Second Order Statistics of SSC/SC Combiner Operating Over Rician Fading Channel

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***Abstract*—The second order statistics, such as average level crossing rate (LCR) and average fade duration (AFD), for dual branch SSC/SC combiner output signals in the presence of Rician fading, are determined in this paper by using earlier obtained closed-form expressions for probability density functions (PDFs) of derivatives at two time instants. The results are graphically presented in some figures versus some parameters values. The analysis of the parameters influence and different types of combiners is given.**

Keywords- Average Fade Duration, Level Crossing Rate, Probability Density Function, Rician Fading, Selection Combining, Switch and Stay Combining, Time Derivative.

I. INTRODUCTION

The fading is one of the most important causes of system performance degradation in wireless communication systems. The communication systems are subjected to fading which is caused by multipath propagation due to reflection, refraction and scattering by buildings, trees and other large structures. After that received signal represents a sum of many signals that arrive via different propagation paths.

Some statistical models are used in the literature to describe the fading envelope of the received signal. These distributions are: Rayleigh, Rician, Nakagami, Weibull, Hoyt, and others. They are used to characterize the envelope of faded signals over small geographical area, or short term fading. The log-normal and gamma distribution are used for describing long term fading, when much wider geographical area is involved.

The performance analysis of complex SSC/MRC combiner in Rice fading channel is given in [1]. This paper presents an extended analysis of the second order statistics, such as average level crossing rate (LCR) and average fade duration (AFD), for dual branch SSC/SC combiner output signals in the presence of Rician fading, based on closed-form expressions for probability density functions (PDFs) of derivatives at two time instants obtained in [2].

Ricean fading is a stochastic model for radio propagation irregularity caused by partial cancellation of a radio signal, i.e., the signal arrives at the receiver by several different paths and at least one of them is lengthened or shorted [3]. Rician fading occurs when one of the paths, typically a line of sight signal, is much stronger than the others. In Rician fading, the amplitude gain is characterized by a Rician distribution [4], [5]. Rayleigh fading is the specialized model for stochastic fading when there is no line of sight signal, and it is considered as a special case of the more generalized concept of Rician fading. In Rayleigh fading, the amplitude is described by a Rayleigh distribution.

There are several ways to reduce fading influence on system performances without increasing the signal power and channel bandwidth. The diversity reception techniques are used extensively in fading radio channels to reduce the fading influence on system performances [5]. Various diversity combining techniques are used.

Selection combining (SC), where the strongest signal is selected between the *N* received signals [6]. When the *N* signals are independent and Rayleigh distributed, the expected diversity gain has been shown to be inversely proportional to the number of antennas [7, 8].

Switched combining: In the case of dual branch SSC, the first branch stay selected as long as its current value of signal-to-noise ratio (SNR) is greater than predetermined switching threshold, even if the SNR value in the second branch maybe is largerer at that time [3]. The receiver switches to another signal when the currently selected signal drops below a predefined threshold [9]. This is a less efficient technique than selection combining.

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. Performance analysis of SSC diversity receiver over correlated Ricean fading channels in the presence of co-channel interference is carried out in [10].

Equal-gain combining (EGC): All the received signals are summed coherently [11].

Maximal-ratio combining (MRC) is often used in large phased-array systems. The received signals are weighted with respect to their SNR and then summed [12]. This is the best and most complicated combining scheme.

In this paper, the probability density functions (PDFs) of derivatives at two time instants for dual branch Switch and Stay (SSC) combiner output signals in the presence of Rician fading in closed-form expressions are presented and used for calculating the second order statistics of SSC/SC combiner. The results are shown in some graphs versus different parameters values. An analysis of the results is provided also. To the best author knowledge the performance of SSC/SC combiner is not reported in open technical literature by other authors.

The remainder of the document is organized as follows: in Section II related works are mentioned; Section III introduces the model of the SSC combiner; the probability density functions of derivatives are presented and graphically shown in Section IV. In Section V, the model of complex SSC/SC combiner is given and statistics for this combiner is calculated. In the last section, some conclusions are presented.

II. Related Works

The probability density functions (PDFs) of derivatives for Switch and Stay Combiner (SSC) output signals at two time instants in the presence of Rician fading are determined in [2]. Now, in this paper, the second-order characteristics will be determined using these PDFs.

The probability density functions and joint probability density functions for SSC combiner output signals at two time instants in the presence of different fading distributions are determined by these authors. Then, they are used for calculating first order system performances, such as the bit error rate and the outage probability, for complex systems sampling at two time instants. Performance analysis of SSC/SC combiner in the presence of Rayleigh fading is given in [13]. The outage probability analysis of the SSC/SC combiner at two time instants in the presence of lognormal fading is done in [14]. The PDF of the combiner output signal is derived. Then, the outage probability is numerically calculated using this PDF. The results are shown graphically in order to compare performances of the SSC/SC combiner with regard to classical SSC and SC combiners sampling at one time instant.

This work is motivated by the desire to obtain better system performance, in the presence of Rician fading, with complex combiner consisting of two cheaper and simpler diversity systems (SSC and SC) against MRC diversity combining scheme witch is much more expensive.

III. System Model of SSC combiner

The SSC combiner with two branches at two time instants is discussed in this section. The model is shown in Fig. 1.

The input signals, at the first time moment, are r_{11} and r_{21} and they are r_{12} and r_{22} at the second time instant. The derivatives are $\dot{r}_{11}$ and $\dot{r}_{21}$ at the first time instant and $\dot{r}_{12}$ and $\dot{r}_{22}$ at the second one.

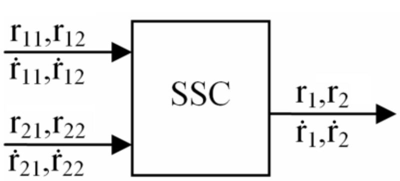

Figure 1. Model of the SSC combiner with two inputs at two time instants

The signals at the output are r_1 and r_2. The derivatives of the SSC combiner output signals are $\dot{r}_1$ and $\dot{r}_2$.

The indices for input signals and their derivatives are as follows: the first index represents the branch ordinal number and the other one signs the time instant observed. The indices for the output signal correspond to the time instants observed.

The probability that combiner examines first the signal from the first branch is P_1 and P_2 for the second one. The values of P_1 and P_2 for SSC combiner are obtained in [3].

The four different cases are discussed here, according to the working algorithm of SSC combiner:

1) $r_1<r_T$, $r_2<r_T$

In this case all signals are less then threshold r_T, i.e.: $r_{11}<r_T$, $r_{12}<r_T$, $r_{21}<r_T$, and $r_{22}<r_T$. Let combiner considers first the signal r_{11}. Because $r_{11}<r_T$, then $\dot{r}_1=\dot{r}_{21}$, and because of $r_{22}<r_T$, then $\dot{r}_2=\dot{r}_{12}$. The probability of this event is P_1. If combiner examines first the signal r_{21}, then $r_{21}<r_T$, $\dot{r}_1=\dot{r}_{11}$, as $r_{21}<r_T$, $\dot{r}_2=\dot{r}_{22}$. The probability of this event is P_2.

2) $r_1\ge r_T$, $r_2<r_T$

In this case first of the signals is greater than the threshold r_T, but the other is less. The possible combinations related to the probability of the first examination of first or second input are:

- $r_{11}\ge r_T$, $r_{12}<r_T$, $r_{22}<r_T$, $\dot{r}_1=\dot{r}_{11}$ $\dot{r}_2=\dot{r}_{22}$ P_1
- $r_{11}<r_T$, $r_{21}\ge r_T$ $r_{22}<r_T$, $r_{12}<r_T$, $\dot{r}_1=\dot{r}_{21}$ $\dot{r}_2=\dot{r}_{12}$ P_1
- $r_{21}\ge r_T$, $r_{22}<r_T$, $r_{12}<r_T$, $\dot{r}_1=\dot{r}_{21}$ $\dot{r}_2=\dot{r}_{12}$ P_2
- $r_{21}<r_T$, $r_{11}\ge r_T$, $r_{12}<r_T$, $r_{22}<r_T$, $\dot{r}_1=\dot{r}_{11}$ $\dot{r}_2=\dot{r}_{22}$ P_2

3) $r_1<r_T$, $r_2\ge r_T$

In this case first of the signals is less then threshold r_T, but the other is bigger. The possible combinations for this case tied with probabilities of order of inputs' consideration are:

- $r_{11}<r_T$, $r_{21}<r_T$, $r_{22}\ge r_T$, $\dot{r}_1=\dot{r}_{21}$ $\dot{r}_2=\dot{r}_{22}$ P_1
- $r_{11}<r_T$, $r_{21}<r_T$, $r_{22}<r_T$, $r_{12}\ge r_T$, $\dot{r}_1=\dot{r}_{21}$ $\dot{r}_2=\dot{r}_{12}$ P_1
- $r_{21}<r_T$, $r_{11}<r_T$, $r_{12}\ge r_T$, $\dot{r}_1=\dot{r}_{11}$ $\dot{r}_2=\dot{r}_{12}$ P_2
- $r_{21}<r_T$, $r_{11}<r_T$, $r_{12}<r_T$, $r_{22}\ge r_T$, $\dot{r}_1=\dot{r}_{11}$ $\dot{r}_2=\dot{r}_{22}$ P_2

4) $r_1\ge r_T$, $r_2\ge r_T$

In the last case all signals are greater then threshold r_T, i.e.: $r_{11}\ge r_T$, $r_{12}\ge r_T$, $r_{21}\ge r_T$, and $r_{22}\ge r_T$. Now, the possible combinations of probabilities of inputs' examinations are:

- $r_{11}\ge r_T$, $r_{12}\ge r_T$, $\dot{r}_1=\dot{r}_{11}$ $\dot{r}_2=\dot{r}_{12}$ P_1
- $r_{11}\ge r_T$, $r_{12}<r_T$, $r_{22}\ge r_T$ $\dot{r}_1=\dot{r}_{11}$ $\dot{r}_2=\dot{r}_{22}$ P_1

- $r_{11}<r_T$, $r_{21}\geq r_T$, $r_{22}\geq r_T$, $\quad \dot{r}_1=\dot{r}_{21} \quad \dot{r}_2=\dot{r}_{22} \quad P_1$
- $r_{11}<r_T$, $r_{21}\geq r_T$, $r_{22}<r_T$, $r_{12}<r_T$ $\quad \dot{r}_1=\dot{r}_{21} \quad \dot{r}_2=\dot{r}_{12} \quad P_1$
- $r_{21}\geq r_T$, $r_{22}\geq r_T$, $\quad \dot{r}_1=\dot{r}_{21} \quad \dot{r}_2=\dot{r}_{22} \quad P_2$
- $r_{21}\geq r_T$, $r_{22}<r_T$, $r_{12}\geq r_T$, $\quad \dot{r}_1=\dot{r}_{21} \quad \dot{r}_2=\dot{r}_{12} \quad P_2$
- $r_{21}<r_T$, $r_{11}\geq r_T$, $r_{12}\geq r_T$, $\quad \dot{r}_1=\dot{r}_{11} \quad \dot{r}_2=\dot{r}_{12} \quad P_2$
- $r_{21}<r_T$, $r_{11}\geq r_T$, $r_{12}<r_T$, $r_{22}\geq r_T$, $\quad \dot{r}_1=\dot{r}_{11} \quad \dot{r}_2=\dot{r}_{22} \quad P_2$

IV. PROBABILITY DENSITY FUNCTIONS OF DERIVATIVES

The joint probability density functions of signal derivatives are:

$r_1<r_T$, $r_2<r_T$

$$p_{r_1 r_2 \dot{r}_1 \dot{r}_2}(r_1,r_2,\dot{r}_1,\dot{r}_2)=P_1\int_0^{r_T}dr_{11}\int_0^{r_T}dr_{22}\,p_{r_{11}r_{22}r_{21}r_{12}\dot{r}_{21}\dot{r}_{12}}(r_{11},r_{22},r_1,r_2,\dot{r}_1,\dot{r}_2)+$$
$$+P_2\int_0^{r_T}dr_{21}\int_0^{r_T}dr_{12}\,p_{r_{21}r_{12}r_{11}r_{22}\dot{r}_{11}\dot{r}_{22}}(r_{21},r_{12},r_1,r_2,\dot{r}_1,\dot{r}_2) \tag{1}$$

$r_1\geq r_T$, $r_2<r_T$

$$p_{r_1 r_2 \dot{r}_1 \dot{r}_2}(r_1,r_2,\dot{r}_1,\dot{r}_2)=P_1\int_0^{r_T}dr_{12}\,p_{r_{12}r_{11}r_{22}\dot{r}_{11}\dot{r}_{22}}(r_{12},r_1,r_2,\dot{r}_1,\dot{r}_2)+$$
$$+P_1\int_0^{r_T}dr_{11}\int_0^{r_T}dr_{22}\,p_{r_{11}r_{22}r_{21}r_{12}\dot{r}_{21}\dot{r}_{12}}(r_{11},r_{22},r_1,r_2,\dot{r}_1,\dot{r}_2)+$$
$$+P_2\int_0^{r_T}dr_{22}\,p_{r_{22}r_{21}r_{12}\dot{r}_{21}\dot{r}_{12}}(r_{22},r_1,r_2,\dot{r}_1,\dot{r}_2)+$$
$$+P_2\int_0^{r_T}dr_{21}\int_0^{r_T}dr_{12}\,p_{r_{21}r_{12}r_{11}r_{22}\dot{r}_{11}\dot{r}_{22}}(r_{21},r_{12},r_1,r,\dot{r}_1,\dot{r}_2) \tag{2}$$

$r_1<r_T$, $r_2\geq r_T$

$$p_{r_1 r_2 \dot{r}_1 \dot{r}_2}(r_1,r_2,\dot{r}_1,\dot{r}_2)=P_1\int_0^{r_T}dr_{11}\,p_{r_{11}r_{21}r_{22}\dot{r}_{21}\dot{r}_{22}}(r_{11},r_1,r_2,\dot{r}_1,\dot{r}_2)+$$
$$+P_1\int_0^{r_T}dr_{11}\int_0^{r_T}dr_{22}\,p_{r_{11}r_{22}r_{21}r_{12}\dot{r}_{21}\dot{r}_{12}}(r_{11},r_{22},r_1,r_2,\dot{r}_1,\dot{r}_2)+$$
$$+P_2\int_0^{r_T}dr_{21}\,p_{r_{21}r_{11}r_{12}\dot{r}_{11}\dot{r}_{12}}(r_{21},r_1,r_2,\dot{r}_1,\dot{r}_2)+$$
$$+P_2\int_0^{r_T}dr_{21}\int_0^{r_T}dr_{12}\,p_{r_{21}r_{12}r_{11}r_{22}\dot{r}_{11}\dot{r}_{22}}(r_{21},r_{12},r_1,r,\dot{r}_1,\dot{r}_2) \tag{3}$$

$r_1\geq r_T$, $r_2\geq r_T$

$$p_{r_1 r_2 \dot{r}_1 \dot{r}_2}(r_1,r_2,\dot{r}_1,\dot{r}_2)=P_1\,p_{r_{11}r_{12}\dot{r}_{11}\dot{r}_{12}}(r_1,r_2,\dot{r}_1,\dot{r}_2)+$$
$$+P_1\int_0^{r_T}dr_{12}\,p_{r_{12}r_{11}r_{22}\dot{r}_{11}\dot{r}_{22}}(r_{12},r_1,r_2,\dot{r}_1,\dot{r}_2)+$$
$$+P_1\int_0^{r_T}dr_{11}\,p_{r_{11}r_{21}r_{22}\dot{r}_{21}\dot{r}_{22}}(r_{11},r_1,r_2,\dot{r}_1,\dot{r}_2)+$$
$$+P_1\int_0^{r_T}dr_{11}\int_0^{r_T}dr_{22}\,p_{r_{11}r_{22}r_{21}r_{12}\dot{r}_{21}\dot{r}_{12}}(r_{11},r_{22},r_1,r_2,\dot{r}_1,\dot{r}_2)+$$
$$+P_2\,p_{r_{21}r_{22}\dot{r}_{21}\dot{r}_{22}}(r_1,r_2,\dot{r}_1,\dot{r}_2)+$$
$$+P_2\int_0^{r_T}dr_{22}\,p_{r_{22}r_{21}r_{12}\dot{r}_{21}\dot{r}_{12}}(r_{22},r_1,r_2,\dot{r}_1,\dot{r}_2)+$$
$$+P_2\int_0^{r_T}dr_{21}\,p_{r_{21}r_{11}r_{12}\dot{r}_{11}\dot{r}_{12}}(r_{21},r_1,r_2,\dot{r}_1,\dot{r}_2)+$$
$$+P_2\int_0^{r_T}dr_{21}\int_0^{r_T}dr_{12}\,p_{r_{21}r_{12}r_{11}r_{22}\dot{r}_{11}\dot{r}_{22}}(r_{21},r_{12},r_1,r,\dot{r}_1,\dot{r}_2) \tag{4}$$

For the case that signal and its derivative are not correlated, after integrating of the whole range of signal values and some mathematical manipulations, the joint PDF of derivative can be expressed as:

$$p_{\dot{r}_1\dot{r}_2}(\dot{r}_1,\dot{r}_2)=P_1\int_0^{r_T}dr_{11}\int_0^{r_T}dr_{22}\,p_{r_{11}r_{22}\dot{r}_{21}\dot{r}_{12}}(r_{11},r_{22},\dot{r}_1,\dot{r}_2)+$$
$$+P_2\int_0^{r_T}dr_{21}\int_0^{r_T}dr_{12}\,p_{r_{21}r_{12}\dot{r}_{11}\dot{r}_{22}}(r_{21},r_{12},\dot{r}_1,\dot{r}_2)+$$
$$+P_1\int_0^{r_T}dr_{12}\int_{r_T}^{\infty}dr_1\,p_{r_{12}r_{11}\dot{r}_{11}\dot{r}_{22}}(r_{12},r_1,\dot{r}_1,\dot{r}_2)+P_2\int_0^{r_T}dr_{22}\int_{r_T}^{\infty}dr_1\,p_{r_{22}r_{21}\dot{r}_{21}\dot{r}_{12}}(r_{22},r_1,\dot{r}_1,\dot{r}_2)+$$
$$+P_1\int_0^{r_T}dr_{11}\int_{r_T}^{\infty}dr_2\,p_{r_{11}r_{22}\dot{r}_{21}\dot{r}_{22}}(r_{11},r_2,\dot{r}_1,\dot{r}_2)+P_2\int_0^{r_T}dr_{21}\int_{r_T}^{\infty}dr_2\,p_{r_{21}r_{12}\dot{r}_{11}\dot{r}_{12}}(r_{21},r_2,\dot{r}_1,\dot{r}_2)+$$
$$+P_1\int_{r_T}^{\infty}dr_1\int_{r_T}^{\infty}dr_2\,p_{r_{11}r_{12}\dot{r}_{11}\dot{r}_{12}}(r_1,r_2,\dot{r}_1,\dot{r}_2)+P_2\int_{r_T}^{\infty}dr_1\int_{r_T}^{\infty}dr_2\,p_{r_{21}r_{22}\dot{r}_{21}\dot{r}_{22}}(r_1,r_2,\dot{r}_1,\dot{r}_2) \tag{5}$$

The signal derivatives PDFs can be found from joint PDF based on:

$$p_{\dot{r}_1}(\dot{r}_1)=\int_{-\infty}^{\infty}p_{\dot{r}_1\dot{r}_2}(\dot{r}_1,\dot{r}_2)d\dot{r}_2 \tag{6}$$

$$p_{\dot{r}_2}(\dot{r}_2)=\int_{-\infty}^{\infty}p_{\dot{r}_1\dot{r}_2}(\dot{r}_1,\dot{r}_2)d\dot{r}_1 \tag{7}$$

By replacing (5) in (6) and (7), it is obtained:

$$p_{\dot{r}_1}(\dot{r}_1)=P_1p_{\dot{r}_{11}}(\dot{r}_1)+P_2p_{\dot{r}_{21}}(\dot{r}_1)+$$
$$+\left(P_2F_{r_{21}}(r_T)-P_1F_{r_{11}}(r_T)\right)p_{\dot{r}_{11}}(\dot{r}_1)+$$
$$+\left(P_1F_{r_{11}}(r_T)-P_2F_{r_{21}}(r_T)\right)p_{\dot{r}_{21}}(\dot{r}_1) \tag{8}$$

$$p_{\dot{r}_2}(\dot{r}_2) = P_1 F_{r_{11}}(r_T) F_{r_{22}}(r_T) p_{\dot{r}_{12}}(\dot{r}_2) + P_2 F_{r_{21}}(r_T) F_{r_{12}}(r_T) p_{\dot{r}_{22}}(\dot{r}_2) + \\ + P_1 B_1(r_T) p_{\dot{r}_{22}}(\dot{r}_2) + P_2 B_2(r_T) p_{\dot{r}_{12}}(\dot{r}_2) + \\ + P_1 F_{r_{11}}(r_T)\left(1 - F_{r_{22}}(r_T)\right) p_{\dot{r}_{22}}(\dot{r}_2) + P_2 F_{r_{21}}(r_T)\left(1 - F_{r_{12}}(r_T)\right) p_{\dot{r}_{12}}(\dot{r}_2) + \\ + P_1 C_1(r_T) p_{\dot{r}_{12}}(\dot{r}_2) + P_2 C_2(r_T) p_{\dot{r}_{22}}(\dot{r}_2) \tag{9}$$

where $F_{r_{ij}}(r_T)$ are signals' CDFs and $F_{r_{i1}}(r_T) = F_{r_{i2}}(r_T)$, while $B_i(r_T)$ and $C_i(r_T)$ are obtained based on [(1), 15]

$$B_i(r_T) = \left(1-\rho_i^{\,2}\right) e^{-\frac{A_i^2}{\sigma_i^2(1+\rho_i)}} \cdot \\ \cdot \sum_{k,l_1,l_2,l_3=0}^{\infty} \varepsilon_k \cdot \frac{1}{l_1! l_2! l_3! (k+l_1)! (k+l_2)! (k+l_3)!} \cdot \\ \cdot \rho^{k+2l_1} \left[\left(\frac{1-\rho_i}{1+\rho_i}\right) \left(\frac{A_i}{2\sigma_i^{\,2}}\right) \right]^{k+l_2+l_3} \cdot \\ \cdot \gamma\left(k+l_1+l_2+1, \frac{r_T^{\,2}}{2\sigma_i^{\,2}(1-\rho_i^{\,2})}\right) \cdot \\ \cdot \left[1 - \gamma\left(k+l_1+l_3+1, \frac{r_T^{\,2}}{2\sigma_i^{\,2}(1-\rho_i^{\,2})}\right)\right] \tag{10}$$

$$C_i(r_T) = \left(1-\rho_i^{\,2}\right) e^{-\frac{A_i^2}{\sigma_i^2(1+\rho_i)}} \cdot \\ \cdot \sum_{k,l_1,l_2,l_3=0}^{\infty} \varepsilon_k \cdot \frac{1}{l_1! l_2! l_3! (k+l_1)! (k+l_2)! (k+l_3)!} \cdot \\ \cdot \rho^{k+2l_1} \left[\left(\frac{1-\rho_i}{1+\rho_i}\right) \left(\frac{A_i}{2\sigma_i^{\,2}}\right) \right]^{k+l_2+l_3} \cdot \\ \cdot \left[1 - \gamma\left(k+l_1+l_2+1, \frac{r_T^{\,2}}{2\sigma_i^{\,2}(1-\rho_i^{\,2})}\right)\right] \cdot \\ \cdot \left[1 - \gamma\left(k+l_1+l_3+1, \frac{r_T^{\,2}}{2\sigma_i^{\,2}(1-\rho_i^{\,2})}\right)\right] \tag{11}$$

$\gamma(.)$ is incomplete gamma function and ε_k is Neumman factor defined with

$$\varepsilon_k = \begin{cases} 1, & k=0 \\ 2, & k>0 \end{cases}$$

The probability density functions of signal derivatives in the presence of Rician fading at the combiner input has normal distribution with zero mean value [16, 17]:

$$p_{\dot{r}_i}(\dot{r}_{i,j}) = \frac{1}{\sqrt{2\pi}\dot{\sigma}_i} e^{-\frac{\dot{r}_{i,j}^{\,2}}{2\dot{\sigma}_i^{\,2}}} \quad , \quad -\infty < \dot{r}_{i,j} < \infty \tag{12}$$

where i=1,2; j=1,2 and $\dot{\sigma}_i^{\,2} = 2\sigma_i^{\,2}\pi^2 f_m^{\,2}$ is the variance and f_m is maximal Doppler frequency.

Probability density function of signal derivatives $\dot{r}_1$ and $\dot{r}_2$ at the SSC combiner output at two time moments in the presence of Rician fading is obtained when (12) putting in previously obtained general expressions for PDFs of signal derivatives and replacing of CDF with [18]:

$$F_{r_i}(r_{i,j}) = 1 - Q_1\left(A_i/\sigma_i, r_{i,j}/\sigma_i\right), \quad r_{i,j} \ge 0 \tag{13}$$

where $Q_1(.)$ is Marcum Q-function of first order. It is obtained as:

$$p_{\dot{r}_1}(\dot{r}_1) = P_1 \frac{1}{\sqrt{2\pi}\dot{\sigma}_1} e^{-\frac{\dot{r}_1^2}{2\dot{\sigma}_1^2}} + P_2 \frac{1}{\sqrt{2\pi}\dot{\sigma}_2} e^{-\frac{\dot{r}_1^2}{2\dot{\sigma}_2^2}} + \\ + \left(P_2\left[1 - Q_1\left(\frac{A_2}{\sigma_2}, \frac{r_T}{\sigma_2}\right)\right] - P_1\left[1 - Q_1\left(\frac{A_1}{\sigma_1}, \frac{r_T}{\sigma_1}\right)\right] \right) \frac{1}{\sqrt{2\pi}\dot{\sigma}_1} e^{-\frac{\dot{r}_1^2}{2\dot{\sigma}_1^2}} + \\ + \left(P_1\left[1 - Q_1\left(\frac{A_1}{\sigma_1}, \frac{r_T}{\sigma_1}\right)\right] - P_2\left[1 - Q_1\left(\frac{A_2}{\sigma_2}, \frac{r_T}{\sigma_2}\right)\right] \right) \frac{1}{\sqrt{2\pi}\dot{\sigma}_2} e^{-\frac{\dot{r}_1^2}{2\dot{\sigma}_2^2}} \tag{14}$$

$$p_{\dot{r}_2}(\dot{r}_2) = P_1\left[1 - Q_1\left(\frac{A_1}{\sigma_1}, \frac{r_T}{\sigma_1}\right)\right]\left[1 - Q_1\left(\frac{A_2}{\sigma_2}, \frac{r_T}{\sigma_2}\right)\right] \frac{1}{\sqrt{2\pi}\dot{\sigma}_1} e^{-\frac{\dot{r}_2^2}{2\dot{\sigma}_1^2}} + \\ + P_2\left[1 - Q_1\left(\frac{A_1}{\sigma_1}, \frac{r_T}{\sigma_1}\right)\right]\left[1 - Q_1\left(\frac{A_2}{\sigma_2}, \frac{r_T}{\sigma_2}\right)\right] \frac{1}{\sqrt{2\pi}\dot{\sigma}_2} e^{-\frac{\dot{r}_2^2}{2\dot{\sigma}_2^2}} + \\ + P_1 B_1(r_T) \frac{1}{\sqrt{2\pi}\dot{\sigma}_2} e^{-\frac{\dot{r}_2^2}{2\dot{\sigma}_2^2}} + P_2 B_2(r_T) \frac{1}{\sqrt{2\pi}\dot{\sigma}_1} e^{-\frac{\dot{r}_2^2}{2\dot{\sigma}_1^2}} + \\ + P_1\left[1 - Q_1\left(\frac{A_1}{\sigma_1}, \frac{r_T}{\sigma_1}\right)\right] Q_1\left(\frac{A_2}{\sigma_2}, \frac{r_T}{\sigma_2}\right) \frac{1}{\sqrt{2\pi}\dot{\sigma}_2} e^{-\frac{\dot{r}_2^2}{2\dot{\sigma}_2^2}} + \\ + P_2\left[1 - Q_1\left(\frac{A_2}{\sigma_2}, \frac{r_T}{\sigma_2}\right)\right] Q_1\left(\frac{A_1}{\sigma_1}, \frac{r_T}{\sigma_1}\right) \frac{1}{\sqrt{2\pi}\dot{\sigma}_1} e^{-\frac{\dot{r}_2^2}{2\dot{\sigma}_1^2}} + \\ + P_1 C_1(r_T) \frac{1}{\sqrt{2\pi}\dot{\sigma}_1} e^{-\frac{\dot{r}_2^2}{2\dot{\sigma}_1^2}} + P_2 C_2(r_T) \frac{1}{\sqrt{2\pi}\dot{\sigma}_2} e^{-\frac{\dot{r}_2^2}{2\dot{\sigma}_2^2}} \tag{15}$$

The curves for probability density functions of signal derivatives at the SSC combiner output at two time instants, versus signal derivatives $\dot{r}$, are presented in Fig. 2 for different values of parameter $\dot{\sigma}_i$.

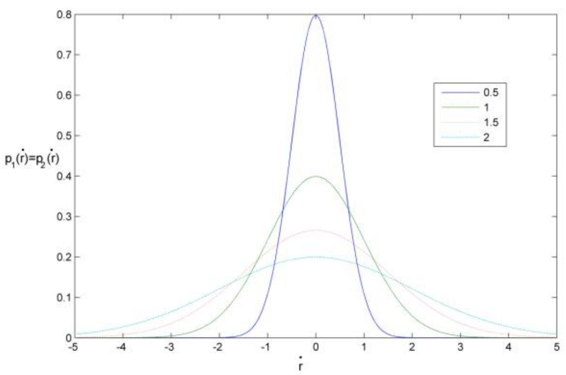

Figure 2. The probability density functions of derivatives at the SSC combiner output at two time instants with parameter $\dot{\sigma}_i$ = 0.5; 1; 1.5; 2

The parameters of PDFs curves are different values of parameter $\dot{\sigma}_i$ (0.5; 1; 1.5; 2). The case of channels with identical distribution is observed.

V. SYSTEM MODEL AND STATISTICS OF SSC/SC COMBINER

The model of the SSC/SC combiner with two inputs at two time instants, considering in this paper, is shown in Fig. 3. The SSC combiner input signals, r_{11} and r_{21} at first time instant, and r_{12} and r_{22} at the second time instant, are overall system inputs. The output signals from SSC part of combiner are r_1 and r_2 and they are inputs for second part of combiner. The overall output signal from complex system is r.

The joint probability density functions at the SSC combiner outputs at two time instants in Rician fading channels for four different cases are:

$r_1<r_T$, $r_2<r_T$

$$p_{r_1r_2}(r_1,r_2)=P_1D_2(r_1)D_1(r_2)+P_2D_1(r_1)D_2(r_2) \tag{16}$$

$r_1\geq r_T$, $r_2<r_T$

$$p_{r_1r_2}(r_1,r_2)=P_1\frac{r_2}{\sigma_2^2}e^{-\frac{r_2^2+A_2^2}{2\sigma_2^2}}I_0\left(\frac{r_2A_2}{\sigma_2^2}\right)D_1(r_1)+P_1D_2(r_1)D_1(r_2)+$$
$$+P_2\frac{r_2}{\sigma_1^2}e^{-\frac{r_2^2+A_1^2}{2\sigma_1^2}}I_0\left(\frac{r_2A_1}{\sigma_1^2}\right)D_2(r_1)+P_2D_1(r_1)D_2(r_2) \tag{17}$$

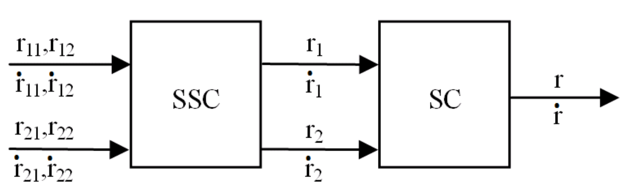

Figure 3. Model of the SSC/SC combiner with two inputs at two time instants

$r_1<r_T$, $r_2\geq r_T$

$$p_{r_1r_2}(r_1,r_2)=P_1\left(1-Q_1\left(A/\sigma_1,r_t/\sigma_1\right)\right)\cdot$$
$$\cdot\frac{r_1r_2}{\sigma_2^4(1-\rho^2)}e^{-\frac{r_1^2+r_2^2+2A_2^2(1-\rho)}{2\sigma_2^2(1-\rho^2)}}\cdot$$
$$\cdot\sum_{i=0}^{\infty}\varepsilon_iI_i\left(\frac{\rho r_1r_2}{\sigma_2^2(1-\rho^2)}\right)I_i\left(\frac{A_2r_1}{\sigma_2^2(1+\rho)}\right)I_i\left(\frac{A_2r_2}{\sigma_2^2(1+\rho)}\right)+$$
$$+P_1D_2(r_1)D_1(r_2)+$$
$$*+P_2\left(1-Q_1\left(A/\sigma_2,r_t/\sigma_2\right)\right)\cdot$$
$$\cdot\frac{r_1r_2}{\sigma_1^4(1-\rho^2)}e^{-\frac{r_1^2+r_2^2+2A_1^2(1-\rho)}{2\sigma_1^2(1-\rho^2)}}\cdot$$
$$\cdot\sum_{i=0}^{\infty}\varepsilon_iI_i\left(\frac{\rho r_1r_2}{\sigma_1^2(1-\rho^2)}\right)I_i\left(\frac{A_1r_1}{\sigma_1^2(1+\rho)}\right)I_i\left(\frac{A_1r_2}{\sigma_1^2(1+\rho)}\right)+$$
$$+P_2D_1(r_1)D_2(r_2) \tag{18}$$

$r_1\geq r_T$, $r_2\geq r_T$

$$p_{r_1r_2}(r_1,r_2)=P_1\frac{r_1r_2}{\sigma_1^4(1-\rho^2)}e^{-\frac{r_1^2+r_2^2+2A_1^2(1-\rho)}{2\sigma_1^2(1-\rho^2)}}\cdot$$
$$\cdot\sum_{i=0}^{\infty}\varepsilon_iI_i\left(\frac{\rho r_1r_2}{\sigma_1^2(1-\rho^2)}\right)I_i\left(\frac{A_1r_1}{\sigma_1^2(1+\rho)}\right)I_i\left(\frac{A_1r_2}{\sigma_1^2(1+\rho)}\right)+$$
$$+P_1\left(1-Q_1\left(A/\sigma_1,r_t/\sigma_1\right)\right)\cdot$$
$$\cdot\frac{r_1r_2}{\sigma_2^4(1-\rho^2)}e^{-\frac{r_1^2+r_2^2+2A_2^2(1-\rho)}{2\sigma_2^2(1-\rho^2)}}\cdot$$
$$\cdot\sum_{i=0}^{\infty}\varepsilon_iI_i\left(\frac{\rho r_1r_2}{\sigma_2^2(1-\rho^2)}\right)I_i\left(\frac{A_2r_1}{\sigma_2^2(1+\rho)}\right)I_i\left(\frac{A_2r_2}{\sigma_2^2(1+\rho)}\right)+$$
$$+P_1\frac{r_2}{\sigma_2^2}e^{-\frac{r_2^2+A_2^2}{2\sigma_2^2}}I_0\left(\frac{r_2A_2}{\sigma_2^2}\right)D_1(r_1)+P_1D_2(r_1)D_1(r_2)+$$
$$+P_2\frac{r_1r_2}{\sigma_2^4(1-\rho^2)}e^{-\frac{r_1^2+r_2^2+2A_2^2(1-\rho)}{2\sigma_2^2(1-\rho^2)}}\cdot$$
$$\cdot\sum_{i=0}^{\infty}\varepsilon_iI_i\left(\frac{\rho r_1r_2}{\sigma_2^2(1-\rho^2)}\right)I_i\left(\frac{A_2r_1}{\sigma_2^2(1+\rho)}\right)I_i\left(\frac{A_2r_2}{\sigma_2^2(1+\rho)}\right)+$$
$$+P_2\left(1-Q_1\left(A/\sigma_2,r_t/\sigma_2\right)\right)\cdot$$
$$\cdot\frac{r_1r_2}{\sigma_1^4(1-\rho^2)}e^{-\frac{r_1^2+r_2^2+2A_1^2(1-\rho)}{2\sigma_1^2(1-\rho^2)}}\cdot$$
$$\cdot\sum_{i=0}^{\infty}\varepsilon_iI_i\left(\frac{\rho r_1r_2}{\sigma_1^2(1-\rho^2)}\right)I_i\left(\frac{A_1r_1}{\sigma_1^2(1+\rho)}\right)I_i\left(\frac{A_1r_2}{\sigma_1^2(1+\rho)}\right)+$$

$$+P_2\frac{r_2}{\sigma_1^2}e^{-\frac{r_2^2+A_1^2}{2\sigma_1^2}}I_0\left(\frac{r_2A_1}{\sigma_1^2}\right)D_2(r_1)+P_2D_1(r_1)D_2(r_2) \qquad (19)$$

where:

$$D_i(r)=\frac{1}{\sigma_i^2}e^{-\frac{A_2^2}{\sigma_i^2(1+\rho)}}\cdot$$

$$\cdot\sum_{k,l_1,l_2,l_3=0}^{\infty}\varepsilon_i\frac{1}{l_1!l_2!l_3!(k+l_1)!(k+l_2)!(k+l_3)!}\frac{\rho^{k+2l_1}}{\left(2\sigma_i^2(1-\rho^2)\right)^{2k+l_1+l_2+2l_3}}\cdot$$

$$\cdot A_i^{2k+2l_2+2l_3}(1-\rho)^{2k+2l_2+2l_3}\cdot r^{2k+2l_1+2l_3+1}e^{-\frac{r^2}{2\sigma_i^2(1-\rho^2)}}\cdot$$

$$\cdot\gamma\left(k+l_1+l_2+1,\frac{r_T^2}{2\sigma_i^2(1-\rho^2)}\right) \qquad (20)$$

For dual SC receiver with correlated diversity branches the joint PDF $p_{r\dot{r}}(r,\dot{r})$ is given by [19, eq. (8.42)]

$$p_{r\dot{r}}(r,\dot{r})=p_{r_1}(\dot{r})\int_0^r p_{r_1r_2}(r,r_2)dr_2+p_{r_2}(\dot{r})\int_0^r p_{r_1r_2}(r_1,r)dr_1 \qquad (21)$$

For SSC/SC combiner, the joint PDF $p_{r\dot{r}}(r,\dot{r})$ is obtained for different values of r:

$r<r_T$ $(r_1<r_T,\ r_2<r_T)$

$$p_{r\dot{r}}(r,\dot{r})=p_{r_1}(\dot{r})\int_0^r p_{r_1r_2}(r,r_2)dr_2+p_{r_2}(\dot{r})\int_0^r p_{r_1r_2}(r_1,r)dr_1 \qquad (22)$$

$r\geq r_T$ $(r_1\geq r_T,\ r_2<r_T)$

$$p_{r\dot{r}}^{\,1}(r,\dot{r})=p_{r_1}(\dot{r})\int_0^{r_T} p_{r_1r_2}(r,r_2)dr_2+p_{r_2}(\dot{r})\int_{r_T}^r p_{r_1r_2}(r_1,r)dr_1 \qquad (23)$$

$r\geq r_T$ $(r_1<r_T,\ r_2\geq r_T)$

$$p_{r\dot{r}}^{\,2}(r,\dot{r})=p_{r_1}(\dot{r})\int_{r_T}^{r} p_{r_1r_2}(r,r_2)dr_2+p_{r_2}(\dot{r})\int_0^{r_T} p_{r_1r_2}(r_1,r)dr_1 \qquad (24)$$

$r\geq r_T$ $(r_1\geq r_T,\ r_2\geq r_T)$

$$p_{r\dot{r}}^{\,3}(r,\dot{r})=p_{r_1}(\dot{r})\int_{r_T}^{r} p_{r_1r_2}(r,r_2)dr_2+p_{r_2}(\dot{r})\int_{r_T}^{r} p_{r_1r_2}(r_1,r)dr_1 \qquad (25)$$

$r\geq r_T$ $(r_1\geq r_T,\ r_2<r_T;\ r_1<r_T,\ r_2\geq r_T;\ r_1\geq r_T,\ r_2\geq r_T)$

$$p_{r\dot{r}}(r,\dot{r})=p_{r\dot{r}}^{\,1}(r,\dot{r})+p_{r\dot{r}}^{\,2}(r,\dot{r})+p_{r\dot{r}}^{\,3}(r,\dot{r}) \qquad (26)$$

Using (14) and (15) for PDFs of derivatives, and (16) – (19) for PDFs of signals and putting them into (22) – (25), the joint PDF $p_{r\dot{r}}(r,\dot{r})$ is obtained as:

For $r<r_T$:

$$p_{r\dot{r}}(r,\dot{r})=\left[P_1\frac{1}{\sqrt{2\pi}\dot{\sigma}_1}e^{-\frac{\dot{r}_1^2}{2\dot{\sigma}_1^2}}+P_2\frac{1}{\sqrt{2\pi}\dot{\sigma}_2}e^{-\frac{\dot{r}_1^2}{2\dot{\sigma}_2^2}}+\right.$$

$$+\left(P_2\left[1-Q_1\left(\frac{A_2}{\sigma_2},\frac{r_T}{\sigma_2}\right)\right]-P_1\left[1-Q_1\left(\frac{A_1}{\sigma_1},\frac{r_T}{\sigma_1}\right)\right]\right)\frac{1}{\sqrt{2\pi}\dot{\sigma}_1}e^{-\frac{\dot{r}_1^2}{2\dot{\sigma}_1^2}}+$$

$$\left.+\left(P_1\left[1-Q_1\left(\frac{A_1}{\sigma_1},\frac{r_T}{\sigma_1}\right)\right]-P_2\left[1-Q_1\left(\frac{A_2}{\sigma_2},\frac{r_T}{\sigma_2}\right)\right]\right)\frac{1}{\sqrt{2\pi}\dot{\sigma}_2}e^{-\frac{\dot{r}_1^2}{2\dot{\sigma}_2^2}}\right]\cdot$$

$$\cdot\int_0^r\left[P_1D_2(r)D_1(r_2)+P_2D_1(r)D_2(r_2)\right]dr_2+$$

$$+\left[P_1\left[1-Q_1\left(\frac{A_1}{\sigma_1},\frac{r_T}{\sigma_1}\right)\right]\left[1-Q_1\left(\frac{A_2}{\sigma_2},\frac{r_T}{\sigma_2}\right)\right]\frac{1}{\sqrt{2\pi}\dot{\sigma}_1}e^{-\frac{\dot{r}_2^2}{2\dot{\sigma}_1^2}}+\right.$$

$$+P_2\left[1-Q_1\left(\frac{A_1}{\sigma_1},\frac{r_T}{\sigma_1}\right)\right]\left[1-Q_1\left(\frac{A_2}{\sigma_2},\frac{r_T}{\sigma_2}\right)\right]\frac{1}{\sqrt{2\pi}\dot{\sigma}_2}e^{-\frac{\dot{r}_2^2}{2\dot{\sigma}_2^2}}+$$

$$+P_1B_1(r_T)\frac{1}{\sqrt{2\pi}\dot{\sigma}_2}e^{-\frac{\dot{r}_2^2}{2\dot{\sigma}_2^2}}+P_2B_2(r_T)\frac{1}{\sqrt{2\pi}\dot{\sigma}_1}e^{-\frac{\dot{r}_2^2}{2\dot{\sigma}_1^2}}+$$

$$+P_1\left[1-Q_1\left(\frac{A_1}{\sigma_1},\frac{r_T}{\sigma_1}\right)\right]Q_1\left(\frac{A_2}{\sigma_2},\frac{r_T}{\sigma_2}\right)\frac{1}{\sqrt{2\pi}\dot{\sigma}_2}e^{-\frac{\dot{r}_2^2}{2\dot{\sigma}_2^2}}+$$

$$+P_2\left[1-Q_1\left(\frac{A_2}{\sigma_2},\frac{r_T}{\sigma_2}\right)\right]Q_1\left(\frac{A_1}{\sigma_1},\frac{r_T}{\sigma_1}\right)\frac{1}{\sqrt{2\pi}\dot{\sigma}_1}e^{-\frac{\dot{r}_2^2}{2\dot{\sigma}_1^2}}+$$

$$\left.+P_1C_1(r_T)\frac{1}{\sqrt{2\pi}\dot{\sigma}_1}e^{-\frac{\dot{r}_2^2}{2\dot{\sigma}_1^2}}+P_2C_2(r_T)\frac{1}{\sqrt{2\pi}\dot{\sigma}_2}e^{-\frac{\dot{r}_2^2}{2\dot{\sigma}_2^2}}\right]\cdot$$

$$\cdot\int_0^r\left[P_1D_2(r_1)D_1(r)+P_2D_1(r_1)D_2(r)\right]dr_1 \qquad (27)$$

For $r\geq r_T$

$$p_{r\dot{r}}(r,\dot{r})=\left[P_1\frac{1}{\sqrt{2\pi}\dot{\sigma}_1}e^{-\frac{\dot{r}_1^2}{2\dot{\sigma}_1^2}}+P_2\frac{1}{\sqrt{2\pi}\dot{\sigma}_2}e^{-\frac{\dot{r}_1^2}{2\dot{\sigma}_2^2}}+\right.$$

$$+\left(P_2\left[1-Q_1\left(\frac{A_2}{\sigma_2},\frac{r_T}{\sigma_2}\right)\right]-P_1\left[1-Q_1\left(\frac{A_1}{\sigma_1},\frac{r_T}{\sigma_1}\right)\right]\right)\frac{1}{\sqrt{2\pi}\dot{\sigma}_1}e^{-\frac{\dot{r}_1^2}{2\dot{\sigma}_1^2}}+$$

$$\left.+\left(P_1\left[1-Q_1\left(\frac{A_1}{\sigma_1},\frac{r_T}{\sigma_1}\right)\right]-P_2\left[1-Q_1\left(\frac{A_2}{\sigma_2},\frac{r_T}{\sigma_2}\right)\right]\right)\frac{1}{\sqrt{2\pi}\dot{\sigma}_2}e^{-\frac{\dot{r}_1^2}{2\dot{\sigma}_2^2}}\right]\cdot$$

$$\cdot\Bigg[\int_0^{r_T}\Bigg[P_1 \frac{r_2}{\sigma_2^2} e^{-\frac{r_2^2+A_2^2}{2\sigma_2^2}} I_0\left(\frac{r_2A_2}{\sigma_2^2}\right) D_1(r) + P_1 D_2(r) D_1(r_2) +$$

$$+P_2 \frac{r_2}{\sigma_1^2} e^{-\frac{r_2^2+A_1^2}{2\sigma_1^2}} I_0\left(\frac{r_2A_1}{\sigma_1^2}\right) D_2(r) + P_2 D_1(r) D_2(r_2)\Bigg] dr_2 +$$

$$+\int_{r_T}^{r}\big[P_1\big(1-Q_1\big(A/\sigma_1, r_t/\sigma_1\big)\big)\cdot$$

$$\cdot \frac{r r_2}{\sigma_2^4(1-\rho^2)} e^{-\frac{r^2+r_2^2+2A_2^2(1-\rho)}{2\sigma_2^2(1-\rho^2)}}\cdot$$

$$\cdot\sum_{i=0}^{\infty} \varepsilon_i I_i\left(\frac{\rho r r_2}{\sigma_2^2(1-\rho^2)}\right) I_i\left(\frac{A_2 r}{\sigma_2^2(1+\rho)}\right) I_i\left(\frac{A_2 r_2}{\sigma_2^2(1+\rho)}\right)+$$

$$+P_1 D_2(r_1) D_1(r_2)+$$

$$+P_2\big(1-Q_1\big(A/\sigma_2, r_t/\sigma_2\big)\big)\cdot$$

$$\cdot\frac{r_1 r_2}{\sigma_1^4(1-\rho^2)} e^{-\frac{r_1^2+r_2^2+2A_1^2(1-\rho)}{2\sigma_1^2(1-\rho^2)}}\cdot$$

$$\cdot\sum_{i=0}^{\infty} \varepsilon_i I_i\left(\frac{\rho r_1 r_2}{\sigma_1^2(1-\rho^2)}\right) I_i\left(\frac{A_1 r_1}{\sigma_1^2(1+\rho)}\right) I_i\left(\frac{A_1 r_2}{\sigma_1^2(1+\rho)}\right)+$$

$$+P_2 D_1(r) D_2(r_2)\big] dr_2 +$$

$$+\int_{r_T}^{r}\Bigg[P_1 \frac{r_1 r_2}{\sigma_1^4(1-\rho^2)} e^{-\frac{r_1^2+r_2^2+2A_1^2(1-\rho)}{2\sigma_1^2(1-\rho^2)}}\cdot$$

$$\cdot\sum_{i=0}^{\infty} \varepsilon_i I_i\left(\frac{\rho r_1 r_2}{\sigma_1^2(1-\rho^2)}\right) I_i\left(\frac{A_1 r_1}{\sigma_1^2(1+\rho)}\right) I_i\left(\frac{A_1 r_2}{\sigma_1^2(1+\rho)}\right)+$$

$$+P_1\big(1-Q_1\big(A/\sigma_1, r_t/\sigma_1\big)\big)\cdot$$

$$\cdot\frac{r_1 r_2}{\sigma_2^4(1-\rho^2)} e^{-\frac{r_1^2+r_2^2+2A_2^2(1-\rho)}{2\sigma_2^2(1-\rho^2)}}\cdot$$

$$\cdot\sum_{i=0}^{\infty} \varepsilon_i I_i\left(\frac{\rho r_1 r_2}{\sigma_2^2(1-\rho^2)}\right) I_i\left(\frac{A_2 r_1}{\sigma_2^2(1+\rho)}\right) I_i\left(\frac{A_2 r_2}{\sigma_2^2(1+\rho)}\right)+$$

$$+P_1 \frac{r_2}{\sigma_2^2} e^{-\frac{r_2^2+A_2^2}{2\sigma_2^2}} I_0\left(\frac{r_2A_2}{\sigma_2^2}\right) D_1(r_1) + P_1 D_2(r_1) D_1(r_2) +$$

$$+P_2 \frac{r_1 r_2}{\sigma_2^4(1-\rho^2)} e^{-\frac{r_1^2+r_2^2+2A_2^2(1-\rho)}{2\sigma_2^2(1-\rho^2)}}\cdot$$

$$\cdot\sum_{i=0}^{\infty} \varepsilon_i I_i\left(\frac{\rho r_1 r_2}{\sigma_2^2(1-\rho^2)}\right) I_i\left(\frac{A_2 r_1}{\sigma_2^2(1+\rho)}\right) I_i\left(\frac{A_2 r_2}{\sigma_2^2(1+\rho)}\right)+$$

$$+P_2\big(1-Q_1\big(A/\sigma_2, r_t/\sigma_2\big)\big)\cdot$$

$$\cdot\frac{r_1 r_2}{\sigma_1^4(1-\rho^2)} e^{-\frac{r_1^2+r_2^2+2A_1^2(1-\rho)}{2\sigma_1^2(1-\rho^2)}}\cdot$$

$$\cdot\sum_{i=0}^{\infty} \varepsilon_i I_i\left(\frac{\rho r_1 r_2}{\sigma_1^2(1-\rho^2)}\right) I_i\left(\frac{A_1 r_1}{\sigma_1^2(1+\rho)}\right) I_i\left(\frac{A_1 r_2}{\sigma_1^2(1+\rho)}\right)+$$

$$+P_2 \frac{r_2}{\sigma_1^2} e^{-\frac{r_2^2+A_1^2}{2\sigma_1^2}} I_0\left(\frac{r_2A_1}{\sigma_1^2}\right) D_2(r_1) + P_2 D_1(r_1) D_2(r_2)\Bigg] dr_2\Bigg] +$$

$$+\Bigg[P_1\left[1-Q_1\left(\frac{A_1}{\sigma_1},\frac{r_T}{\sigma_1}\right)\right]\left[1-Q_1\left(\frac{A_2}{\sigma_2},\frac{r_T}{\sigma_2}\right)\right]\frac{1}{\sqrt{2\pi}\dot\sigma_1} e^{-\frac{\dot r_2^2}{2\dot\sigma_1^2}}+$$

$$+P_2\left[1-Q_1\left(\frac{A_1}{\sigma_1},\frac{r_T}{\sigma_1}\right)\right]\left[1-Q_1\left(\frac{A_2}{\sigma_2},\frac{r_T}{\sigma_2}\right)\right]\frac{1}{\sqrt{2\pi}\dot\sigma_2} e^{-\frac{\dot r_2^2}{2\dot\sigma_2^2}}+$$

$$+P_1 B_1(r_T)\frac{1}{\sqrt{2\pi}\dot\sigma_2} e^{-\frac{\dot r_2^2}{2\dot\sigma_2^2}}+P_2 B_2(r_T)\frac{1}{\sqrt{2\pi}\dot\sigma_1} e^{-\frac{\dot r_2^2}{2\dot\sigma_1^2}}+$$

$$+P_1\left[1-Q_1\left(\frac{A_1}{\sigma_1},\frac{r_T}{\sigma_1}\right)\right]Q_1\left(\frac{A_2}{\sigma_2},\frac{r_T}{\sigma_2}\right)\frac{1}{\sqrt{2\pi}\dot\sigma_2} e^{-\frac{\dot r_2^2}{2\dot\sigma_2^2}}+$$

$$+P_2\left[1-Q_1\left(\frac{A_2}{\sigma_2},\frac{r_T}{\sigma_2}\right)\right]Q_1\left(\frac{A_1}{\sigma_1},\frac{r_T}{\sigma_1}\right)\frac{1}{\sqrt{2\pi}\dot\sigma_1} e^{-\frac{\dot r_2^2}{2\dot\sigma_1^2}}+$$

$$+P_1 C_1(r_T)\frac{1}{\sqrt{2\pi}\dot\sigma_1} e^{-\frac{\dot r_2^2}{2\dot\sigma_1^2}}+P_2 C_2(r_T)\frac{1}{\sqrt{2\pi}\dot\sigma_2} e^{-\frac{\dot r_2^2}{2\dot\sigma_2^2}}\Bigg]\cdot$$

$$\cdot\Bigg[\int_{r_T}^{r}\Bigg[P_1 \frac{r}{\sigma_2^2} e^{-\frac{r^2+A_2^2}{2\sigma_2^2}} I_0\left(\frac{rA_2}{\sigma_2^2}\right) D_1(r_1) + P_1 D_2(r_1) D_1(r) +$$

$$+P_2 \frac{r}{\sigma_1^2} e^{-\frac{r_2^2+A_1^2}{2\sigma_1^2}} I_0\left(\frac{rA_1}{\sigma_1^2}\right) D_2(r_1) + P_2 D_1(r_1) D_2(r)\Bigg] dr_1 +$$

$$+\int_{0}^{r_T}\big[P_1\big(1-Q_1\big(A/\sigma_1, r_t/\sigma_1\big)\big)\cdot$$

$$\cdot\frac{r_1 r}{\sigma_2^4(1-\rho^2)} e^{-\frac{r_1^2+r^2+2A_2^2(1-\rho)}{2\sigma_2^2(1-\rho^2)}}\cdot$$

$$\cdot\sum_{i=0}^{\infty} \varepsilon_i I_i\left(\frac{\rho r_1 r}{\sigma_2^2(1-\rho^2)}\right) I_i\left(\frac{A_2 r_1}{\sigma_2^2(1+\rho)}\right) I_i\left(\frac{A_2 r}{\sigma_2^2(1+\rho)}\right)+$$

$$+P_1 D_2(r_1) D_1(r)+$$

$$+P_2\left(1-Q_1\left(A/\sigma_2, r_t/\sigma_2\right)\right)\cdot$$

$$\cdot\frac{r_1 r}{\sigma_1^4(1-\rho^2)}e^{-\frac{r_1^2+r^2+2A_1^2(1-\rho)}{2\sigma_1^2(1-\rho^2)}}\cdot$$

$$\cdot\sum_{i=0}^{\infty}\varepsilon_i I_i\left(\frac{\rho r_1 r}{\sigma_1^2(1-\rho^2)}\right)I_i\left(\frac{A_1 r_1}{\sigma_1^2(1+\rho)}\right)I_i\left(\frac{A_1 r}{\sigma_1^2(1+\rho)}\right)+$$

$$+P_2 D_1(r_1) D_2(r)\Big]dr_1+$$

$$+\int_{r_T}^{r}\Bigg[P_1\frac{r_1 r_2}{\sigma_1^4(1-\rho^2)}e^{-\frac{r_1^2+r_2^2+2A_1^2(1-\rho)}{2\sigma_1^2(1-\rho^2)}}\cdot$$

$$\cdot\sum_{i=0}^{\infty}\varepsilon_i I_i\left(\frac{\rho r_1 r_2}{\sigma_1^2(1-\rho^2)}\right)I_i\left(\frac{A_1 r_1}{\sigma_1^2(1+\rho)}\right)I_i\left(\frac{A_1 r_2}{\sigma_1^2(1+\rho)}\right)+$$

$$+P_1\left(1-Q_1\left(A/\sigma_1, r_t/\sigma_1\right)\right)\cdot$$

$$\cdot\frac{r_1 r_2}{\sigma_2^4(1-\rho^2)}e^{-\frac{r_1^2+r_2^2+2A_2^2(1-\rho)}{2\sigma_2^2(1-\rho^2)}}\cdot$$

$$\cdot\sum_{i=0}^{\infty}\varepsilon_i I_i\left(\frac{\rho r_1 r_2}{\sigma_2^2(1-\rho^2)}\right)I_i\left(\frac{A_2 r_1}{\sigma_2^2(1+\rho)}\right)I_i\left(\frac{A_2 r_2}{\sigma_2^2(1+\rho)}\right)+$$

$$+P_1\frac{r_2}{\sigma_2^2}e^{-\frac{r_2^2+A_2^2}{2\sigma_2^2}}I_0\left(\frac{r_2 A_2}{\sigma_2^2}\right)D_1(r_1)+P_1 D_2(r_1)D_1(r_2)+$$

$$+P_2\frac{r_1 r_2}{\sigma_2^4(1-\rho^2)}e^{-\frac{r_1^2+r_2^2+2A_2^2(1-\rho)}{2\sigma_2^2(1-\rho^2)}}\cdot$$

$$\cdot\sum_{i=0}^{\infty}\varepsilon_i I_i\left(\frac{\rho r_1 r_2}{\sigma_2^2(1-\rho^2)}\right)I_i\left(\frac{A_2 r_1}{\sigma_2^2(1+\rho)}\right)I_i\left(\frac{A_2 r_2}{\sigma_2^2(1+\rho)}\right)+$$

$$+P_2\left(1-Q_1\left(A/\sigma_2, r_t/\sigma_2\right)\right)\cdot$$

$$\cdot\frac{r_1 r_2}{\sigma_1^4(1-\rho^2)}e^{-\frac{r_1^2+r_2^2+2A_1^2(1-\rho)}{2\sigma_1^2(1-\rho^2)}}\cdot$$

$$\cdot\sum_{i=0}^{\infty}\varepsilon_i I_i\left(\frac{\rho r_1 r_2}{\sigma_1^2(1-\rho^2)}\right)I_i\left(\frac{A_1 r_1}{\sigma_1^2(1+\rho)}\right)I_i\left(\frac{A_1 r_2}{\sigma_1^2(1+\rho)}\right)+$$

$$+P_2\frac{r_2}{\sigma_1^2}e^{-\frac{r_2^2+A_1^2}{2\sigma_1^2}}I_0\left(\frac{r_2 A_1}{\sigma_1^2}\right)D_2(r_1)+P_2 D_1(r_1)D_2(r_2)\Bigg]dr_1\Bigg] \quad (28)$$

The average LCR at envelope level, r, is defined as the rate at which a fading signal envelope crosses level r in a positive or negative going direction. Denoting the signal envelope and its time derivative by r and $\dot{r}$, respectively, the average LCR is given by [16],[17]

$$N_r(r)=\int_0^{\infty}\dot{r}p_{r\dot{r}}(r,\dot{r})d\dot{r} \quad (29)$$

The average fade duration is defined as the average time that the fading envelope remains below the specified signal level, after crossing the level in a downward direction and is given by [20]

$$T_r(r)=\frac{P_{out}(r)}{N_r(r)} \quad (30)$$

where $P_{out}(r)$ is outage probability at the output of SSC/SC combiner. It can be obtained by using (16) - (19) similarly like for obtaining LCR:

$r<r_T$

$$P_{out}(r)=\int_0^r\int_0^r P_1 D_2(r_1)D_1(r_2)+P_2 D_1(r_1)D_2(r_2)dr_1 dr_2 \quad (31)$$

$r\geq r_T$

$$P_{out}(r)=\int_0^{r_T}\int_0^{r_T} P_1 D_2(r_1)D_1(r_2)+P_2 D_1(r_1)D_2(r_2)dr_1 dr_2+$$

$$+\int_{r_T}^{r}\int_0^{r_T}\Bigg[P_1\frac{r_2}{\sigma_2^2}e^{-\frac{r_2^2+A_2^2}{2\sigma_2^2}}I_0\left(\frac{r_2 A_2}{\sigma_2^2}\right)D_1(r_1)+P_1 D_2(r_1)D_1(r_2)+$$

$$+P_2\frac{r_2}{\sigma_1^2}e^{-\frac{r_2^2+A_1^2}{2\sigma_1^2}}I_0\left(\frac{r_2 A_1}{\sigma_1^2}\right)D_2(r_1)+P_2 D_1(r_1)D_2(r_2)\Bigg]dr_1 dr_2+$$

$$+\int_0^{r_T}\int_{r_T}^{r}\Big[P_1\left(1-Q_1\left(A/\sigma_1, r_t/\sigma_1\right)\right)\cdot$$

$$\cdot\frac{r_1 r_2}{\sigma_2^4(1-\rho^2)}e^{-\frac{r_1^2+r_2^2+2A_2^2(1-\rho)}{2\sigma_2^2(1-\rho^2)}}\cdot$$

$$\cdot\sum_{i=0}^{\infty}\varepsilon_i I_i\left(\frac{\rho r_1 r_2}{\sigma_2^2(1-\rho^2)}\right)I_i\left(\frac{A_2 r_1}{\sigma_2^2(1+\rho)}\right)I_i\left(\frac{A_2 r_2}{\sigma_2^2(1+\rho)}\right)+$$

$$+P_1 D_2(r_1)D_1(r_2)+$$

$$+P_2\left(1-Q_1\left(A/\sigma_2, r_t/\sigma_2\right)\right)\cdot$$

$$\cdot\frac{r_1 r_2}{\sigma_1^4(1-\rho^2)}e^{-\frac{r_1^2+r_2^2+2A_1^2(1-\rho)}{2\sigma_1^2(1-\rho^2)}}\cdot$$

$$\cdot\sum_{i=0}^{\infty}\varepsilon_i I_i\left(\frac{\rho r_1 r_2}{\sigma_1^2(1-\rho^2)}\right)I_i\left(\frac{A_1 r_1}{\sigma_1^2(1+\rho)}\right)I_i\left(\frac{A_1 r_2}{\sigma_1^2(1+\rho)}\right)+$$

$$+P_2 D_1(r_1)D_2(r_2)\Big]dr_1 dr_2+$$

$$+\int_{r_T}^{r}\int_{r_T}^{r}\Bigg[P_1\frac{r_1 r_2}{\sigma_1^4(1-\rho^2)}e^{-\frac{r_1^2+r_2^2+2A_1^2(1-\rho)}{2\sigma_1^2(1-\rho^2)}}\cdot$$

$$\cdot\sum_{i=0}^{\infty}\varepsilon_i I_i\left(\frac{\rho r_1 r_2}{\sigma_1^2(1-\rho^2)}\right)I_i\left(\frac{A_1 r_1}{\sigma_1^2(1+\rho)}\right)I_i\left(\frac{A_1 r_2}{\sigma_1^2(1+\rho)}\right)+$$

$$
\begin{aligned}
&+P_1\left(1-Q_1\left(A/\sigma_1, r_t/\sigma_1\right)\right)\cdot \\
&\cdot\frac{r_1 r_2}{\sigma_2{}^4(1-\rho^2)} e^{-\frac{r_1{}^2+r_2{}^2+2A_2{}^2(1-\rho)}{2\sigma_2{}^2(1-\rho^2)}}\cdot \\
&\cdot\sum_{i=0}^{\infty}\varepsilon_i I_i\left(\frac{\rho r_1 r_2}{\sigma_2{}^2(1-\rho^2)}\right) I_i\left(\frac{A_2 r_1}{\sigma_2{}^2(1+\rho)}\right) I_i\left(\frac{A_2 r_2}{\sigma_2{}^2(1+\rho)}\right)+ \\
&+P_1\frac{r_2}{\sigma_2{}^2} e^{-\frac{r_2{}^2+A_2{}^2}{2\sigma_2{}^2}} I_0\left(\frac{r_2 A_2}{\sigma_2{}^2}\right) D_1(r_1)+P_1 D_2(r_1) D_1(r_2)+ \\
&+P_2\frac{r_1 r_2}{\sigma_2{}^4(1-\rho^2)} e^{-\frac{r_1{}^2+r_2{}^2+2A_2{}^2(1-\rho)}{2\sigma_2{}^2(1-\rho^2)}}\cdot \\
&\cdot\sum_{i=0}^{\infty}\varepsilon_i I_i\left(\frac{\rho r_1 r_2}{\sigma_2{}^2(1-\rho^2)}\right) I_i\left(\frac{A_2 r_1}{\sigma_2{}^2(1+\rho)}\right) I_i\left(\frac{A_2 r_2}{\sigma_2{}^2(1+\rho)}\right)+ \\
&+P_2\left(1-Q_1\left(A/\sigma_2, r_t/\sigma_2\right)\right)\cdot \\
&\cdot\frac{r_1 r_2}{\sigma_1{}^4(1-\rho^2)} e^{-\frac{r_1{}^2+r_2{}^2+2A_1{}^2(1-\rho)}{2\sigma_1{}^2(1-\rho^2)}}\cdot \\
&\cdot\sum_{i=0}^{\infty}\varepsilon_i I_i\left(\frac{\rho r_1 r_2}{\sigma_1{}^2(1-\rho^2)}\right) I_i\left(\frac{A_1 r_1}{\sigma_1{}^2(1+\rho)}\right) I_i\left(\frac{A_1 r_2}{\sigma_1{}^2(1+\rho)}\right)+ \\
&\left.+P_2\frac{r_2}{\sigma_1{}^2} e^{-\frac{r_2{}^2+A_1{}^2}{2\sigma_1{}^2}} I_0\left(\frac{r_2 A_1}{\sigma_1{}^2}\right) D_2(r_1)+P_2 D_1(r_1) D_2(r_2)\right] dr_1 dr_2
\end{aligned}
\tag{32}
$$

The level crossing rate (LRC) and average fade duration (AFD) curves for complex SSC/SC combiner at two time instants in the presence of Rician fading, depending on different values of the signal and derivative distributions' parameters, are shown in Figs. 4 to 7.

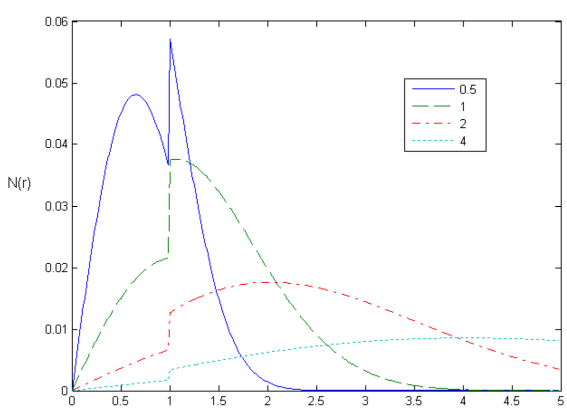

Figure 4. Level crossing rate $N(r)$ of SSC/SC combiner, at two time instants, versus signal amplitude for r_t=1, σ =0.5; 1; 2; 4, A =0.5 and $\dot{\sigma}$ =0.2

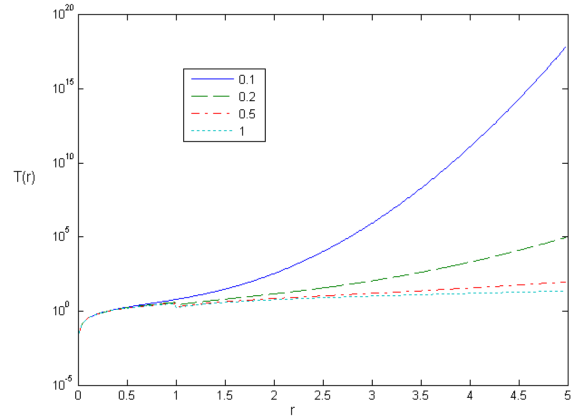

Figure 5. Average fade duration $T(r)$ of SSC/SC combiner, at two time instants, versus signal amplitude r, for r_t=1, σ =0.1; 0.2; 0.5; 1, A =0.5 and $\dot{\sigma}$ =0.2

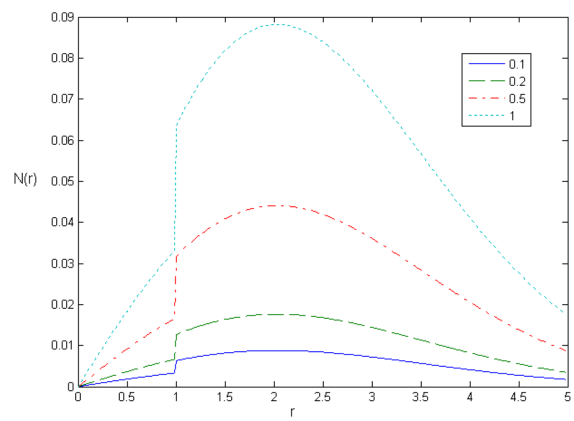

Figure 6. Level crossing rate $N(r)$ of SSC/SC combiner, at two time instants, versus signal amplitude r, for r_t=1, σ =2, A =0.5 and $\dot{\sigma}$ =0.1; 0.2; 0.5; 1

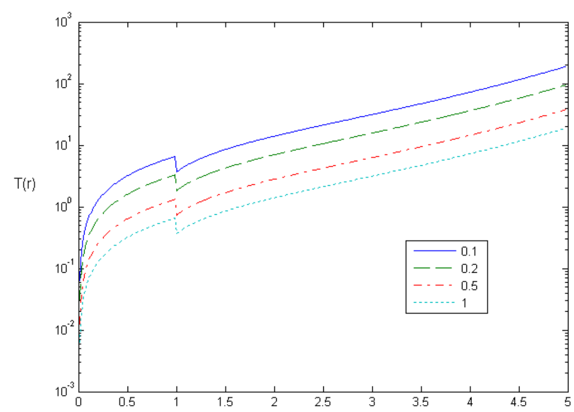

Figure 7. Average fade duration $T(r)$ of SSC/SC combiner, at two time instants, versus signal amplitude r, for r_t=1, σ =2, A =0.5 and $\dot{\sigma}$ =0.1; 0.2; 0.5; 1

Observing the first order system characteristics of SSC/SC combiner at two time instants presented in Fig. 2. [13, 14], it is obvious that the benefit of using complex SSC/SC combiner exists and it increases with decreasing of correlation between input signals.

Because of that, the expressions for second order system performance are derived in this paper and the influence of system parameters at second order system characteristics is shown in all these figures. These results are useful for designing and analyzing of wireless communication systems.

The level crossing rate of SSC/SC combiner at two time instants versus signal amplitude, $N(r)$, for r_t=1, A =0.5 and $\dot{\sigma}$=0 and different values of σ is presented in Fig. 4. It is visible from this figure that system performances are better for bigger values of parameter σ, because the system performances are better for lower values of average level crossing rate.

The level crossing rate of SSC/SC combiner at two time instants $N(r)$, for r_t=1, σ =2, A =0.5 and different values of $\dot{\sigma}$ is plotted in Fig. 6. One can see from this figure that system performances are better for lower values of parameter $\dot{\sigma}$.

The curves for average fade duration of SSC/SC combiner at two time instants, $T(r)$, are drawn in Figs. 5 and 7. The parameters' values are r_t=1, A =0.5 and $\dot{\sigma}$=0.2 in Fig. 5. Variable is parameter σ. It is evident that performances are better for greater values of parameter σ (lower values for AFD). The parameters' values are r_t=1, σ=2, A=0.5 in Fig. 7, with changeable $\dot{\sigma}$. One can conclude that results are more favorable for greater values of parameter $\dot{\sigma}$.

From all this figures it can be noticed that values of the LCR and AFD are growing, have discontinuity in the value of the threshold, where there is a drop in the values, and then are continuing to grow. In the case of LCR, the increasing of the value is evident till it reaches a maximum and then begins to fall. The system performance are better for lower values of average level crossing rate. For smaller LCR (i.e., the shallower fades), correspondingly AFD is larger. AFD increases with the value of the signal amplitude in whole range, but the curves also have drops at the threshold values.

VI. CONCLUSION

In this paper, the expressions for probability density functions (PDFs) of the time derivatives at two time instants for output signals from dual branch SSC combiner in the presence of Rician fading are given. The second order characteristics: the average level crossing rate and the average fade duration for complex combiner who makes the decision based on sampling at two time instants, are calculated by using derived closed-form expressions for the case of SSC/SC combiner. To point out the improvement of using complex SSC/SC combiner compared to classical SSC and SC combiners at one time instant, some graphs are presented earlier for several fading distributions.

Here, the second order system performances are calculated and presented graphically. These results are valuable in analyzing and projecting of wireless communication systems in the presence of Rician fading.

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