Level Crossing Rate of Macrodiversity SC Receiver Output Process in the Presence of Weibull Short Term Fading, Gamma Long Term Fading and Weibull Cochanell Interference

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Abstract: - In this paper, macrodiversity reception with macrodiversity (MAD) selection combining (SC) receiver and two microdiversity (MID) SC receivers operating over Gamma shadowed Weibull short term fading channel in the presence of cochannel interference subjected to Weibull multipath fading is observed. Level crossing rate (LCR) of the ratio of two Weibull random processes is evaluated and this expression is used for calculation the LCR at the output of MID SC receivers. The closed form expression of LCR at the output of MAD SC receiver is also determined. The influence of Gamma long term fading severity parameter, Gamma long term fading correlation coefficient, Weibull fading nonlinearity parameter of desired signal and Weibull fading nonlinearity parameter of cochannel interference on LCR of MAD system is studied and discussed.

Key-Words: - cochannel interference, Gamma long term fading, Level crossing rate (LCR), Weibull short term fading

1 Introduction

Macrodiversity technique can be used to reduce long term fading effects and short term fading effects on the outage probability and bit error probability of wireless system, simultaneously [1]. MAD system consists of MAD SC receiver and two MID SC receivers. MAD SC receiver selects MID SC receiver with higher signal envelope average power to provide service to user resulting in Gamma long term fading effects reduction. MID SC receiver selects the branch with the highest signal to interference ratio to enable service to user resulting in short term fading effects reduction.

Level crossing rate is important performance measure at the second order of wireless mobile communication radio system which is defined as the number of crossing of random process at the determined level in positive direction and can be calculated as average value of the first derivative of random process [2]. In this paper, MAD system with MAD SC receiver and two MID SC receivers in the presence of Weibull short term fading, Gamma long term fading and Weibull cochannel interference is considered. Weibull describes signal envelope variation in nonlinear and non line of sight multipath fading environment. This distribution has parameter of nonlinearity α. When α= 2, Weibull distribution reduces to Rayleigh distribution. When α goes to infinity, wireless Weibull channel becomes no fading channel.

Long term fading can be described by using Gamma distribution or log-normal distribution. In this paper, signal envelope average power is modelled by using Gamma distribution due to results for the level crossing rate can be obtained in the closed form [3].

There are more works in open technical literature considering MAD systems in the presence of short term fading and long term fading and wireless communication systems in the presence of short term fading, long term fading and cochannel interference.

In [4] and [5], Gamma shadowed Rician multipath fading channel is considered. The level crossing rate of macrodiversity SC receiver with two microdiversity SC receivers in such fading condition is derived in [4], while the moments of macrodiversity SC receiver with two microdiversity EGC receivers are obtained in [5].

MAD system with MAD SC receiver and two MID maximal ratio combining (MRC) receivers operating over Gamma shadowed Nakagami-m short term fading channel is considered in [6]. For this system, the level crossing rate of MAD SC receiver output signal is calculated and average fade duration of proposed system is also evaluated as a ratio of outage probability and level crossing rate. Average fade duration and average level crossing rate of MAD wireless communication system in the presence of Gamma large scale fading and Rician small scale fading are evaluated in [6]. In [7], outage probability and bit error probability of wireless communication system with SC receiver operating over Weibull multipath fading channel in the presence of cochannel interference affected to Weibull short term fading are evaluated.

In [8], the performance of L-branch selection combining receiver over correlated Weibull fading channels in the presence of correlated Weibull-distributed cochannel interference is analyzed. Closed-form expressions for probability density function and cumulative distribution function of the signal-to-interference ratio at the output of the selection combining receiver are obtained.

The signal to interference ratio at inputs of MID SC receivers is ratio of two Weibull random variables. In this paper, level crossing rate of the ratio of two Weibull random processes is calculated as the expression in the closed form. By using this expression, the expressions for level crossing rate of MID SC receiver output signal to interference ratio processes are efficiently calculated. MAD SC receiver selects MIC SC receiver with higher signal envelope average power at inputs. By using this rule, the level crossing rate of signal to interference ratio at the output of MAD SC receiver is calculated. The obtained results can be used for evaluation the average fade duration of proposed MAD system.

By our cognition, MAD reception level crossing rate in the presence of Weibull short term fading, Gamma long term fading and Weibull cochannel interference is not reported yet. The results can be used in performance analysis and design of MAD wireless communication system in the presence of Weibull desired signal and Weibull cochannel interference.

2 The Ratio of Two Weibull Random Variables

Weibull random variables x_1 and x_2 follow distributions:

$$p_{x_1}(x_1) = \frac{\alpha}{\Omega_1} x_1^{\alpha-1} e^{-\frac{1}{\Omega_1} x_1^{\alpha}}, \quad x_1 \geq 0, \tag{1}$$

$$p_{x_2}(x_2) = \frac{\alpha}{\Omega_2} x_2^{\alpha-1} e^{-\frac{1}{\Omega_2} x_2^{\alpha}}, \quad x_2 \geq 0, \tag{2}$$

The ratio of x_1 and x_2 is:

$$x = \frac{x_1}{x_2}, \; x_1 = x \cdot x_2 . \tag{3}$$

The probability density function of ratio of x_1 and x_2 is:

$$p_x(x) = \int_0^{\infty} dx_2 x_2 p_{x_1}(x \cdot x_2) p_{x_2}(x_2) =$$

$$= \frac{\alpha^2}{\Omega_1 \Omega_2} x^{\alpha-1} \int_0^{\infty} dx_2 x_2^{2\alpha-1} e^{-\left(\frac{1}{\Omega_1} x^{\alpha} + \frac{1}{\Omega_2}\right) x_2^{\alpha}} =$$

$$= \frac{\alpha^2}{\Omega_1 \Omega_2} x^{\alpha-1} \frac{1}{\alpha} (\Omega_1 \Omega_2)^2 \frac{1}{\left(\Omega_2 x^{\alpha} + \Omega_1\right)^2} \Gamma(2) =$$

$$= \frac{\alpha x^{\alpha-1} \Omega_1 \Omega_2}{\left(\Omega_2 x^{\alpha} + \Omega_1\right)^2} \tag{4}$$

Cumulative distribution function (CDF) of the ratio of two Weibull random variables is:

$$F_x(x) = \int_0^x dt \cdot p_x(t) = \int_0^x dt \, \alpha \Omega_1 \Omega_2 \frac{t^{\alpha-1}}{\left(\Omega_1 + \Omega_2 t^{\alpha}\right)^2}, \tag{5}$$

Introducting the substitution:

$$\Omega_1 + \Omega_2 t^{\alpha} = y, \qquad t^{\alpha-1} dt = \frac{1}{\alpha \Omega_2} dy, \tag{6}$$

previous expression becomes:

$$F_x(x) = \int_{\Omega_1}^{\Omega_1 + \Omega_2 x^{\alpha}} dy \cdot \frac{\alpha \Omega_1 \Omega_2}{\alpha \Omega_2} \frac{1}{y^2} =$$

$$= \Omega_1 \left(\frac{1}{\Omega_1} - \frac{1}{\Omega_1 + \Omega_2 x^{\alpha}} \right) = 1 - \frac{\Omega_1}{\Omega_1 + \Omega_2 x^{\alpha}} =$$

$$= \frac{\Omega_2 x^{\alpha}}{\Omega_1 + \Omega_2 x^{\alpha}} \tag{7}$$

The ratio of two Weibull random variables x_1 and x_2 is:

$$x = \frac{x_1}{x_2} = \frac{y_1^{\frac{2}{\alpha}}}{y_2^{\frac{2}{\alpha}}}, \; x^{\frac{\alpha}{2}} = \frac{y_1}{y_2} \tag{8}$$

where y_1 and y_2 are Rayleigh random variables:

$$p_{y_1}(y) = \frac{2y_1}{\Omega_1} e^{-\frac{y_1^2}{\Omega_1}}, \; y_1 \geq 0 \tag{9}$$

$$p_{y_2}(y) = \frac{2y_2}{\Omega_2} e^{-\frac{y_2^2}{\Omega_2}}, \; y_2 \geq 0, \tag{10}$$

and $\Omega_1 = \overline{y_1^2}$ and $\Omega_2 = \overline{y_2^2}$.

The first derivative of x is:

$$\dot{x} = \frac{2}{\alpha x^{\alpha/2-1}} \left(\frac{\dot{y}_1}{y_2} - \frac{y_1 \dot{y}_2}{y_2^2} \right). \tag{11}$$

The first derivative of Rayleigh random process has Gaussian distribution. Thas, $\dot{y}_1$ and $\dot{y}_2$ are Gaussian random variables. Linear transformation of Gaussian random variables is Gaussian random variable. Therefore, $\dot{x}$ has conditional Gaussian distribution. The main of $\dot{x}$ is zero. The variance of $\dot{x}$ is:

$$\sigma_{\dot{x}}^2 = \frac{2}{\alpha^2 x^{\alpha-2}} \left(\frac{1}{y_2^2} \sigma_{\dot{y}_1}^2 - \frac{y_1^2}{y_2^4} \sigma_{\dot{y}_2}^2 \right) \tag{12}$$

where:

$$\sigma_{\dot{y}_1}^2 = \pi^2 f_m^2 \Omega_1 \text{ and } \sigma_{\dot{y}_2}^2 = \pi^2 f_m^2 \Omega_2. \tag{13}$$

After substituting, the expression for variance of $\dot{x}$ becomes:

$$\sigma_{\dot{x}}^2 = \frac{4\pi^2 f_m^2}{\alpha^2 x^{\alpha-2} y_2^2} \left(\Omega_1 + x^\alpha \Omega_2 \right). \tag{14}$$

The joint probability density function of x, $\dot{x}$ and y_2 is:

$$p_{x\dot{x}y_2}\left(x\dot{x}y_2 \right) = p_{\dot{x}}\left(\dot{x}/ xy_2 \right) \cdot p_{xy_2}(xy_2) =$$

$$= p_{\dot{x}}\left(\dot{x}/ xy_2 \right) \cdot p_x(x/y_2) p_{y_2}(y_2) =$$

$$= p_{\dot{x}}\left(\dot{x}/ xy_2 \right) \cdot p_{y_2}(y_2) \cdot \frac{\alpha}{2} x^{\frac{\alpha}{2}-1} y_2 p_{y_1}\left(x^{\frac{\alpha}{2}} y_2 \right) \tag{15}$$

The joint probability density function of x and $\dot{x}$ can be evaluated by integrating previously expression with respect to y_2.

$$p_{x\dot{x}}\left(x\dot{x} \right) = \int_0^\infty dy_2 p_{x\dot{x}y_2}\left(x\dot{x}y_2 \right) = p_{\dot{x}}\left(\dot{x}/ xy_2 \right) \cdot p_{xy_2}(xy_2) =$$

$$= \frac{\alpha}{2} x^{\frac{\alpha}{2}-1} \int_0^\infty dy_2 y_2 p_{y_1}\left(x^{\frac{\alpha}{2}} y_2 \right) p_{\dot{x}}\left(\dot{x}/ xy_2 \right) \cdot p_{y_2}(y_2) \tag{16}$$

The level crossing rate of x is:

$$N_x = \int_0^\infty d\dot{x}\, \dot{x}\, p_{x\dot{x}}\left(x\dot{x} \right) =$$

$$= \frac{\alpha}{2} x^{\frac{\alpha}{2}-1} \int_0^\infty dy_2 y_2 p_{y_1}\left(x^{\frac{\alpha}{2}} y_2 \right) \cdot p_{y_2}(y_2) \frac{1}{\sqrt{2\pi}} \sigma_{\dot{x}} =$$

$$= \frac{\alpha}{2} x^{\frac{\alpha}{2}-1} \frac{1}{\sqrt{2\pi}} \frac{\sqrt{2\pi} f_m}{\alpha x^{\frac{\alpha}{2}-1}} \sqrt{\Omega_1 + x^\alpha \Omega_2}$$

$$\cdot \frac{4}{\Omega_1 \Omega_2} x^{\frac{\alpha}{2}} \int_0^\infty dy_2\, y_2^2 e^{-y_2^2 \left(\frac{x^\alpha}{\Omega_1} + \frac{1}{\Omega_2} \right)} =$$

$$= \frac{\alpha \sqrt{2\pi} f_m}{2} \frac{4}{\Omega_1 \Omega_2} x^{\frac{\alpha}{2}} \sqrt{\Omega_1 + x^\alpha \Omega_2} \cdot$$

$$\frac{1}{8} (\Omega_1 \Omega_2)^{3/2} \frac{1}{\left(\Omega_1 + x^\alpha \Omega_2 \right)^{3/2}} = \frac{\sqrt{2\pi} f_m\, x^{\alpha/2}}{\left(\Omega_1 + x^\alpha \Omega_2 \right)} \tag{17}$$

3 Macrodiversity reception

Macrodiversity system considered in this paper has MAD SC receiver and two MID SC receivers. The model of proposed wireless communication system is illustrated in Fig. 1.

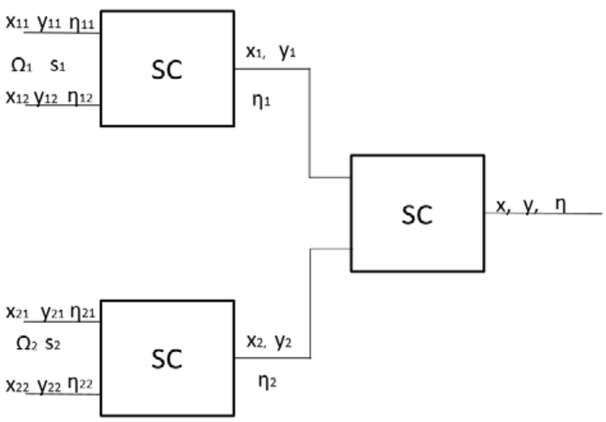

Fig.1. System model

Signal envelopes are denoted in figure as x_{11}, x_{12}, x_{21}, and x_{22}. Signal envelope average powers are denoted with Ω_1 and s_1. Signal envelopes of interferences are y_{11}, y_{12}, y_{21}, and y_{22}. Signal envelopes average powers are denoted with Ω_2 and s_2. Ratios of signals envelopes and interferences envelopes are η_{11}, η_{12}, η_{21}, and η_{22}.

The joint probability density function of x_1 and $\dot{x}_1$ is:

$$p_{x_1\dot{x}_1}\left(x_1\dot{x}_1\right) = p_{x_{11}\dot{x}_{11}}\left(x_1\dot{x}_1\right)F_{x_{12}}\left(x_1\right) + p_{x_{12}\dot{x}_{12}}\left(x_1\dot{x}_1\right)F_{x_{11}}\left(x_1\right) = = 2p_{x_{11}\dot{x}_{11}}\left(x_1\dot{x}_1\right)F_{x_{12}}\left(x_1\right) \quad (18)$$

The level crossing rate of x_1 is:

$$N_{x_1}\left(x_1\dot{x}_1\right) = \int_0^\infty d\dot{x}_1\,\dot{x}_1\,p_{x_1\dot{x}_1}\left(x_1\dot{x}_1\right) = = 2F_{x_{12}}\left(x_1\right)N_{x_{11}} = 2\sqrt{2\pi}\,f_m S_2\frac{x_1^{\alpha/2}}{\left(\Omega_1 + x_1^{\alpha}S_1\right)^2} \quad (19)$$

Random variables Ω_1 and Ω_2 follow correlated Gamma distribution:

$$p_{\Omega_1\Omega_2}\left(\Omega_1\Omega_2\right) = \frac{1}{\Gamma(c)\left(1-\rho^2\right)\rho^{c-1}\Omega_0^{c+1}}\cdot \cdot e^{-\frac{\Omega_1+\Omega_2}{\Omega_0\left(1-\rho^2\right)}} I_{c-1}\left(\frac{2\rho}{\Omega_0\left(1-\rho^2\right)}\Omega_1^{1/2}\Omega_2^{1/2}\right) = = \frac{1}{\Gamma(c)\left(1-\rho^2\right)\rho^{c-1}\Omega_0^{c+1}}\cdot \sum_{i_1=0}^{\infty}\left(\frac{\rho}{\Omega_0\left(1-\rho^2\right)}\right)^{2i_1+c-1}\frac{1}{i_1!\,\Gamma\left(i_1+c\right)}\cdot \Omega_1^{i_1+c-1}\Omega_2^{i_1+c-1}e^{-\frac{\Omega_1+\Omega_2}{\Omega_0\left(1-\rho^2\right)}},\ \Omega_1 \ge 0,\ \Omega_2 \ge 0 \quad (20)$$

where c is Gamma long term fading severity parameter, ρ is correlation coefficient, $\Gamma(.)$ is a Gamma function and $\Omega_0 = \overline{\Omega_1} = \overline{\Omega_2}$.

Random variables S_1 and S_2 follow Gamma distribution:

$$p_{S_1S_2}\left(S_1S_2\right) = \frac{1}{\Gamma\left(c_1\right)\beta^{c_1}}\cdot S_1^{c_1-1}e^{-\frac{1}{\beta}S_1}\cdot\frac{1}{\Gamma\left(c_1\right)\beta^{c_1}}\cdot S_2^{c_1-1}e^{-\frac{1}{\beta}S_2} \quad (21)$$

where c_1 is severity parameter and $\beta = \overline{S_1} = \overline{S_2}$.

Level crossing rate at output of MAD SC receiver signal to interference ratio is level crossing rate at output of the first MID SC receiver signal to interference ratio when the signal envelope average power at its inputs is higher then the signal envelope average power at inputs in the second MID SC receiver. Level crossing rate at output of MAD SC receiver signal to interference ratio is level crossing rate from the output of the second MID SC receiver signal to interference ratio when the signal envelope average power at its inputs is higher then the signal envelope average power at inputs of the first MID SC receiver. Therefore, level crossing rate at output of MAD SC receiver signal to interference ratio is:

$$N_x = \int_0^\infty dS_1\int_0^\infty dS_2\left[\int_0^\infty d\Omega_1\int_0^{\Omega_1} d\Omega_2 N_{x_1/\Omega_1S_1}p_{\Omega_1\Omega_2}\left(\Omega_1\Omega_2\right) + + \int_0^\infty d\Omega_2\int_0^{\Omega_2} d\Omega_1 N_{x_2/\Omega_2S_2}p_{\Omega_1\Omega_2}\left(\Omega_1\Omega_2\right)\right]p_{S_1S_2}\left(S_1S_2\right) = = 2\int_0^\infty dS_1\int_0^\infty dS_2\int_0^\infty d\Omega_1\int_0^{\Omega_1} d\Omega_2 N_{x_1/\Omega_1S_1}p_{\Omega_1\Omega_2}\left(\Omega_1\Omega_2\right)p_{S_1S_2}\left(S_1S_2\right) = = 4\sqrt{2\pi}\,f_m x^{\alpha/2}\frac{1}{\Gamma\left(c_1\right)\beta^{c_1}}\cdot\frac{1}{\Gamma(c)\left(1-\rho^2\right)\rho^{c-1}\Omega_0^{c+1}}\cdot \sum_{i_1=0}^{\infty}\left(\frac{\rho}{\Omega_0\left(1-\rho^2\right)}\right)^{2i_1+c-1}\frac{1}{i_1!\,\Gamma\left(i_1+c\right)}\cdot\frac{1}{i_1+c}\cdot \sum_{j_1=0}^{\infty}\frac{1}{\left(i_1+c+1\right)\left(j_1\right)}\frac{1}{\left(\Omega_0\left(1-\rho^2\right)\right)j_1}\cdot \int_0^\infty dS_1\,S_1^{c_1-1+1}e^{-\frac{1}{\beta}S_1}\int_0^\infty d\Omega_1\,\Omega_1^{2i_1+2c-1+j_1}e^{-\frac{2\Omega_1}{\Omega_0\left(-\rho^2\right)}}\cdot \cdot\frac{1}{\left(\Omega_1 + x_1^{\alpha}S_1\right)^2} \quad (22)$$

Previous integral can be solved by using the formula derived in Appendix. The parameters are:

$p_1 = \alpha + 1$

$p_2 = 2i_1 + 2c + j_1$

$\alpha_1 = \frac{1}{\beta}$, $\alpha_2 = \frac{2}{\Omega_0\left(1-\rho^2\right)}$

$a = 1$, $b = x^{\alpha}$, $n = 2$

$p_1 + p_2 = 2i_1 + 2c + j_1 + \alpha + 1$

$p_1 + p_2 - n = 2i_1 + 2c + j_1 + \alpha - 1$

$p_1 - n = \alpha - 1$

After substituting, the expression for N_x becomes:

$$N_x = 4\sqrt{2\pi}\,f_m x^{\alpha/2}\frac{1}{\Gamma\left(c_1\right)\beta^{c_1}}\cdot\frac{1}{\Gamma(c)\left(1-\rho^2\right)\rho^{c-1}\Omega_0^{c+1}}\cdot \sum_{i_1=0}^{\infty}\left(\frac{\rho}{\Omega_0\left(1-\rho^2\right)}\right)^{2i_1+c-1}\frac{1}{i_1!\,\Gamma\left(i_1+c\right)}\cdot\frac{1}{i_1+c}\cdot$$

$$\sum_{j_1=0}^{\infty}\frac{1}{(i_1+c+1)(j_1)}\frac{1}{(\Omega_0(1-\rho^2))j_1}\cdot$$
$$\left(\frac{\Omega_0(1-\rho^2)}{2}\right)^{2i_1+2c+j_1+\alpha-1}\Gamma(2i_1+2c+j_1)\frac{1}{x^{\alpha(\alpha+1)}}\cdot$$
$$ {}_2F_1\left(2i_1+2c+j_1+\alpha-1,\alpha+1,2i_1+2c+j_1+\alpha+1,1-\frac{\Omega_0(1-\rho^2)}{\beta\cdot 2x^{\alpha}}\right) \tag{23}$$

Here, ${}_2F_1$ is hypergeometric function [9] [10].

4 Numerical results

The average level crossing rate of the macrodiversity SC receiver output signal versus the SC receiver output signal envelope is plotted at Figures 2 to 6, for several values of Gamma fading severity, the correlation coefficient of shadowing ρ, Weibull short term fading nonlinearity parameter and powers of the useful signal and interference.

One can see from these figures that LCR has smaller values for higher SC receiver output signal envelope, bigger values of Gamma fading severity parameters of desired signal and interference, for smaller power of interference, bigger power of desired signal and also greater Weibull short term fading nonlinearity parameter α

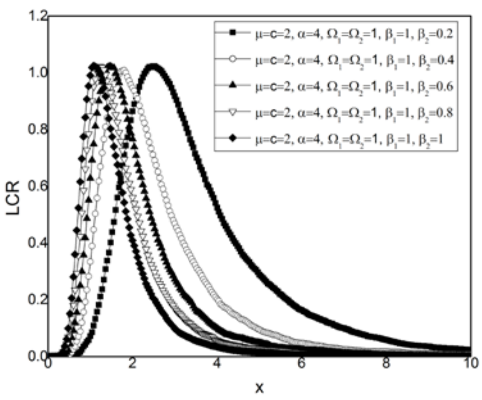

Fig. 2. Level crossing rate of macrodiversity SC receiver output signal versus the SC receiver output signal envelope for variable Gamma fading severity of interference.

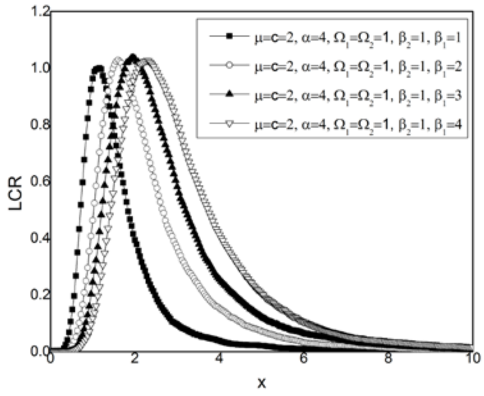

Fig. 3. The Level crossing rate versus macrodiversity SC receiver output signal envelope for variable Gamma fading severity parameter of desired signal.

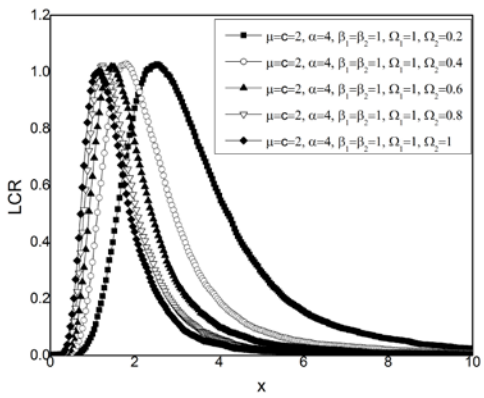

Fig. 4. The level crossing rate versus macrodiversity SC receiver output signal envelope for different power of interference.

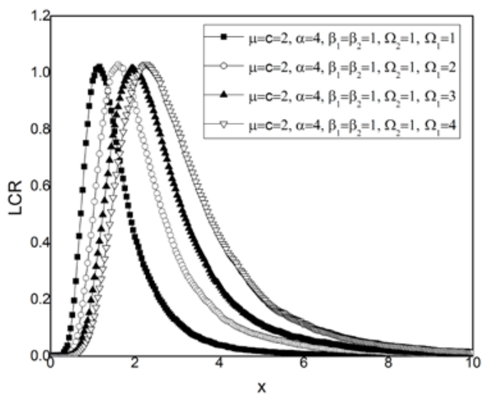

Fig. 5. The level crossing rate versus macrodiversity output signal envelope for different power of desired signal.

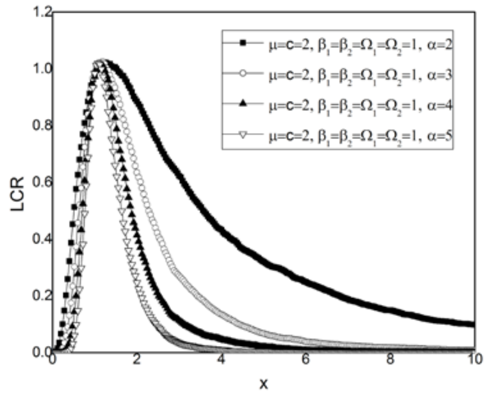

Fig. 6. The level crossing rate of macrodiversity SC receiver output signal versus SC receiver output signal envelope for variable Weibull short term fading nonlinearity parameter α.

System performances are better for lower values of the average level crossing rate. The previous few figures for the level crossing rate versus signal envelope are drown to show the influence of different fading parameters to LCR and to give possibilitz to the wireless system designers to choose optimal parameters.

5 Conclusion

In this paper, MAD technique with MAD SC receiver and two MID SC receivers in the presence of Weibull short term fading, Gamma long term fading and Weibull cochannel interference is analyzed. MAD reception reduces short term fading effects, Gamma long term fading effects and cochannel interference effects on system performance. MAD SC receiver reduces Gamma long term fading effects and MID SC receivers reduce Weibull short term fading effects on the level crossing rate of signal to interference ratio at the output of MAD SC receiver. Received signal experiences correlated Gamma fading and Weibull independent fading.

When correlation coefficient goes to one, MAD system becomes MID system. When Gamma shadowing severity parameter goes to infinity, Gamma shadowed Weibull short term fading channel becomes Weibull short term fading channel. When Weibull nonlinear parameter goes to infinity, Gamma shadowed Weibull short term fading channel becomes Gamma short term fading channel. When Gamma severerity parameter goes to infinity and Weibull nonlinearity parameter goes to infinity, Gamma shadowed Weibull short term fading channel becomes no fading channel.

In this paper, probability density function, cumulative distribution function and level crossing rate of the ratio of two Weibull random variables are calculated. These results are used for calculation the level crossing rate of signal to interference ratio at output of MID SC receivers and level crossing rate of signal to interference ratio at output of MAD SC receiver in the closed form. The obtained results can be used for evaluation the level crossing rate of MAD system operating over Gamma shadowed Rayleigh multipath fading channel. The influence of Gamma long term fading severity parameter, Gamma long term fading correlation coefficient and Weibull short term fading nonlinearity parameter on level crossing rate of MAD SC receiver output signal to interference ratio is analyzed.

Further, the expression for the level crossing rate derived here can be used for the evaluation of the average fade duration for wireless communication system operating over shadowed multipath fading channels.

Apendix

The integral J is:

$$J=\int_0^\infty dS\, S^{p_1-1}e^{-\alpha_1 S}\int_0^\infty d\Omega\,\Omega^{p_2-1}e^{\alpha_2\Omega}\frac{1}{(a\Omega+bS)^n}=$$

$$=b^{-n}\int_0^\infty dS\, S^{p_1-n-1}e^{-\alpha_1 S}\int_0^\infty d\Omega\,\Omega^{p_2-1}e^{\alpha_2\Omega}\frac{1}{\left(\frac{a}{bS}\Omega+1\right)^n}$$

Introducting the substitute:

$$\frac{a}{bS}\Omega=x,\ \Omega=\frac{bS}{a}x,\ d\Omega=\frac{bS}{a}dx$$

previous integral becomes:

$$J=\frac{b^{p_2-n}}{a^{p_2}}\int_0^\infty dS\, S^{p_1-n-1+p_2}e^{-\alpha_1 S}\int_0^\infty dx\, x^{p_2-1}e^{\frac{\alpha_2 bS}{a}x}\frac{1}{(x+1)^n}.$$

By using the formula:

$$\int_0^\infty dt\, t^{a-1}e^{-ct}\frac{1}{(t+1)^n}=\Gamma(a)U(a,a+1-n,c),$$

the integral J obtains the form:

$$J=\frac{b^{p_2-n}}{a^{p_2}}\int_0^\infty dS\, S^{p_1-n-1+p_2}e^{-\alpha_1 S}\,\Gamma(p_2)U\left(p_2,p_2+1-n,\frac{\alpha_2 bS}{a}\right),$$

with *U(a,b,z)* being the confluent hypergeometric function of the second kind [10] [11].

After new substitution:

$$\frac{\alpha_2 bS}{a} = y,\ S = \frac{a}{\alpha_2 b} y,\ dS = \frac{a}{\alpha_2 b} dy\ ,$$

the integral J becomes:

$$J = \frac{1}{\alpha_2^{p_1+p_2-n} b^{p_1}} a^{p_1-n} \Gamma(p_2)$$

$$\int_0^\infty dy\, y^{p_1-n+p_2-1} e^{\frac{\alpha_1 a}{\alpha_2 b} y} U(p_2, p_2+1-n, y).$$

Because:

$$\int_0^\infty dy\, y^{b-1} e^{Sy} U(a,c,y) = \frac{\Gamma(b)\Gamma(b+c-1)}{\Gamma(a+b+c-1)} \cdot$$

$${}_2F_1(b, b+c-1, a+b+c-1, 1-S),$$

the integral J finally becomes:

$$J = \frac{a^{p_1-n}}{\alpha_2^{p_1-p_2-n}} \frac{\Gamma(p_2)}{b^{p_1}} \frac{\Gamma(p_1+p_2-n)\Gamma(p_1)}{\Gamma(p_1+p_2)}$$

$${}_2F_1\left(p_1+p_2-n, p_1, p_1+p_2, 1-\frac{a\alpha_1}{b\alpha_2}\right).$$

where ${}_2F_1(a,b,z)$ is a regularized confluent hypergeometric function of the second kind.

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