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SECOND ORDER STATISTICS OF DUAL SELECTION DIVERSITY OVER CORRELATED WEIBULL FADING CHANNELS IN THE PRESENCE OF INTERFERENCE

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Abstract. *In this paper, second order statistics of dual selection combining (SC) system applying desired signal decision algorithm are obtained for the case when that diversity system operates in Weibull interference-limited environment. Namely, a novel closed-form expression for outage probability (OP), necessary for an analysis of average fade duration (AFD), in the term of Meijer's G-function is derived for general case in which desired signal and cochannel interference (CCI) are exposed to fading with different severities. Depending on fading environment, semi-analytical and analytical expressions for average lever crossing rate (LCR) are obtained, too. Numerical results are presented to accomplish proposed mathematical analysis and to examine the effects of system and channel parameters on concerned quantities.*

Key words: *average fade duration, branch correlation, level crossing rate, selection combining, Weibull fading*.

1. INTRODUCTION

Due to moving mobile station or changes in the scattering environment, phenomenon called fading, time variation of received amplitude and phase, appears in wireless system. Moreover, wireless performance is usually limited by interference rather than noise [1]. To combat these two deleterious effects, most of wireless systems use one of the diversity techniques. The most frequently used diversity techniques are equal gain combining (EGC), maximal ratio combining (MRC) and selection combining (SC). The best system performance can be reached with MRC at the expense of more complicated receiver realization. The SC system, which is considered in this paper, has

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the least complex practical implementation since it processes signal only from one of diversity antennas, which is selectively chosen, and no channel information is required. Normally, SC receiver chooses the antenna with the highest signal-to-noise ratio (SNR) or, equivalently, with the strongest signal assuming equal noise power among the antennas [2]. However, in interference-limited fading environment, the influence of the thermal noise may be negligible as compared to the influence of CCI [3]. In that case, three different decision algorithms can be applied: the desired signal power algorithm, the total signal power algorithm and signal-to-interference ratio (SIR) algorithm [4].

Depending on nature of wireless environment, different models describing the statistical behavior of fading can be applied. Some of them produce very accurate results, especially Rice and Nakagami-m. Another useful statistical model is Weibull. This distribution exhibits an excellent fit to experimental fading channel measurements, for both indoor [5] and outdoor [6], [7] environment. It is reason why Weibull distribution paves its way for applying in wireless communications.

In adaptive transmission scheme, the first order statistics (outage probability, channel capacity, average symbol error probability, average output signal, etc) do not provide enough information for overall system design and configuration. In this case, evaluation of average level crossing rate (LCR) and average fade duration (AFD) are important for the proper selection of transmission rate, packet length, interleaver depth and time slot duration. These second order statistics reflect correlation properties of the fading channels and provide dynamic representation of the system's outage performance [4]. The average LCR and AFD of SC diversity system over Rayleigh [8]–[10], Nakagami-m [8], [9], Rician [9] and Weibull fading environment [11]–[13] without CCI have been extensively studied. Influence of CCI, as a result of frequency reuse which is essential in increasing cellular radio capacity, on considered second order performance metrics has been investigated in [4], [14-17].

The outage probability (OP) and other first order performance metrics of dual and triple SC receiver with desired signal decision algorithm which operates over correlated Weibull fading channel in the presence of CCI are studied in [18], [19] for the special case in which desired signal and CCI are exposed to the influence of same fading severity. However, it is shown that in microcellular environment CCI experiences significantly deeper fading than desired signal [20]. Therefore, we tackle the determination of the OP and second order metrics of previous described diversity system for general case in which desired signal and CCI experience different fading. In the best of our knowledge, no study has appeared in open technical literature that studies the same object.

2. Channel and System Model

Due to insufficient space between diversity antennas installed on small terminal, the desired signal envelopes, r_1 and r_2, experience correlated Weibull distribution with joint probability density function (PDF) [21]

$$p_{r_1 r_2}(r_1, r_2) = \frac{\beta^2 r_1^{\beta-1} r_2^{\beta-1}}{\Omega^2 (1-\rho)} \exp\left[-\frac{1}{1-\rho}\left(\frac{r_1^{\beta} + r_2^{\beta}}{\Omega}\right)\right] I_0\left[\frac{2\sqrt{\rho} r_1^{\beta/2} r_2^{\beta/2}}{(1-\rho)\Omega}\right], \quad (1)$$

where β is Weibull parameter expressing the fading severity ($\beta > 0$). As it increases, the severity of fading decreases, while for $\beta = 2$, the Weibull distribution reduces to Rayleigh. Moreover, for $\beta = 1$, Weibull distribution transforms into the well-known negative exponential PDF. The parameter Ω represents the average power of desired signal, ρ is the branch correlation coefficient and $I_0(\cdot)$ is modified Bessel function of the first kind and zero order.

Traditionally, SC receiver selects the antenna with the highest SNR or, equivalently, with the strongest signal assuming equal noise power among the diversity antennas. However, in interference-limited environment SC receiver can apply one of three decision algorithms: the desired signal power algorithm, the total signal power algorithm and SIR algorithm. Concerning to the OP and second order statistics, it can be said that in almost all cases receiver with total signal decision algorithm has advantage than other algorithms. In addition, that algorithm does not require an estimation of interference level which makes it easier for practical realization. On the other hand, SC receiver with desired signal decision algorithm reaches almost same performance as SC receiver with total signal decision algorithm, but it is easier to be mathematically modeled [4]. All of these direct our research to SC receiver with desired signal decision algorithm. In such system the envelope of the strongest CCI at the selected antenna, a, follows Weibull PDF expressed as [21]

$$p_a(a) = \frac{\beta_1 a^{\beta_1 - 1}}{\Omega_1} \exp\left[-\frac{a^{\beta_1}}{\Omega_1}\right], \quad (2)$$

where β_1 and Ω_1 are Weibull fading parameter and average power of CCI, respectively. Now, the instantaneous SIR at the output of dual SC receiver can be defined as [4]

$$\eta = \frac{\max\{r_1^2, r_2^2\}}{a^2} = \frac{r^2}{a^2}. \quad (3)$$

3. Outage Probability

The OP, $F_\mu(\mu)$, is performance criterion which shows probability that output SIR envelope, $\mu = \sqrt{\eta}$, falls below a certain specified threshold μ_{th}. For diversity system considered in this paper, the OP is defined as [17]

$$F_\mu(\mu_{th}) = 1 - \int_0^{+\infty}\left[\int_0^{r/\mu_{th}} p_{ar}(a,r)\,da\right]dr, \quad (4)$$

where $p_{ar}(a,r)$ is joint PDF of desired signal and CCI at the selected antenna. It is defined as [15]

$$p_{ar}(a,r) = p_a(a)\int_0^r p_{r_1 r_2}(r,r_2)dr_2 + p_a(a)\int_0^r p_{r_1 r_2}(r_1,r)dr_1. \qquad (5)$$

Substituting (1) and (2) into (5), integrals can be solved using [22, eq. (3.351.1)] after applying infinite-series representation of $I_0(\cdot)$ [22, eq. (8.447.1)] in (1) and changing order of summation and integration. The infinite-series representation of $p_{ar}(a,r)$ can be written as

$$\begin{aligned} p_{ar}(a,r) &= \sum_{k=0}^{+\infty} \frac{2\beta\beta_1 r^{\beta k+\beta-1}\rho^k a^{\beta_1-1}}{\Omega^{k+1}\Omega_1(1-\rho)^k\Gamma(k+1)} \exp\left[-\frac{a^{\beta_1}}{\Omega_1} - \frac{r^\beta}{(1-\rho)\Omega}\right] \\ &\times\left(1-\exp\left[-\frac{r^\beta}{(1-\rho)\Omega}\right]\sum_{l=0}^{k}\frac{r^{\beta l}}{\Gamma(l+1)(1-\rho)^l\Omega^l}\right), \end{aligned} \qquad (6)$$

where $\Gamma(\cdot)$ is Gamma function.

Let substitute previous equation into (4). Now, we should solve four integrals. Two of them can be solved using [22, eq. (3.351.1)], while the rest two integrals can be solved using [23] after representing exponential functions as Meijer's G-functions, i.e. $\exp[-x] = G_{0,1}^{1,0}[x\,|_{0}^{-}]$. Finally, the analytical expression for the OP can be written as

$$\begin{aligned} F_\mu(\mu_{th}) &= 1 - \sum_{k=0}^{+\infty}\frac{2\rho^k(1-\rho)}{\Gamma(k+1)}\Bigg(\Gamma(k+1) - \sum_{l=0}^{k}\frac{\Gamma(k+l+1)}{2^{k+l+1}\Gamma(l+1)} \\ &+\sum_{l=0}^{k}\frac{k_1^{0.5} l_1^{k+l+0.5}}{2^{k+l+1}\Gamma(l+1)(2\pi)^{\frac{k_1+l_1}{2}-1}} \\ &\times G_{l_1,k_1}^{k_1,l_1}\left(\frac{(1-\rho)^{l_1}\Omega^{l_1} l_1^{l_1}}{2^{l_1}\mu_{th}^{\beta_1 k_1}\Omega_1^{k_1}k_1^{k_1}}\middle|\begin{matrix}\frac{-(k+l)+0}{l_1} & \frac{-(k+l)+1}{l_1} & \dots & \frac{-(k+l)+l_1-1}{l_1}\\ \frac{0}{k_1} & \frac{1}{k_1} & \dots & \frac{k_1-1}{k_1}\end{matrix}\right) \\ &-\frac{k_1^{0.5} l_1^{k+0.5}}{(2\pi)^{\frac{k_1+l_1}{2}-1}} G_{l_1,k_1}^{k_1,l_1}\left(\frac{(1-\rho)^{l_1}\Omega^{l_1} l_1^{l_1}}{\mu_{th}^{\beta_1 k_1}\Omega_1^{k_1}k_1^{k_1}}\middle|\begin{matrix}\frac{-k+0}{l_1} & \frac{-k+1}{l_1} & \dots & \frac{-k+l_1-1}{l_1}\\ \frac{0}{k_1} & \frac{1}{k_1} & \dots & \frac{k_1-1}{k_1}\end{matrix}\right)\Bigg), \end{aligned} \qquad (7)$$

where $\beta_1/\beta = l_1/k_1$ and $\gcd(k_1,l_1) = 1$. Function $\gcd(x,y)$ represents greatest common divisor of two integer numbers x and y. For $\beta = \beta_1$ the OP can be evaluated as

$$F_\mu(\mu_{th}) = 1 + \sum_{k=0}^{+\infty} 2\rho^k(1-\rho)\left(\frac{1}{\left(1+\frac{S(1-\rho)}{\mu_{th}^{\beta}}\right)^{k+1}} - 1\right.$$

$$+\sum_{l=0}^{k}\frac{\Gamma(k+l+1)}{\Gamma(k+1)\Gamma(l+1)}\left(\frac{1}{2^{k+l+1}}-\frac{1}{\left(2+\frac{S(1-\rho)}{\mu_{th}^{\beta}}\right)^{k+l+1}}\right)\Bigg)\Bigg), \quad (8)$$

where $S=\Omega/\Omega_1$.

4. AVERAGE LEVEL CROSSING RATE

The average LCR at threshold is defined as the rate at which a fading process crosses threshold level in a positive (or a negative) going direction and it is mathematically defined by Rice's formula [9]

$$N_{\mu}(\mu_{th})=\int_{0}^{+\infty}\dot{\mu}p_{\mu\dot{\mu}}(\mu_{th},\dot{\mu})d\dot{\mu}, \quad (9)$$

where $\dot{\mu}$ is time derivative of μ and $p_{\mu\dot{\mu}}(\mu,\dot{\mu})$ is their joint PDF. The $p_{\mu\dot{\mu}}(\mu,\dot{\mu})$ for SC operating in Weibull interference-limited environment can be written as [4, 24]

$$p_{\mu\dot{\mu}}(\mu,\dot{\mu})=\int_{0}^{+\infty}\int_{-\infty}^{+\infty}a^2 p_{r\dot{r}}(a\mu,a\dot{\mu}+\dot{a}\mu)p_{\dot{a}}(\dot{a}|a)p_a(a)d\dot{a}da, \quad (10)$$

where the conditional PDF of time derivative of CCI, $p_{\dot{a}}(\dot{a}|a)$, is defined as [24]

$$p_{\dot{a}}(\dot{a}|a)=\frac{\beta_1 a^{\frac{\beta_1}{2}-1}}{f_m(2\pi)^{1.5}\Omega_1^{0.5}}\exp\left[-\frac{\beta_1^2 a^{\beta_1-2}\dot{a}^2}{8\pi^2 f_m^2\Omega_1}\right], \quad (11)$$

in which f_m is maximum Doppler frequency.

The joint PDF $p_{r\dot{r}}(r,\dot{r})$ for dual SC receiver over correlated Weibull channels is given as [4]

$$p_{r\dot{r}}(r,\dot{r})=p_{\dot{r}}(\dot{r}|r)\int_{0}^{r}p_{r_1r_2}(r,r_2)dr_2+p_{\dot{r}}(\dot{r}|r)\int_{0}^{r}p_{r_1r_2}(r_1,r)dr_1, \quad (12)$$

where $p_{\dot{r}}(\dot{r}|r)$ is the conditional PDF of time derivative of desired signal defined as [24]

$$p_{\dot{r}}(\dot{r}|r)=\frac{\beta r^{\frac{\beta}{2}-1}}{f_m(2\pi)^{1.5}\Omega^{0.5}}\exp\left[-\frac{\beta^2 r^{\beta-2}\dot{r}^2}{8\pi^2 f_m^2\Omega}\right]. \quad (13)$$

Using infinite-series representation of $I_0(\cdot)$ in (1), integrals in (12) are solved using [22, eq. (3.351.1)], so infinite-series representation of $p_{r\dot{r}}(r,\dot{r})$ is presented as

$$p_{r\dot{r}}(r,\dot{r})=\sum_{k=0}^{+\infty}\frac{\beta^2 r^{1.5\beta+\beta k-2}\rho^k}{\Omega^{k+1.5}f_m(1-\rho)^k\Gamma(k+1)\sqrt{2\pi^3}}\exp\left[-\frac{\beta^2 r^{\beta-2}\dot{r}^2}{8\pi^2 f_m^2\Omega}-\frac{r^\beta}{(1-\rho)\Omega}\right]$$
$$\times\left(1-\exp\left[-\frac{r^\beta}{(1-\rho)\Omega}\right]\sum_{l=0}^{k}\frac{r^{\beta l}}{\Gamma(l+1)}\right). \quad (14)$$

For $\beta\neq\beta_1$ using infinite-series representation of exponential function [22, eq. (1.211.1)] and definite integral [22, eq. (3.323.2)], the average LCR can be determine in semi-analytical form as

$$N_\mu(\mu_{th})=\int_0^{+\infty}\int_0^{+\infty}\sum_{k,p=0}^{+\infty}\frac{\rho^k\mu_{th}^{\beta(1.5+k+2p)-2p-2}\beta^{4p+2}\beta_1^2 a^{\beta(1.5+k+2p)-2p-2+1.5\beta_1}\Omega_1^{p-1}\dot{\mu}^{2p+1}}{\Gamma(k+1)\Gamma(p+1)\pi^{2p+1.5}2^{3p+0.5}f_m^{2p+1}\Omega^{k+p+1}(1-\rho)^k}$$
$$\times\frac{1}{(\beta^2\mu_{th}^\beta\Omega_1 a^{\beta-2}+\beta_1^2 a^{\beta_1-2}\Omega)^{p+0.5}}\exp\left[-\frac{a^{\beta_1}}{\Omega_1}-\frac{a^\beta\mu_{th}^\beta}{(1-\rho)\Omega}-\frac{a^\beta\mu_{th}^{\beta-2}\dot{\mu}^2\beta^2}{8\pi^2 f_m^2\Omega}\right] \quad (15)$$
$$\times\left(1-\sum_{l=0}^{k}\frac{\mu_{th}^{\beta l}a^{\beta l}}{\Gamma(l+1)(1-\rho)^l\Omega^l}\exp\left[-\frac{a^\beta\mu_{th}^\beta}{(1-\rho)\Omega}\right]\right)da\,d\dot{\mu},$$

while for $\beta=\beta_1$ the average LCR could be obtained in the closed form. Namely, applying [22, eq. (3.351.1)] after [22, eq. (3.323.2)], the joint PDF $p_{\mu\dot{\mu}}(\mu,\dot{\mu})$ can be written as

$$p_{\mu\dot{\mu}}(\mu,\dot{\mu})=\sum_{k,p=0}^{+\infty}\frac{\rho^k\mu^{\beta(1.5+k+2p)-2p-2}\beta^{2p+2}\dot{\mu}^{2p}(1-\rho)^{p+2.5}S^{1.5}}{\Gamma(k+1)\Gamma(p+1)\pi^{2p+1.5}2^{3p+0.5}f_m^{2p+1}(\mu^\beta+S)^{p+0.5}}$$
$$\times\left(\frac{\Gamma(k+p+2.5)}{\left(S(1-\rho)+\mu^\beta+\frac{(1-\rho)\beta^2\mu^{\beta-2}\dot{\mu}^2}{8\pi^2 f_m^2}\right)^{k+p+2.5}}\right.$$
$$\left.-\sum_{l=0}^{k}\frac{\Gamma(k+p+l+2.5)\mu^{\beta l}}{\Gamma(l+1)\left(S(1-\rho)+2\mu^\beta+\frac{(1-\rho)\beta^2\mu^{\beta-2}\dot{\mu}^2}{8\pi^2 f_m^2}\right)^{k+p+l+2.5}}\right). \quad (16)$$

Let substitute (16) into (9) and apply [22, eq. (3.241.4)] to get the average LCR

$$N_\mu(\mu_{th})=\sum_{k,p=0}^{+\infty}\frac{\rho^k\mu_{th}^{\beta(0.5+k+p)}(1-\rho)^{1.5}S^{1.5}2^{1.5}\pi^{0.5}f_m}{\Gamma(k+1)(\mu_{th}^\beta+S)^{p+0.5}}\left(\frac{\Gamma(k+1.5)}{(S(1-\rho)+\mu_{th}^\beta)^{k+1.5}}\right.$$
$$\left.-\sum_{l=0}^{k}\frac{\Gamma(k+l+1.5)\mu_{th}^{\beta l}}{\Gamma(l+1)(S(1-\rho)+2\mu_{th}^\beta)^{k+l+1.5}}\right). \quad (17)$$

5. AVERAGE FADE DURATION

The AFD, $T_\mu(\mu_{th})$, is measure of how long, on the average, the system remains in the outage state, i.e. average time in which envelope ratio remains below threshold level after crossing that level in the downward direction. It can be obtained as

$$T_\mu(\mu_{th}) = \frac{F_\mu(\mu_{th})}{N_\mu(\mu_{th})}. \tag{18}$$

It is obvious that dividing Eqs. (7) by (15), i.e. (8) by (17), this second performance metric can be easily evaluated.

6. NUMERICAL RESULTS

The aim of this section is to accomplish previous mathematical analysis giving at the same time the total overview how the system and channel parameters effect on performance of consider diversity system.

Figures 1 and 2 depict the OP versus SIR threshold evaluated for the different values of correlation coefficient and fading severity parameter. Note, the probability that envelope falls bellow some level increases with decrease of distance between diversity antennas, i.e. with increase of correlation coefficient. Figure 1 points out that deeper fading (less Weibull parameter) degrades the outage system performance for $\mu_{th} < 0$ dB almost to the same extent for any values of average SIR, i.e. S, while for $\mu_{th} > 0$ dB the performance degrades very slowly with increase of fading severity parameter. Also, higher average SIR provides better outage performance. Comparison between Figs. 1 and 2 shows that influence of fading severity of CCI on outage performance is more evident than influence of desired signal fading. The expression with Meijer's G-functions related with the OP must fulfill some conditions related with convergence of Meijer's integral from two G-function [23] limiting minimum value of threshold level for which the OP can be evaluated.

Normalized average LCR ($N_\mu(\mu_{th})/f_m$) in function of SIR threshold is presented in Figs. 3 and 4. The LCR curve increases with increase of SIR threshold level until it reaches maximum at μ_{th_0} and then decreases. It is obvious from these two figures that the influence of branch correlation can be neglected for SIR threshold greater than μ_{th_0}, while fading severity exposes more significant influence on the average LCR in that region. In addition, more sever fading environment provokes more frequent fluctuation of signal expressing as higher average LCR what is confirmed through these two figures.

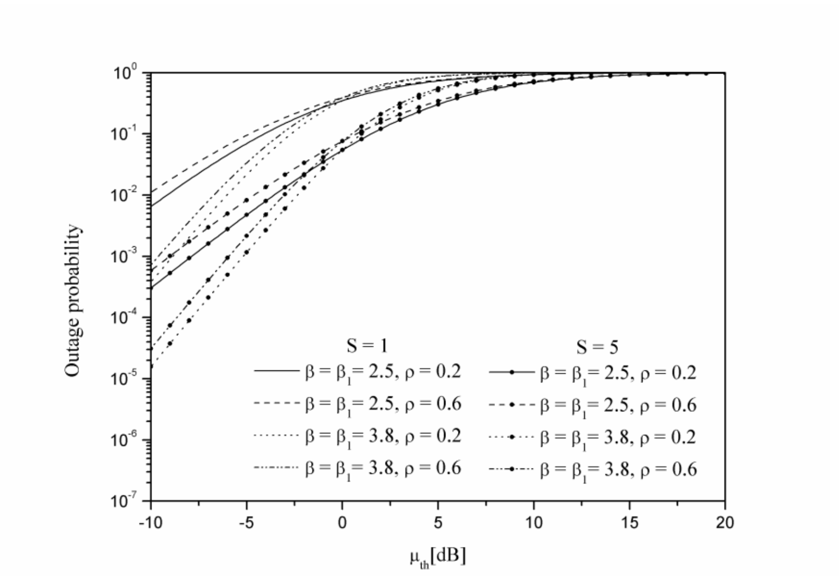

Fig. 1 Outage probability versus envelope threshold for $\beta = \beta_1$

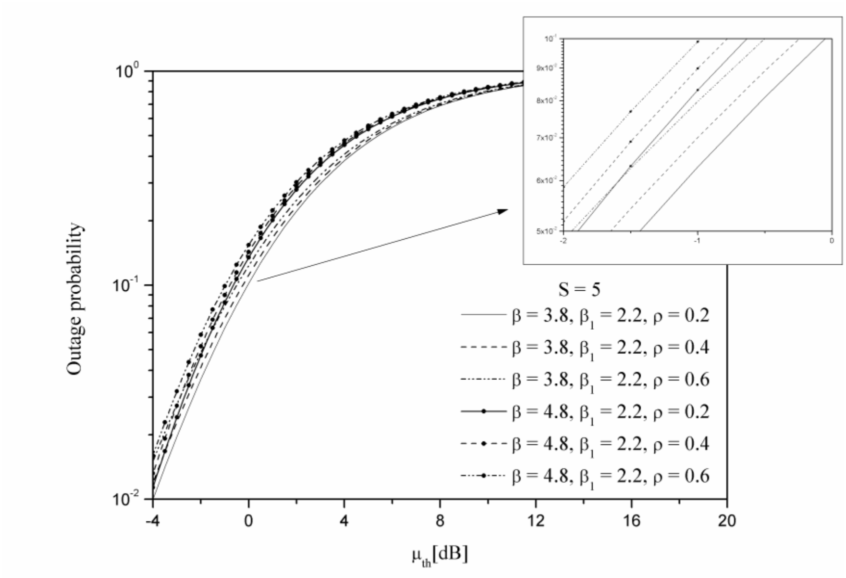

Fig. 2 Outage probability versus envelope threshold for $\beta \neq \beta_1$

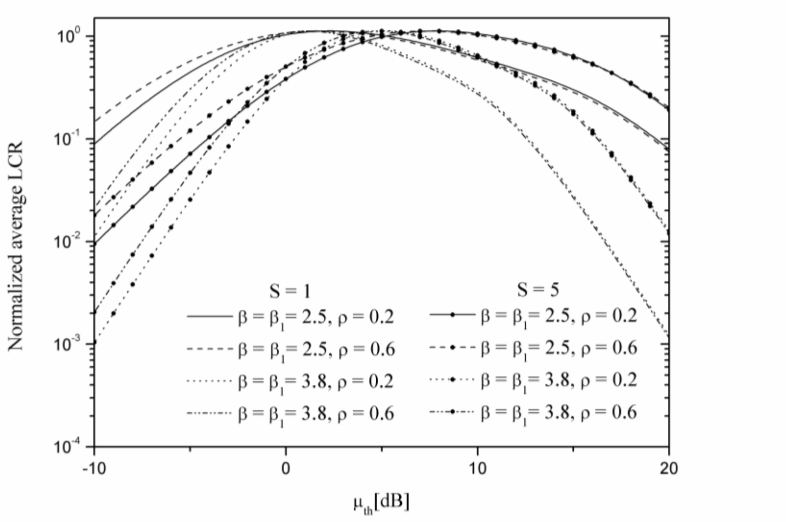

Fig. 3 Normalized average LCR versus envelope threshold for $\beta = \beta_1$

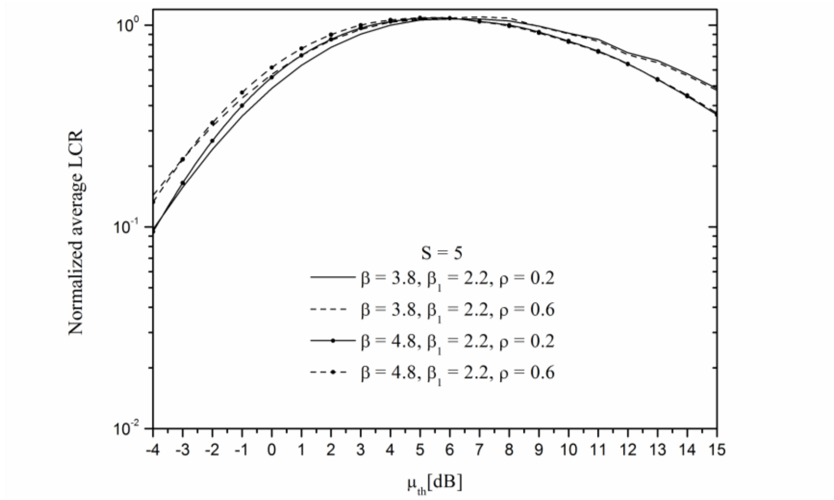

Fig. 4 Normalized average LCR versus envelope threshold for $\beta \neq \beta_1$

Figures 5 and 6 depict normalized AFD ($T_\mu(\mu_{th})f_m$) versus SIR threshold. This performance metric constantly increases what is expected since output SIR would spend more time below high than low value of threshold level. It is interesting that influence of distance between diversity antennas is very small in all consider range of threshold, while the effect of the fading severity depends of threshold value. Actually, for $\mu_{th_0} > 0$ dB the AFD increases with decrease of fading severity of signals. Opposite, for $\mu_{th_0} < 0$ dB the AFD decreases with decrease of fading severity. Namely, less fading severity, the less time the signal remains in deep fades. Figure 6 confirms conclusion derived from Figs. 1 and 2 that influence of fading severity of CCI is more evident than influence of desired signal fading.

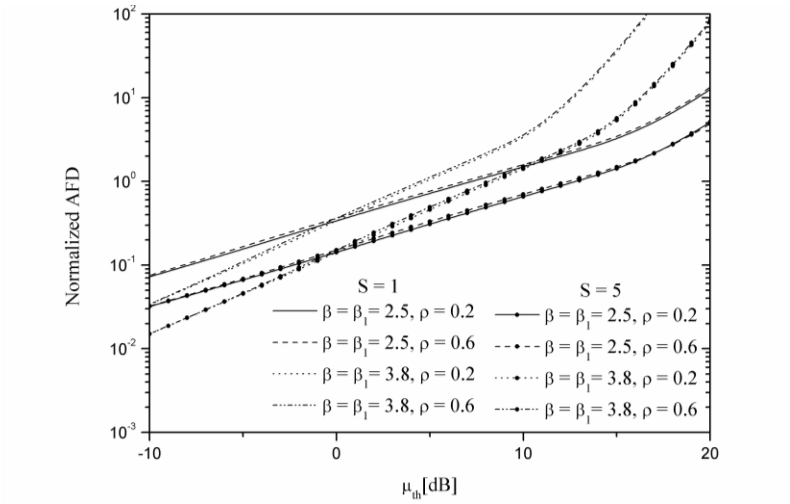

Fig. 5 Normalized AFD versus envelope threshold for $\beta = \beta_1$

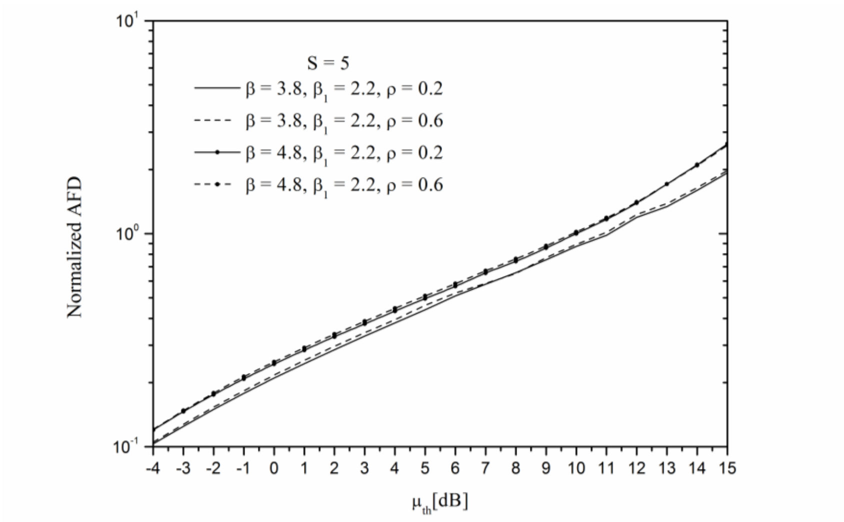

Fig. 6 Normalized AFD versus envelope threshold for $\beta \neq \beta_1$

The convergence rate of the expression for OP is examined in Table 1. This table summarizes the number of terms needed to be summed to achieve accuracy at the 3rd significant digit. Note, that number strongly depends on branch correlation, fading severity and envelope threshold.

Table 1 The number of terms needed to be summed in (7) to achieve accuracy at the 3rd significant digit

$S=5$		$\mu_{th}=0\,dB$	$\mu_{th}=10\,dB$	$\mu_{th}=20\,dB$
$\beta=4.8$	$\rho=0.2$	5	4	4
$\beta_1=2.2$	$\rho=0.6$	13	13	7
$\beta=3.8$	$\rho=0.2$	4	3	3
$\beta_1=2.2$	$\rho=0.2$	15	12	11

6. CONCLUSION

This paper provides analytical and semi-analytical expressions, depending on the fading environment, for the second order performance metrics of dual SC receiver with correlated branches. Applied SC receiver uses desired signal decision algorithm and operates in Weibull interference-limited environment. Derived expressions are presented in the form of infinite-series characterized with rapid convergence providing the accurate and fast way to investigate the influence of system and channel parameters on dynamic characteristics of SC system.

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