Performance Analysis of SSC Diversity Receiver over Correlated Hoyt Fading Channels

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Abstract. *An infinite-series-based approach for the performance analysis of a dual-branch switched-and-stay combining (SSC) diversity receiver operating over correlated Hoyt fading channels is presented. The performance analysis is based on outage probability (P_{out}) and average bit error probability (ABEP) criteria. More precisely, the ABEP performance is evaluated for binary differential phase-shift-keying (BDPSK) and binary non-coherent frequency-shift keying (BNFSK) modulation schemes. Derived analytical expressions are easily computable and fast converging, which provides a significant improvement in calculation speed. Obtained numerical results corresponding to different fading channel conditions are graphically illustrated and analyzed.*

Keywords

Bivariate Hoyt distribution, performance analysis, outage probability, average bit error probability.

1. Introduction

Hoyt distribution was introduced as an approximation of Nakagami-m distribution [1]. It's normally observed on satellite links subject to strong ionospheric scintillation and ranges from one-sided Gaussian fading to Rayleigh distribution [2]. However, there are a number of papers where Hoyt distribution has been used in performance analysis of mobile radio communications and for describing fading statistics of the real-world communication channels, for example [3]-[5]. The performance analyses of diversity receivers operating over Hoyt fading channels usually assume independent fading channels, neglecting the impact of cross-channel correlation, for example [6]-[8]. The main reasons for this are very complex and not tractable mathematical expressions that appear in performance analyses involving multivariate Hoyt probability density function (PDF). There are a number of papers dealing with infinite series based representations of the most frequently used bivariate distributions, such as Rayleigh, Nakagami-m and Rician distributions [9]-[10]. Recently, an infinite series based expression for the bivariate Hoyt distribution with arbitrary correlation in a non-stationary environment was derived [11]. In the same paper, expressions for the joint PDF and joint cumulative distribution function (CDF) are also derived in infinite series form, as well as expressions for P_{out} of the dual-branch equal-gain combining (EGC) and maximal-ratio combining (MRC) diversity receivers in correlated Hoyt fading channels. Exploiting the same mathematical approach, a performance analysis of a dual-branch selection combining (SC) diversity receiver in terms of P_{out} and ABEP has been presented in [12]. A novel easily computable infinite series based expression for bivariate Hoyt distribution has been derived and proposed for performance evaluation of dual-branch diversity receivers operating over correlated Hoyt fading channels in [13]. A detailed analysis of the proposed solution and its practical applicability have been presented in [13] on the example of a dual SC receiver in terms of P_{out} and ABEP criteria.

In this paper, capitalizing on the expression for Hoyt bivariate PDF derived in [13], the performance evaluation of a dual-branch SSC diversity receiver operating over correlated Hoyt fading channels in terms of P_{out} and ABEP has been performed. The ABEP performance is evaluated for BDPSK and BNFSK modulation schemes. To the best knowledge of authors, here presented performance analysis is a novelty, since still there is no paper published in the open scientific literature dealing with this topic.

2. System and Channel Model

Let us consider a dual-branch SSC diversity receiver operating over correlated Hoyt fading channels. The additive white Gaussian noise (AWGN) is assumed to be uncorrelated between two diversity branches. Let $\gamma_i = r_i^2 E_s / 2N_0$, with E_s / N_0 being the symbol energy-to-Gaussian noise spectral density ratio, denote the instantaneous signal-to-noise ratio (SNR) at the $i-$branch ($i = 1, 2$). In the above equation, r_i is modelled as $r_i^2 = x_{i1}^2 + x_{i2}^2$, where x_{i1} and x_{i2} are independent, in phase and quadrature, zero-mean Gaussian random variables with variances σ_1^2 and σ_1^2, respectively [13]. Also, let

$$\bar{\gamma}_1 = \sigma_1^2 E_s / 2N_0 \text{ and } \bar{\gamma}_2 = \sigma_2^2 E_s / 2N_0$$

denote the mean SNR of the signal components in-phase and quadrature, respectively. Finally, let γ_{SSC} represent the instantaneous SNR per symbol at the output of the SSC diversity receiver, and γ_τ the predetermined switching threshold.

2.1 The Bivariate Hoyt PDF

The PDF of γ_{ssc} is given by [14]

$$f_{\gamma_{ssc}}(\gamma)=\begin{cases} r_{ssc}(\gamma), & \gamma \le \gamma_\tau, \\ r_{ssc}(\gamma)+f_\gamma(\gamma), & \gamma > \gamma_\tau. \end{cases} \quad (1)$$

Moreover, $r_{ssc}(\gamma)$ is given in [15, eq. (21b)] as

$$r_{ssc}(\gamma)=\int_0^{\gamma_\tau} f_{\gamma_1,\gamma_2}(\gamma,\gamma_2)d\gamma_2,$$

i.e.

$$r_{ssc}(\gamma)=\int_0^{\infty} f_{\gamma_1,\gamma_2}(\gamma,\gamma_2)d\gamma_2-\int_{\gamma_\tau}^{\infty} f_{\gamma_1,\gamma_2}(\gamma,\gamma_2)d\gamma_2 \quad (2)$$

where $f_{\gamma_1,\gamma_2}(\cdot,\cdot)$ is the joint PDF of γ_1 and γ_2, while $f_\gamma(\gamma)$ is the PDF of the SNR of the Hoyt distribution given in [2, eq. (2.11)]. The joint PDF of γ_1 and γ_2, based on [13, eq. (6) – (10)] can be expressed in the form of infinite series as

$$f_{\gamma_1\gamma_2}(\gamma_1,\gamma_2)=\upsilon(\gamma_1,\gamma_2)$$

$$\times \sum_{k,l,m,n=0}^{\infty} \zeta(\gamma_1,\gamma_2,k,l,m,n)\delta(k,l,m,n)\,\xi(k,l,m,n) \quad (3)$$

where

$$\upsilon(\gamma_1,\gamma_2)=\frac{Exp\left[-\frac{\gamma_1+\gamma_2}{4(1-\rho^2)}\left(\frac{1}{\bar{\gamma}_1}+\frac{1}{\bar{\gamma}_2}\right)\right]}{16\pi^2\bar{\gamma}_1\bar{\gamma}_2(1-\rho^2)}, \quad (4)$$

$$\zeta(\gamma_1,\gamma_2,k,l,m,n)=$$

$$=I_k\left(\frac{\gamma_1}{4(1-\rho^2)}\left(\frac{1}{\bar{\gamma}_2}-\frac{1}{\bar{\gamma}_1}\right)\right)I_l\left(\frac{\gamma_2}{4(1-\rho^2)}\left(\frac{1}{\bar{\gamma}_2}-\frac{1}{\bar{\gamma}_1}\right)\right)$$

$$\times I_m\left(\frac{\rho\gamma_1\gamma_2}{2(1-\rho^2)}\left(\frac{1}{\bar{\gamma}_1}+\frac{1}{\bar{\gamma}_2}\right)\right)I_n\left(\frac{\rho\gamma_1\gamma_2}{2(1-\rho^2)}\left(\frac{1}{\bar{\gamma}_1}-\frac{1}{\bar{\gamma}_2}\right)\right), \quad (5)$$

$$\delta(k,l,m,n)=\begin{cases} 1 & \textit{iff } k=l=m=n=0, \\ 2 & \textit{iff} \text{ one of the parameters is} \ne 0, \\ 4 & \textit{iff} \text{ two of the parameters are} \ne 0, \\ 8 & \textit{iff} \text{ three of the parameters are} \ne 0, \\ 16 & \textit{iff } k\ne 0 \wedge l\ne 0 \wedge m\ne 0 \wedge n\ne 0, \end{cases} \quad (6)$$

$$\xi(k,l,m,n)=\int_{-\pi}^{\pi}\int_{-\pi}^{\pi} Cos[2k\theta]Cos[2l\varphi]$$

$$\times Cos[m(\theta-\varphi)]Cos[n(\theta+\varphi)]d\theta d\varphi. \quad (7)$$

In (4) and (5), ρ is the correlation coefficient between γ_1 and γ_2, while in (7), θ and φ are polar angles of r_1 and r_2, respectively [13]. After a series of mathematical manipulation, the authors have found and proposed the following closed form solution of the integral in (7)

$$\xi(k,l,m,n)=\begin{cases} 4\pi^2 & k=l=m=n=0 \\ \pi^2 & ((k=0\wedge l\ne 0)\vee(k\ne 0\wedge l=0)\vee k=l\ne 0)\wedge \\ & ((m=k+l\wedge n=|k-l|)\vee(m=|k-l|\wedge n=k+l)) \\ \frac{\pi^2}{2} & k\ne l\ne 0\wedge((m=k+l\wedge n=|k-l|)\vee \\ & (m=|k-l|\wedge n=k+l)) \\ 0 & \textit{for all other cases} \end{cases}$$

(8)

Capitalizing on the previous expression, i.e. the function $\xi(k, l, m, n)$, the largest number of terms in (3) is equal to zero, while only a relatively small number of non-zero terms need to be summed in order to obtain the given accuracy [13, Tab. 1] . This is also partially illustrated in the following Tab. 1, where we assumed due to simplicity, but without losing on validity that $k = l = m = n$

k,l,m,n	$NoT \ne 0$	$NoT = 0$
0	1	0
1	3	13
2	7	74
3	13	243
4	21	604
5	31	1265
6	43	2358
7	57	4039
8	73	6488
9	91	9909

Tab. 1. The number of non-zero terms ($NoT \ne 0$) and the number of equal to zero terms ($NoT = 0$) in (3), for different values of *k, l, m* and *n*.

2.2 The Bivariate Hoyt CDF

Similar to [15, eq. (20)], the CDF of γ_{ssc}, $F_{\gamma_{ssc}}(\gamma)$, after some manipulations can be expressed as

$$F_{\gamma_{ssc}}(\gamma)=\begin{cases} F_{\gamma_1,\gamma_2}(\gamma,\gamma_\tau), & \gamma\le\gamma_\tau, \\ F_\gamma(\gamma)-F_\gamma(\gamma_\tau)+F_{\gamma_1,\gamma_2}(\gamma,\gamma_\tau) & \gamma>\gamma_\tau, \end{cases} \quad (9)$$

where

$$F_{\gamma_1,\gamma_2}(\gamma,\gamma_\tau)=\int_0^{\gamma}\int_0^{\gamma_\tau} f_{\gamma_1,\gamma_2}(\gamma_1,\gamma_2)d\gamma_1 d\gamma_2. \quad (10)$$

3. Outage Probability

The outage probability of the SSC receiver, P_{out}, defined as the probability that the SSC receiver output SNR falls below a given outage threshold γ_{th}, can be expressed as

$$P_{out}(\gamma_{th})=F_{\gamma_{ssc}}(\gamma_{th}). \quad (11)$$

It is straightforward to show that based on (3) - (8), and after some mathematical manipulations, (10) can be expressed as

$$F_{\gamma_1,\gamma_2}(\gamma_{th},\gamma_\tau) = \sum_{k,l,m,n=0}^{\infty}\delta(k,l,m,n)\,\xi(k,l,m,n)$$
$$\times\sum_{a,b,c,d=0}^{\infty}\frac{(-1)^{2d+n}(1-\rho^2)\rho^{2(c+d)+m+n}}{2^{2(a+b)+k+l}\pi^2(\bar{\gamma}_1+\bar{\gamma}_2)^{2(a+b+d+1)+k+l+n}}$$
$$\times\frac{\bar{\gamma}_1\bar{\gamma}_2(\bar{\gamma}_1-\bar{\gamma}_2)^{2(a+b+d)+k+l+n}}{a!b!c!d!\Gamma(a+k+1)\Gamma(b+l+1)\Gamma(c+m+1)\Gamma(d+n+1)}$$
$$\times\left(\Gamma\left(2a+c+d+k+\frac{m+n}{2}+1\right)-\right.$$
$$\left.\Gamma\left(2a+c+d+k+\frac{m+n}{2}+1,\frac{\gamma_{th}}{4(1-\rho^2)}\left(\frac{1}{\bar{\gamma}_1}+\frac{1}{\bar{\gamma}_2}\right)\right)\right)$$
$$\times\left(\Gamma\left(2b+c+d+l+\frac{m+n}{2}+1\right)-\right.$$
$$\left.\Gamma\left(2b+c+d+l+\frac{m+n}{2}+1,\frac{\gamma_\tau}{4(1-\rho^2)}\left(\frac{1}{\bar{\gamma}_1}+\frac{1}{\bar{\gamma}_2}\right)\right)\right). \tag{12}$$

4. Average Bit Error Probability

The ABEP, $\bar{P}_e$, can be evaluated by averaging the conditional symbol error probability, $P_e(\gamma)$, over the PDF of γ_{SSC}, i.e.

$$\bar{P}_e = \int_0^\infty P_e(\gamma) f_{\gamma_{ssc}}(\gamma)d\gamma \tag{13}$$

where $P_e(\gamma)$ depends on applied modulation scheme. Thus, for BDPSK and BNFSK $P_e(\gamma) = \exp(-\lambda\gamma)/2$, where $\lambda = 1$ and $\lambda = 1/2$, respectively [16]. Accordingly, $f_{\gamma_{ssc}}(\gamma)$ is the PDF of the SSC receiver output SNR. By using (1), $\bar{P}_e$ can be expressed as

$$\bar{P}_e = \frac{1}{2}\left[\int_0^\infty \exp(-\lambda\gamma) r_{ssc}(\gamma)d\gamma + \int_{\gamma_{th}}^\infty \exp(-\lambda\gamma) f_\gamma(\gamma)d\gamma\right], \tag{14}$$

i.e. $\bar{P}_e = I_1 + I_2$, whereby after some straightforward mathematical manipulations I_1 and I_2 can be expressed respectively as

$$I_1 = \frac{1}{2}\int_0^\infty \exp(-\lambda\gamma) r_{ssc}(\gamma)d\gamma$$
$$= \sum_{k,l,m,n=0}^{\infty}\frac{(1-\rho^2)\bar{\gamma}_1\bar{\gamma}_2\delta(k,l,m,n)\,\xi(k,l,m,n)}{\left(\bar{\gamma}_1+\bar{\gamma}_2+4\lambda\bar{\gamma}_1\bar{\gamma}_2(1-\rho^2)\right)^{2a+c+d+k+(\frac{n}{2}+\frac{m}{2})+1}}$$
$$\times\sum_{a,b,c,d=0}^{\infty}\frac{\rho^{2(c+d)+m+n}(\bar{\gamma}_1-\bar{\gamma}_2)^{2(a+b+d)+k+l+n}}{(-1)^{2d+n}\pi^2(\bar{\gamma}_1+\bar{\gamma}_2)^{2b-c+d+l+(n/2-m/2)+1}}s$$
$$\times\frac{2^{-2(a+b)-k-l-1}\Gamma\left(2a+c+d+k+\frac{m+n}{2}+1\right)}{a!b!c!d!\Gamma(a+k+1)\Gamma(b+l+1)\Gamma(c+m+1)\Gamma(d+n+1)}$$
$$\times\left(\Gamma\left(2a+c+d+k+\frac{m+n}{2}+1\right)-\right.$$
$$\left.\Gamma\left(2a+c+d+k+\frac{m+n}{2}+1,\frac{\gamma_{th}}{4(1-\rho^2)}\left(\frac{1}{\bar{\gamma}_1}+\frac{1}{\bar{\gamma}_2}\right)\right)\right) \tag{15}$$

and

$$I_2 = \frac{1}{2}\int_{\gamma_{th}}^\infty \exp(-\lambda\gamma) f_\gamma(\gamma)d\gamma$$
$$I_2 = \sum_{t=0}^{\infty}\frac{4^{-t}q(1+q^2)(1-q^4)^{2t}}{\left(1+q^4+q^2(2+4\lambda\bar{\gamma})\right)^{2t+1}t!\Gamma(1+t)}$$
$$\times\Gamma\left(1+2t,\frac{\gamma_{th}\left(1+q^4+q^2(2+4\lambda\bar{\gamma})\right)}{q^2\bar{\gamma}}\right) \tag{16}$$

where q is the Nakagami-q fading parameter, which ranges from 0 to 1 [2, eq. (2.11)].

5. Results and Discussion

Using (11), the outage performance of a dual-branch SSC receiver operating in correlated Hoyt fading channels have been numerically evaluated. In Fig. 1, the outage performance is plotted as a function of the normalized outage threshold, $\gamma_{th}/\bar{\gamma}_1$, for several values of ρ. It is assumed $\bar{\gamma}_1 = 2\,\bar{\gamma}_2$ and $\gamma_\tau/\bar{\gamma}_1 = 2.5$ dB. As expected, the results show that the outage performance degrades with increase of ρ. By using (13), in Fig. 2 is plotted the ABEP performance for BDPSK and BNFSK modulation schemes, as a function of the input in-phase average SNR per bit, $\bar{\gamma}_1$, for several values of ρ. It is assumed $\bar{\gamma}_1 = 2\,\bar{\gamma}_2$ and $\gamma_{th} = 5$ dB. Fig. 2 indicates that the ABEP performance improves as ρ decreases, and better performance of the BDPSK modulation schemes.

Additionally, as expected, it is observed for both (11) and (13) that the number of required terms, that need to be summed in order to obtain the given accuracy, increases as the correlation coefficient ρ and/or the ratio $\bar{\gamma}_1/\bar{\gamma}_2$ increase. It is a consequence of the fact that the both (11) and (13) are derived from (3), i.e. [13, eq. (6) – (10)]. On the other hand, it has been also indicated by results presented in Tab. 2.

Similarly to analyses presented in [13] and [17], in Tab. 2 the CPU times for (11) are presented and compared, in cases when $F_{\gamma_1,\gamma_2}(\gamma, \gamma_\tau)$ is given by (12), i.e. by using our method (OM), and (10), i.e. by using the traditional integral expression (TIE), for several values of ρ. The adaptive

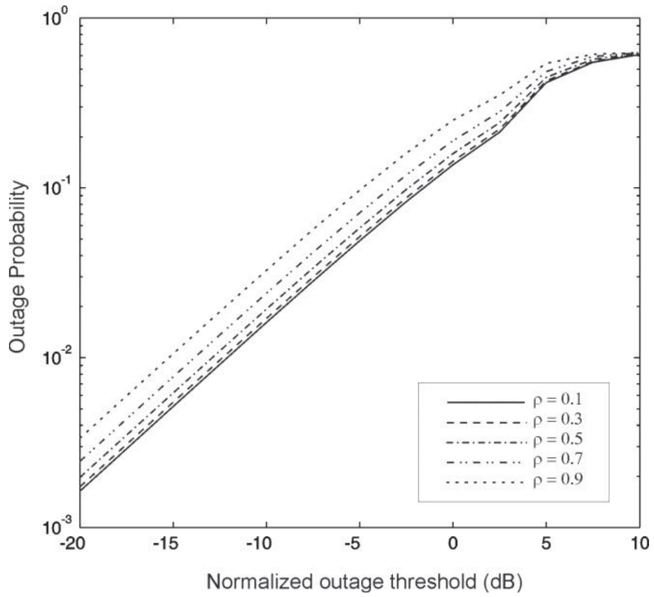

Fig. 1. P_{out} of a dual-branch SSC receiver as a function of $\gamma_{th} / \bar{\gamma}_1$, for several values of ρ.

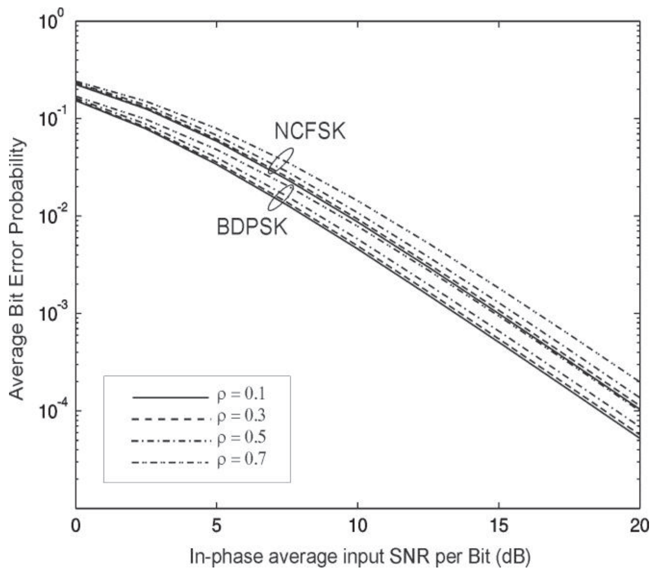

Fig. 2. ABEP of a dual-branch SSC receiver as a function of $\bar{\gamma}_1$, for several values of ρ.

ρ	TIE	OM
0.1	47.467	1.156
0.3	55.186	3.546
0.5	85.711	3.703
0.7	175.487	85.013
0.9	760.466	486.881

Tab. 2. Comparison of the CPU times (in seconds) for (11), where $F_{\gamma_1,\gamma_2}(\gamma, \gamma_2)$ is given by (12) and (10), for several values of ρ and six significant digits accuracy.

numerical integration technique [18] was used for evaluation of (10). In both cases, an accuracy of six significant digits was required. All calculations were performed under the identical conditions, on a system with Intel® Core™2 Duo CPU P9400 at 2.4GHz. The obtained results clearly show that the CPU time is increased proportionally with the correlation, and that (11) is evaluated significantly faster by using our method for all values of the correlation coefficient, especially for its lower values.

6. Conclusion

A recently published infinite series based expression for bivariate Hoyt distribution has been used for performance evaluation of a dual-branch SSC diversity receiver operating over correlated Hoyt fading channels. The performance is evaluated in terms of the outage probability and the average bit error probability criteria. Derived analytical expressions are also infinite series based, relatively simple for calculation and fast converging. The obtained numerical results, corresponding to different values of the correlation coefficient are graphically presented.

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