount of fading for MRC combiner is defined by [12]:

$$AF = \frac{E[r^2]}{(E[r])^2} - 1 = \frac{E[(r_1+r_2)^2]}{(E[(r_1+r_2)])^2} - 1 \tag{9}$$

where $E(r)$ is N-th moment of r, and using Eqs. (2) – (5), AF is finally:

$$AF = \frac{\int_0^\infty [p_1(r) + p_2(r) + p_3(r) + p_4(r)] r^2 dr}{\left(\int_0^\infty [p_1(r) + p_2(r) + p_3(r) + p_4(r)] r dr\right)^2} - 1 \tag{10}$$

3. Numerical Results

The combining techniques like SSC and MRC are simple and frequently used for signals combining in diversity the bit error rate curves, for different types of combiners and correlation parameters, are presented in Figs. 2 and 3. It is assumed that both branches at the input have the same channel parameters and r_t is the optimal decision threshold [12]:

$$r_t = \sigma \sqrt{\frac{\pi}{2}} \tag{11}$$

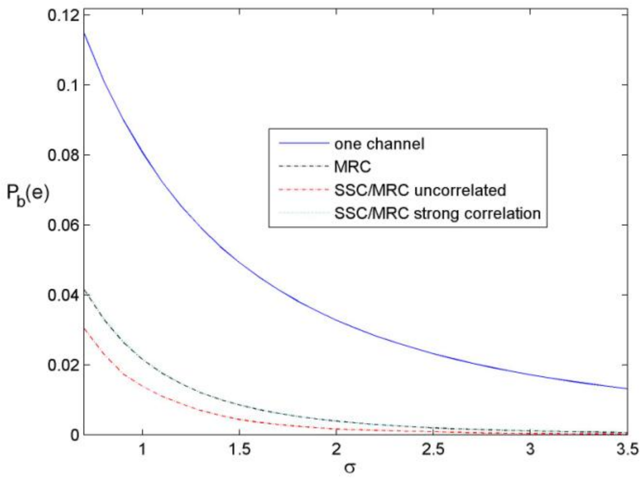

Figure 2. The bit error rate for different types of combiners versus parameter σ

The BER family of curves for one channel receiver, for MRC combiner at one time instant and for complex SSC/MRC combiner at two time instants, for uncorrelated case and for very strong correlation is shown in Fig. 2. The influence of correlation to the bit error rate of the complex SSC/MRC combiner, versus distribution parameter σ is presented in Fig. 3.

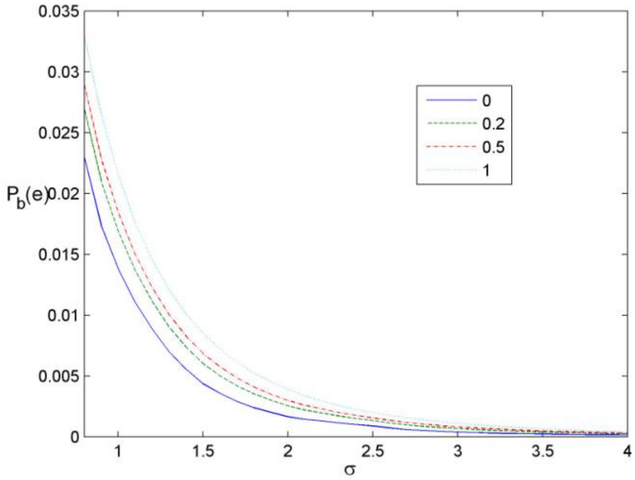

Figure 3. The bit error rate for complex SSC/MRC combiner versus parameter σ for different values of ρ

One can conclude from these figures that complex SSC/MRC combiner has better performances for uncorrelated case then MRC combiner at one time instant. For the value of correlation coefficient ρ = 1, the BER of complex SSC/MRC combiner follows the results for MRC combiner. It is evident that usage of this complex SSC/MRC combiner gives better performance in the entire range, except in the case of strongly correlated signals. In this occasion it is not economic to use complex combiner. Thus, the advantages of utilization such type of complex combiner increases with decreasing of correlation between input signals.

The family of curves for the outage probabilities and for amount of fading for one channel receiver and for MSC combiner at one time instant and SSC/MRC combiner at two time instants for uncorrelated case and for very strong correlation is shown in Fig. 4. We can see that SSC/MRC combiner has significant better performances for both, uncorrelated case and for ρ=1 regarding classical MRC combiner at one time instant and one single channel receiver.

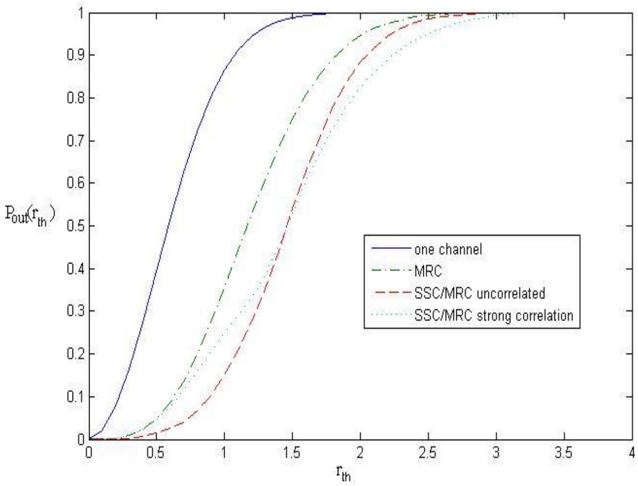

Figure 4. Outage probability for different types of combiners for parameters σ=0.5, ρ=0.1

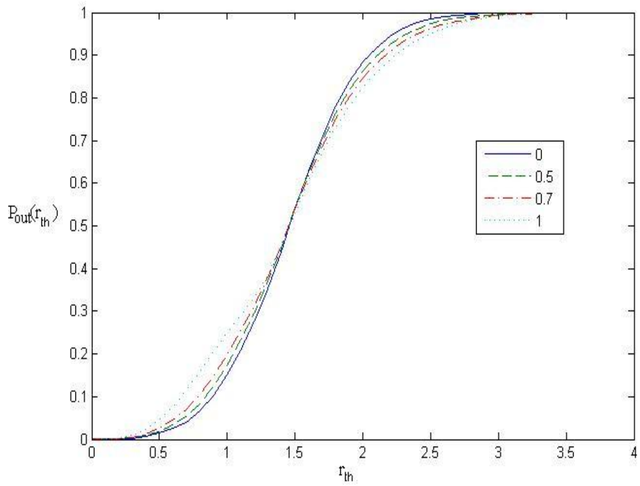

Figure 5. Outage probability for SSC/MRC combiner for parameters σ=0.5, for different values of ρ

It can be seen from Fig. 5 that SSC/MRC combiner has better performances for small value of r_{th} for uncorrelated signals and for large values of outage probability. This value increases with decreasing of the correlation.

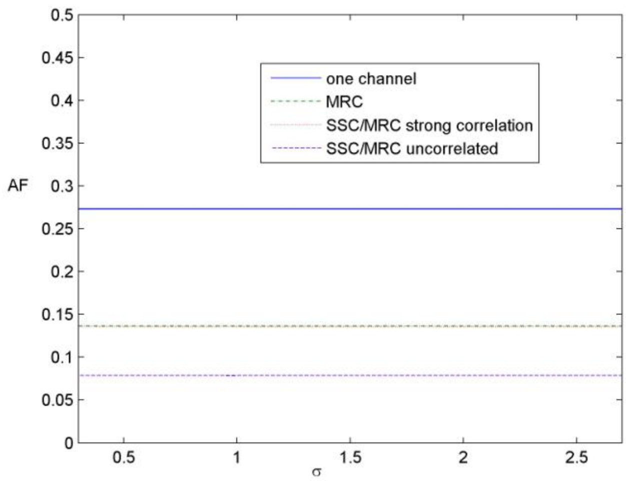

Figure 6. Amount of fading for different types of combiners

From Fig. 6 it can be seen once again that complex SSC/MRC combiner has better performances for uncorrelated case then MRC combiner at one time instant. For strong correlation, when the correlation coefficient ρ is equal to 1, the Amount of fading of complex SSC/MRC combiner follows the results for MRC combiner. It is evident that this complex SSC/MRC combiner has better performance in the whole range, except in the case of strongly correlated signals. Thus, the utility of this complex SSC/MRC combiner increases with decreasing of correlation between input signals.

4. Conclusion

The combining techniques like SSC and MRC are simple and frequently used for signals combining in diversity systems for reducing fading effects. The probability density function of the complex dual SSC/MRC combiner output signal at two time instants, in the presence of Rayleigh fading, is determined in this paper. Bit error probability, outage probability, and amount of fading are calculated based on this PDF and obtained results are presented graphically in some figures. This means improvement characteristics of complex SSC/MRC combiner at two time instants comparing with classical SSC and MRC combiners. Also, it is obvious that using of this complex SSC/MRC combiner is not economical in the case of strongly correlated signals because it does not give better BER and AF than MRC combiner.

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