Performance Analysis of Selection Combining Over Correlated Nakagami-*m* Fading Channels with Constant Correlation Model for Desired Signal and Cochannel Interference

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Abstract. *A very efficient technique that reduces fading and channel interference influence is selection diversity based on the signal to interference ratio (SIR). In this paper, system performances of selection combiner (SC) over correlated Nakagami-m channels with constant correlation model are analyzed. Closed-form expressions are obtained for the output SIR probability density function (PDF) and cumulative distribution function (CDF) which is main contribution of this paper. Outage probability and the average error probability for coherent, noncoherent modulation are derived. Numerical results presented in this paper point out the effects of fading severity and correlation on the system performances. The main contribution of this analysis for multibranch signal combiner is that it has been done for general case of correlated co-channel interference (CCI).*

Keywords

Correlated co-channel interference, Nakagami-*m* constant correlation fading, selection combining (SC), signal to interference ratio (SIR).

1. Introduction

Interest in wireless communications has increased recently due to the rapid growth of mobile communications as well as the emergence of wireless Local Area Network (LAN) technologies. Multipath fading can seriously degrade system performances of wireless communications. In wireless communication systems various techniques for reducing fading effect and influence of cochannel interference are used [1]. The goal of diversity techniques is to upgrade transmission reliability without increasing transmission power and bandwidth and to increase channel capacity. Space diversity is an efficient method for amelioration system's quality of service (QoS) when multiple receiver antennas are used [2]. There are several principal types of combining techniques and division can be generally performed by their dependence on complexity restriction put on the communication system and amount of channel state information available at the receiver. Selection combining (SC) is one of the least complicated combining methods. In general, selection combining, assuming that noise power is equally distributed over branches, selects the branch with the highest signal-to-noise ratio (SNR), which is the branch with the strongest signal [1-4]. In fading environments as in cellular systems where the level of the cochannel interference is sufficiently high as compared to the thermal noise, SC selects the branch with the highest signal-to-interference ratio (SIR-based selection diversity) [5] This type of SC can be measured in real time both in base stations and in mobile stations using specific SIR estimators as well as those for both analog and digital wireless systems (e.g., GSM, IS-54) [6], [7]. Most of the recently the published papers assume independent fading between the diversity branches and also between the cochannel interferers [8]-[10].

However, independent fading assumes antenna elements to be placed sufficiently apart, which is not general case in practice due to insufficient spacing between antennas. When diversity system is applied on small terminals with multiple antennas, correlation arises between branches [11].

It has been found experimentally, that the Nakagami-*m* distribution offers a better fit for a wider range of fading conditions in wireless communications [12], [13]. Several correlation models have been proposed and used in the literature for evaluating performance of diversity systems. The constant correlation model corresponds to a scenario with closely placed diversity antennas and circular symmetric antenna arrays [14], [15]. The effect of correlated fading has been extensively analyzed on the performance metrics of wireless communication system. In papers [16]-[19] selection diversity over Weibull fading channels has been analyzed. In recent works [20], [21] the joint PDF and CDF of the multivariate Nakagami-*m* and Rayleigh distributions, respectively, are developed for the case of exponential correlation. In paper [22] analysis of signal combining for Nakagami-*m* distributed with constant correlation model of fading has been given, but with the total independence between interferences received on any pair of inputs of the combiner.

More general case is when the arbitrary correlation is present between the signals and interferences. Moreover, to the best author's knowledge, no analytical study of multi-branch selection combining involving assumed constant correlated Nakagami-*m* fading for both desired signal and co-channel interference, with arbitrary correlation coefficients between fading signals and between interferences has been reported in the literature.

2. Statistic of the SC Output SIR

The performance of the multibranch SC can be carried out by considering, as in [11], [16], [23], the insufficient antenna spacing, both desired and interfering signal envelopes experience correlative multivariate Nakagami-*m* fading with joint distributions.

We are considering constant correlation Nakagmi-*m* model of distribution. The power correlation coefficient ρ_d for desired signal is defined as $cov(R_i^2, R_j^2)/(var(R_i^2)var(R_j^2))^{1/2}$ and power correlation coefficient ρ_c for interfering signal is defined as $cov(r_i^2, r_j^2)/(var(r_i^2)var(r_j^2))^{1/2}$.

We are assuming arbitrary correlation coefficients between fading signals and between interferences, because correlation coefficients depend on the arrival angles of the contribution with the broadside directions of antennas, which are in general case arbitrary [24].

The constant correlation model [25] can be obtained from by setting in correlation matrix $\Sigma_{i,j} \equiv 1$ for $i = j$ and $\Sigma_{i,j} \equiv \rho$ for $i \neq j$, for both desired signal and interference. Now joint distributions of pdf for both desired and interfering signal correlated envelopes for multi-branch signal combiner could be expressed by [22]:

$$p_{R_1 \ldots R_n}(R_1,...,R_n) = \frac{\left(1-\sqrt{\rho_d}\right)^{m_d}}{\Gamma(m_d)} \sum_{k_1=0}^{\infty} ... \sum_{k_n=0}^{\infty} \left[\frac{2^n}{\Gamma(m_d+k_1)\cdots\Gamma(m_d+k_n)} \right.$$
$$\times \frac{\Gamma(m_d+k_1+...+k_n)}{k_1!\cdots k_n!} \rho_d^{\frac{k_1+...+k_n}{2}} \left(\frac{1}{1+(n-1)\sqrt{\rho_d}} \right)^{m_d+k_1...+k_n}$$
$$\times \left(\frac{m_d}{\Omega_{d_1}\left(1-\sqrt{\rho_d}\right)} \right)^{m_d+k_1} \cdots \left(\frac{m_d}{\Omega_{d_n}(1-\rho_d)} \right)^{m_d+k_n} R_1^{2m_d+2k_1-1} \cdots R_n^{2m_d+2k_n-1}$$
$$\left. \times \exp\left(\frac{m_d R_1^2}{\Omega_{d_1}\left(1-\sqrt{\rho_d}\right)} \right) \cdots \exp\left(\frac{m_d R_n^2}{\Omega_{d_n}(1-\rho_d)} \right) \right]$$

$$p_{r_1 \ldots r_n}(r_1,...,r_n) = \frac{\left(1-\sqrt{\rho_c}\right)^{m_c}}{\Gamma(m_c)} \sum_{l_1=0}^{\infty} ... \sum_{l_n=0}^{\infty} \left[\frac{2^n}{\Gamma(m_c+l_1)\cdots\Gamma(m_c+l_n)} \right.$$
$$\times \frac{\Gamma(m_c+l_1+...+l_n)}{l_1!\cdots l_n!} \rho_c^{\frac{l_1+...+l_n}{2}} \left(\frac{1}{1+(n-1)\sqrt{\rho_c}} \right)^{m_c+l_1...+l_n} \quad (1)$$
$$\times \left(\frac{m_c}{\Omega_{c1}\left(1-\sqrt{\rho_c}\right)} \right)^{m_c+l_1} \cdots \left(\frac{m_c}{\Omega_{cn}(1-\rho_c)} \right)^{m_d+l_n} r_1^{2m_c+2l_1-1} \cdots r_n^{2m_c+2l_n-1}$$
$$\left. \times \exp\left(\frac{m_c r_1^2}{\Omega_{c_1}\left(1-\sqrt{\rho_c}\right)} \right) \cdots \exp\left(\frac{m_c r_n^2}{\Omega_{c_n}(1-\rho_c)} \right) \right]$$

where m_d ,$m_c > 0.5$ are the fading severity parameters for the desired and interference signal, correspondingly. $\Omega_{dk}=\overline{R_k^2}$ and $\Omega_{ik}=\overline{r_k^2}$ are the average signal desired and interference powers at *i*-th branch, respectively. Instantaneous values of SIR at the *k*-th diversity branch input can be defined as $\lambda_k=R_k^2/r_k^2$ [26]. The selection combiner chooses and outputs the branch with the largest SIR, following $\lambda = \lambda_{out} = \max(\lambda_1, \lambda_2, ..., \lambda_N)$.

Let $S_k = \Omega_{dk} / \Omega_{ik}$ be the average SIR's at the *k*-th input branch of the multi-branch selection combiner. Joint probability density function of instantaneous values of SIR in *n* output branches λ_k, $k = 1,\ldots,N$, as in [5],

$$p_{\lambda_1,...,\lambda_n}(t_1,...,t_n) = \frac{1}{2^n\sqrt{t_1\cdots t_n}} \times$$
$$\times \int_0^{\infty}\int_0^{\infty} p_{R_1,...,R_n}\left(r_1\sqrt{t_1},...,r_n\sqrt{t_n}\right) p_{r_1,...,r_n}(r_1,...,r_n) r_1\cdots r_n d_{r_1}\cdots d_{r_n} \quad .(2)$$

Substituting (1) in (2), we obtain:

$$p_{\lambda_1,...,\lambda_n}(t_1,...,t_n) = \underbrace{\sum_{k_1,...k_n=0}^{\infty} \sum_{l_1,...,l_n=0}^{\infty}}_{2n} G_1 \left(\frac{m_c\left(1-\sqrt{\rho_d}\right)}{m_d\left(1-\sqrt{\rho_c}\right)} S_1 \right)^{m_c+l_1} \cdots \left(\frac{m_c\left(1-\sqrt{\rho_d}\right)}{m_d\left(1-\sqrt{\rho_c}\right)} S_n \right)^{m_c+l_n}$$
$$\times \frac{t_1^{m_d+k_1-1}}{\left(t_1 + \frac{m_c\left(1-\sqrt{\rho_d}\right)}{m_d\left(1-\sqrt{\rho_c}\right)} S_1 \right)^{m_d+m_c+k_1+l_1}} \cdots \frac{t_n^{m_d+k_n-1}}{\left(t_n + \frac{m_c\left(1-\sqrt{\rho_d}\right)}{m_d\left(1-\sqrt{\rho_c}\right)} S_n \right)^{m_d+m_c+k_n+l_n}}$$

$$G_1 = \frac{\left(1-\sqrt{\rho_d}\right)^{m_d}\left(1-\sqrt{\rho_c}\right)^{m_c}\Gamma(m_d+k_1+...+k_n)\Gamma(m_c+l_1+...+l_n)}{\Gamma(m_d)\Gamma(m_c)\Gamma(m_d+k_1)\cdots\Gamma(m_d+k_n)} \quad . (3)$$
$$\times \frac{\Gamma(m_d+m_c+k_1+l_1)\cdots\Gamma(m_d+m_c+k_1+l_n)}{\Gamma(m_c+l_1)\cdots\Gamma(m_c+l_n)k_1!\cdots k_n! l_1!\cdots l_n!}$$
$$\times \rho_d^{\frac{k_1+...+k_n}{2}} \rho_c^{\frac{l_1+...+l_n}{2}} \left(\frac{1}{1+(n-1)\sqrt{\rho_d}} \right)^{m_d+k_1+...+k_n} \left(\frac{1}{1+(n-1)\sqrt{\rho_c}} \right)^{m_c+l_1+...+l_n}$$

For this case joint cumulative distribution function can be written as [3]:

$$F_{\lambda_1,...,\lambda_n}(t_1,...,t_n) = \int_0^{t_1}\cdots\int_0^{t_n} p_{\lambda_1,...,\lambda_n}(x_1,...,x_n) dx_1\cdots dx_n \quad .(4)$$

Substituting expression (3) in (4), and after integration joint cumulative distribution function becomes:

$$F_{\lambda_1,\ldots,\lambda_n}(t_1,\ldots,t_n)=\underbrace{\sum_{k_1,\ldots k_n=0}^{\infty}\sum_{l_1,\ldots,l_n=0}^{\infty}}_{2n}$$

$$\left[G_2\left(\frac{t_1}{t_1+\frac{m_c\left(1-\sqrt{\rho_d}\right)}{m_d\left(1-\sqrt{\rho_c}\right)}S_1}\right)^{m_d+k_1}\cdots\left(\frac{t_n}{t_n+\frac{m_c\left(1-\sqrt{\rho_d}\right)}{m_d\left(1-\sqrt{\rho_c}\right)}S_n}\right)^{m_d+k_n}\right.$$

$$\times{}_2F_1\left(m_d+k_1,1-m_c-l_1;1+m_d+k_1;\frac{t_1}{t_1+\frac{m_c\left(1-\sqrt{\rho_d}\right)}{m_d\left(1-\sqrt{\rho_c}\right)}S_1}\right)\cdots$$

$$\times{}_2F_1\left(m_d+k_n,1-m_c-l_n;1+m_d+k_n;\frac{t_n}{t_1+\frac{m_c\left(1-\sqrt{\rho_d}\right)}{m_d\left(1-\sqrt{\rho_c}\right)}S_n}\right). \quad (5)$$

$$G_2=\frac{G_1}{\left(m_d+k_1\right)\cdots\left(m_d+k_n\right)}$$

and ${}_2F_1(u_1,u_2;u_3;x)$, being the Gaussian hypergeometric function [27, (9.100)].

Cumulative distribution function of output SIR could be derived from (5) by equating the arguments $t_1= t_2= t_n= t$ as in [11]:

$$F_\lambda(t)=\underbrace{\sum_{k_1,\ldots k_n=0}^{\infty}\sum_{l_1,\ldots,l_n=0}^{\infty}}_{2n}G_2 t^{n\cdot m_d+k_1+\ldots+k_n}\,.$$

$$\frac{\prod_{i=1}^{n}{}_2F_1\left(m_d+k_i,1-m_c-l_i;1+m_d+k_i;\frac{t}{t+\frac{m_c\left(1-\sqrt{\rho_d}\right)}{m_d\left(1-\sqrt{\rho_c}\right)}S_i}\right)}{\left(t+\frac{m_c\left(1-\sqrt{\rho_d}\right)}{m_d\left(1-\sqrt{\rho_c}\right)}S_i\right)^{m_d+k_i}}. \quad (6)$$

The nested infinite sum in (6) converges for any granted value of the parameters ρ_d, ρ_c, S_1, S_2, S_3, m_d and m_c. Eq. (6) has been evaluated with n terms in each summation using the Mathematica Sum function. As is shown in Tab. 1, the number of the terms needs to be summed to achieve a desired accuracy, depend strongly on the correlation coefficients $0 \le \rho_d < 1$, $0 \le \rho_c < 1$ [28]. The number of the terms increases as correlation coefficients increase. For the special case of $m_d = 1$ and $m_c = 1$ we can evaluate expression for cdf for Rayleigh- desired signal and co-channel interference.

As it is shown in Tab. 1 for cases of $\rho_d = 0.4$, $\rho_c = 0.3$ and $\rho_d = 0.3$, $\rho_c = 0.4$, convergence is slower and we need more terms when $\rho_c > \rho_d$. Also, expected results are obtained for higher values of correlation coefficients. Convergence becomes slow and we need much more terms when ρ_c and ρ_d are higher and closer to 1. Now, if for instance, we consider triple branch selection combining diversity case and number of terms in six summations for 10^{-7} accuracy, we observe that convergence is slower and we need totally more terms for higher number of diversity branches.

S_1/t = 10 dB dual branch selection combining diversity case		m_d = 1	m_d = 1.2
		m_c = 1	m_c = 1.5
ρ_d = 0.3	ρ_c = 0.2	24	21
ρ_d = 0.3	ρ_c = 0.3	28	25
ρ_d = 0.3	ρ_c = 0.4	37	35
ρ_d = 0.4	ρ_c = 0.3	31	27
ρ_d = 0.5	ρ_c = 0.5	51	47
ρ_d = 0.6	ρ_c = 0.6	67	61
ρ_d = 0.7	ρ_c = 0.7	82	77
S_1/t = 10 dB triple branch selection combining diversity case		m_d = 1	m_d = 1.2
		m_c = 1	m_c = 1.5
ρ_d = 0.3	ρ_c = 0.2	11	11
ρ_d = 0.3	ρ_c = 0.3	17	16
ρ_d = 0.3	ρ_c = 0.4	23	22
ρ_d = 0.4	ρ_c = 0.3	20	19

Tab. 1. Terms need to be summed in (6) to achieve accuracy at the 7th significant digit. We consider dual and triple branch selection combining diversity case.

Probability density function (PDF) of the output SIR can be obtained easily from previous expression:

$$p_\lambda(t)=\frac{d}{dt}F_\lambda(t)=\underbrace{\sum_{k_1,\ldots k_n=0}^{\infty}\sum_{l_1,\ldots,l_n=0}^{\infty}}_{2n}G_1 t^{n\cdot m_d+k_1+\ldots+k_n}\left(A_1(t)+\ldots A_n(t)\right)$$

$$A_i(t)=\left(\frac{S_i}{t+\frac{m_c\left(1-\sqrt{\rho_d}\right)}{m_d\left(1-\sqrt{\rho_c}\right)}S_i}\right)^{m_c+l_i}\times$$

$$\times\prod_{\substack{j=1\\ j\neq i}}^{n}\frac{{}_2F_1\left(m_d+k_j,1-m_c-l_j;1+m_d+k_j;\frac{t}{t+\frac{m_c\left(1-\sqrt{\rho_d}\right)}{m_d\left(1-\sqrt{\rho_c}\right)}S_j}\right)}{\left(m_d+k_j\right)}. \quad (7)$$

3. Outage Probability and Average Error Probability

Outage probability P_{out} is standard performance criterion of communication systems operating over fading channels. This performance measure is also used to control the noise or cochannel interference level, helping the designers of wireless communications system's to meet the QoS and grade of service (GoS) demands. Outage probability P_{out} is defined as the probability that combined SNR falls below a given outage threshold γ, also known as a protection ratio. Protection ratio depends on modulation technique and expected QoS.

If the environment is interference limited, P_{out} is defined as the probability that the output SIR of used combiner falls below protection ratio:

$$P_{out} = P_R(\xi < \gamma) = \int_0^{\gamma} p_{\xi}(t)dt = F_{\xi}(\gamma). \quad (8)$$

Outage probability versus normalized parameter S_1/γ for balanced and unbalanced ratio of SIR at the input of the branches and various values of correlation coefficient ρ is shown in Fig. 1.

The average error probability at the SC output is derived for noncoherent and coherent binary signaling according to the following expressions:

$$P_e = \int_0^{\infty} p_{\lambda}(t)\frac{1}{2}e^{-gt}dt \quad (9)$$

where g denotes modulation constant, i.e., $g = 1$ for BDPSK and $g = 1/2$ for BFSK. Substituting (7) in (9) numerically obtained average error probability is shown in Fig. 2 for several values of correlation coefficient and balanced (unbalanced) SIRs.

It is very interesting to observe that the outage probability behavior improves as the diversity order (number of branches) increases.

Considering the average error probability at the SC output, we conclude that effects of some parameters on this system performances are similar to the effects on the system outage probability. Generally, convergence is slower and we need more terms when $\rho_c > \rho_d$. Considering dual branch selection combining diversity case and number of terms in four summations for 10^{-5} accuracy for BDPSK modulation and the evaluation parameters (m_d=1.2, m_c=1.5, S_1= S_2=S_3=0 dB), we found that required number of terms is 31 for the case of ρ_d= 0.4, ρ_c= 0.3 and 38 for the case ρ_d= 0.3, ρ_c= 0.4. Also from Fig. 2 we can see that BDPSK modulation scheme has better performances comparing to BFSK modulation scheme.

4. Conclusion

System performances of selection combining over correlated Nakagami-*m* channels with constant correlation model have been analyzed. Fading at the diversity branches that also affects interferers is correlated and Nakagami-*m* distributed with constant correlation model. The complete statistics for the SC output SIR is provided in the closed form, i.e., PDF, CDF, Outage probability. Capitalizing on these new formulae, average error probability was efficiently evaluated for some modulation schemes. Numerical results of these performance criteria are presented, in the function on correlation coefficient and fading severity. The main contribution of this analysis of multibranch signal combiner is that it has been done for general case of correlated cochanel interference.

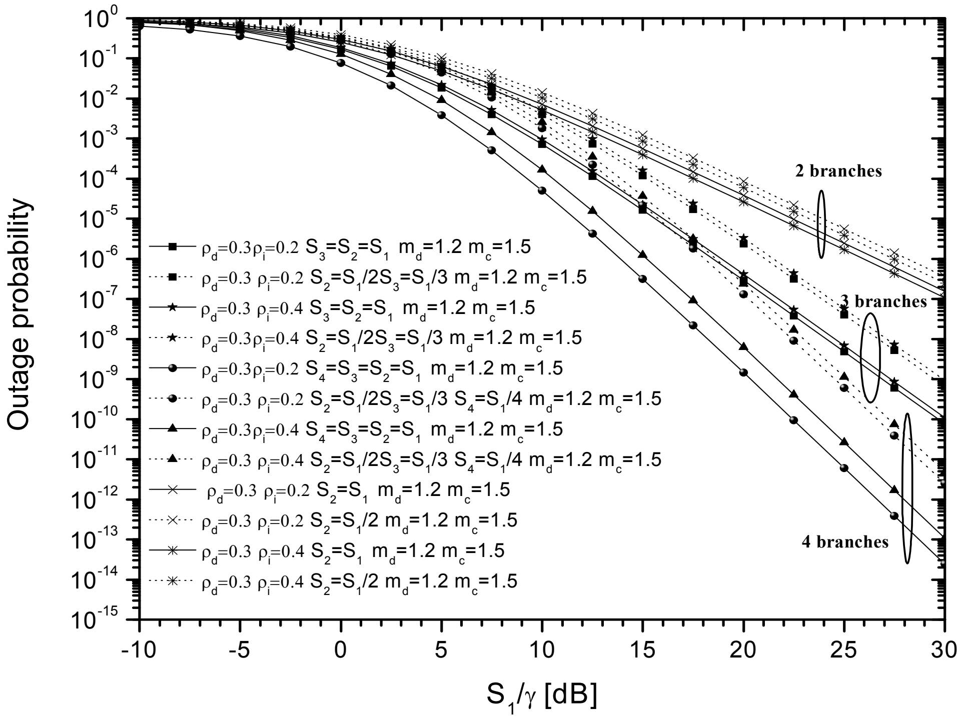

Fig. 1. Outage probability versus S_1/γ.

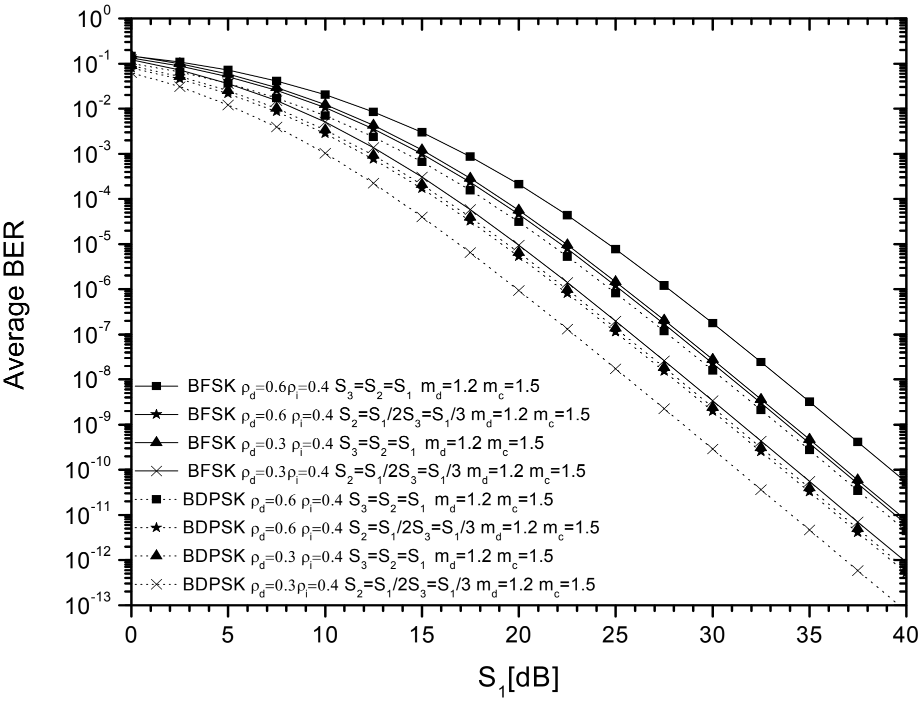

Fig. 2. Average BER versus S_1 in noncoherent BDPSK and BFSK.

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