SECOND ORDER STATISTICS AND CHANNEL SPECTRAL EFFICIENCY FOR SELECTION DIVERSITY RECEIVERS IN WEIBULL FADING

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Abstract - Motivated by the suitability of the Weibull distribution to model multipath fading channels, the second order statistics and the spectral efficiency (SE) of L-branch SC receivers are studied. Deriving a novel closed-form expression for the probability density function (pdf) of the SC output SNR, the average level crossing rate (LCR), the average fade duration (AFD) and the Shannon's average SE, at the output of the SC, are derived in closed-forms. Our results are sufficiently general to handle arbitrary fading parameter and dissimilar branch powers.

Keywords - Selection combining (SC), Weibull fading channels, level crossing rate (LCR), average fade duration (AFD), spectral efficiency (SE).

I. INTRODUCTION

SELECTION combining (SC) receivers are utilized to mitigate the detrimental effects of channel fading and co-channel interference in wireless digital communications systems. Their major advantage is the reduced complexity compared to other well-known diversity techniques, such as equal-gain combining (EGC), maximal-ratio combining (MRC) and generalized-selection combing (GSC). In L-branch selection diversity receivers, the instantaneous signal-to-noise ratio (SNR) of the L branches are estimated and the one with the highest value is selected [1].

The second order statistics and the channel capacity, in Shannon's sense, of SC receivers have been extensively studied in the open technical literature for Rayleigh [2], [3], Rice [4]–[6] and Nakagami-m fading channel models [7]–[9]. Hoever, experimental fading channel measurements show, that the Weibull model also exhibits excellent fit for indoors [10], [11], as well as outdoors [12], [13] environments. To the best of the authors' knowledge, only a published work related to the second order statistics and the average channel spectral efficiency (SE) has been presented by Sagias *et al.* in [14]. In this work, novel analytical expressions for the average level crossing rate (LCR), the average fade duration (AFD) [2] and the average SE, when the Weibull model is considered, have been extracted. However, such performance metrics have not been previously addressed for SC receivers in Weibull fading.

In this paper, the channel SE and the second order statistics of SC receivers for non-identical Weibull fading channels, are studied. More specifically, deriving a novel and mathematical trackable formula for the probability density function (pdf) of the SC output SNR, closed-form expressions for the average LCR, the AFD and the average SE, at the output of the combiner, are obtained. Selected numerical examples are presented, showing the effects of various channels and systems parameters, such as the fading severity and the number of diversity branches on the SC performance.

II. SYSTEM AND CHANNEL MODEL

We consider an L-branch SC receiver, where $x_{1,\ell}(t) = \sqrt{2}\,\sigma_\ell \sum_{k=1}^{\mathcal{K}} s_{k,\ell} \cos(2\pi f_{k,\ell}\, t - \vartheta_{k,\ell})$ and $x_{2,\ell}(t) = \sqrt{2}\,\sigma_\ell \sum_{k=1}^{\mathcal{K}} s_{k,\ell} \sin(2\pi f_{k,\ell}\, t - \vartheta_{k,\ell})$ are the in-phase and quadrature components of a narrow-band process at timing instance t in the ℓth input branch, $\ell = 1, 2, \dots, L$. In the above equations, $\sqrt{2}\,\sigma_\ell\, s_{k,\ell}$ is the fading amplitude of the kth wave which satisfies $\sum_{k=1}^{\mathcal{K}} s_{k,\ell}^2 = 1$, $\vartheta_{k,\ell}$ is the random phase uniformly distributed in $[0, 2\pi)$, $\mathcal{K}$ is the total number of waves and $f_{k,\ell}$ is the Doppler shift given by $f_{k,\ell} = f_d \cos(\theta_{k,\ell})$, where f_d is the maximum Doppler shift and $\theta_{k,\ell}$ is the corresponding angle of wave arrival.

Taking into account the central limit theorem, for fixed t and for a large value of $\mathcal{K}$, $x_{1,\ell}(t)$ and $x_{2,\ell}(t)$ can be considered as zero mean Gaussian random variables (rv) with variance σ_ℓ^2. Here, it is convenient to alleviate this notation, by omitting the variable t in the equations. It is well-known that a sum of two quadrature Gaussian rvs is also a Gaussian one, i.e., $z_\ell = x_{1,\ell} + \jmath\, x_{2,\ell} = x_\ell\, e^{\jmath \varphi_\ell}$, where $\sqrt{\jmath} = -1$. The phase $\varphi_\ell = \tan^{-1}(x_{2,\ell}/x_{1,\ell})$ of this new Gaussian rv is uniformly distributed in $[0, 2\pi)$ and the amplitude $x_\ell = \sqrt{x_{1,\ell}^2 + x_{2,\ell}^2}$ is Rayleigh distributed, having pdf

$$p_{x_\ell}(x_\ell) = 2\, x_\ell \exp\left(-x_\ell^2/\Omega_\ell\right)/\Omega_\ell \tag{1}$$

where $\Omega_\ell = E\left\langle x_\ell^2\right\rangle = 2\,\sigma_\ell^2$, with $E\langle\cdot\rangle$ denotes expectation. Let the received sampled envelope in the ℓth diversity branch be $y_\ell = z_\ell^{2/\beta_\ell} = x_\ell^{2/\beta_\ell} e^{j\,2\,\varphi_\ell/\beta_\ell}$, where β_ℓ is a positive real constant value. Using (1), the pdf of the envelope

$$r_\ell = x_\ell^{2/\beta_\ell} \tag{2}$$

can be easily obtained as

$$p_{r_\ell}(r_\ell) = \beta_\ell\, r_\ell^{\beta_\ell - 1} \exp\left(-r_\ell^{\beta_\ell}/\Omega_\ell\right)/\Omega_\ell \tag{3}$$

with $E\left\langle r_\ell^{\beta_\ell}\right\rangle = \Omega_\ell$. It is easily recognized that (3) follows the Weibull distribution [15]. The parameter β_ℓ is the Weibull fading parameter ($\beta_\ell \geq 0$) and expresses the severity of fading. As the value of β_ℓ increases, the severity of the fading decreases, while for the special case of $\beta_\ell = 2$, (3) reduces to the well-known Rayleigh pdf. The corresponding cumulative density function (cdf) and the nth moment of r_ℓ are

$$F_{r_\ell}(r_\ell) = 1 - \exp\left(-r_\ell^{\beta_\ell}/\Omega_\ell\right) \tag{4}$$

and

$$E\left\langle r_\ell^n\right\rangle = \Omega^{n/\beta_\ell}\,\Gamma\left(d_{n,\ell}\right) \tag{5}$$

respectively, where $\Gamma(\cdot)$ is the Gamma function [16, eq. (8.310/1)] and $d_{n,\ell}$ is defined as $d_{n,\ell} = 1 + n/\beta_\ell$. Let the instantaneous input SNR per symbol in the ℓth branch be as

$$\gamma_\ell = r_\ell^2\, E_s/N_0 \tag{6}$$

and the corresponding average input SNR per symbol as

$$\overline{\gamma}_\ell = \overline{r_\ell^2}\, E_s/N_0 \tag{7}$$

where E_s is the transmitted symbols' energy, $\overline{r_\ell^2}$ is the fading power, $\overline{r_\ell^2} = \Omega^{2/\beta_\ell}\,\Gamma\left(d_{2,\ell}\right)$ and N_0 is the single-sided noise power spectral density (psd) of the additive white Gaussian noise (AWGN), assumed identical and uncorrelated among the L diversity branches. Using (5), (6) and (7) with (4), the cdf of γ_ℓ can be written as

$$F_{\gamma_\ell}(\gamma_\ell) = 1 - \exp\left[-\left(\frac{\gamma_\ell}{a_\ell \overline{\gamma}_\ell}\right)^{\beta_\ell/2}\right] \tag{8}$$

where $a_\ell = 1/\Gamma\left(d_{2,\ell}\right)$.

The envelope r at the output of the SC receiver will be the one with the highest value among the L branches, i.e.,

$$r = \max\left\{r_\ell\right\} \tag{9}$$

and having assumed identical noise psd to all diversity branches during the sampling process, the instantaneous output SNR will be

$$\gamma_{sc} = \max\left\{\gamma_\ell\right\} = r^2\, E_s/N_0. \tag{10}$$

The cdfs of r and γ_{sc} are the probability that the signal levels of all branches fall below a certain level, which using (4) and (8), can be expressed as

$$F_r(r) = \prod_{k=1}^{L}\left[1 - \exp\left(-r^{\beta_k}/\Omega_k\right)\right] \tag{11}$$

and

$$F_{\gamma_{sc}}(\gamma_{sc}) = \prod_{k=1}^{L}\left\{1 - \exp\left[-\left(\frac{\gamma_{sc}}{a_k\,\overline{\gamma}_k}\right)^{\beta_k/2}\right]\right\} \tag{12}$$

respectively. The pdf of γ_{sc} is obtained by differentiating (12) with respect to γ_{sc}, yielding

$$p_{\gamma_{sc}}(\gamma_{sc}) = \frac{1}{2}\sum_{k=1}^{L}\frac{\beta_k\,\gamma_{sc}^{\beta_k/2-1}}{(a_k\overline{\gamma}_k)^{\beta_k/2}}\exp\left[-\left(\frac{\gamma_{sc}}{a_k\,\overline{\gamma}_k}\right)^{\beta_k/2}\right] \times \prod_{\substack{i=1\\ i\neq k}}^{L}\left\{1 - \exp\left[-\left(\frac{\gamma_{sc}}{a_i\,\overline{\gamma}_i}\right)^{\beta_i/2}\right]\right\}. \tag{13}$$

The above expression for the pdf of γ_{sc} can not be easily manipulated in the current form. Therefore, we rearrange (13), performing all the multiplications required and thus, for $\beta_\ell = \beta$, $\forall\ell$ ($a_\ell = a$ and $d_{n,\ell} = d_n$), valid for practical applications, after manipulations (13) can be efficiently written as

$$p_{\gamma_{sc}}(\gamma_{sc}) = \frac{1}{2}\,\gamma_{sc}^{\frac{\beta}{2}-1}\sum_{k=1}^{L}(-1)^{k+1} \sum_{\lambda_1=1}^{L-k+1}\sum_{\lambda_2=\lambda_1+1}^{L-k+2}\cdots\sum_{\lambda_k=\lambda_{k-1}+1}^{L}\prod_{j=1}^{L}t_{\lambda_j}\sum_{i=1}^{k}u_{\lambda_i} \tag{14}$$

where $u_\ell = \beta/\left(a\,\overline{\gamma}_\ell\right)^{\beta/2}$ and $t_\ell = \exp\left(u_\ell\,\gamma_{sc}^{\beta/2}/\beta\right)$, respectively. Equation (14) includes only sums of simple products of powers and exponential functions, which are mathematically trackable. For independent and identically distributed (i.i.d.) input paths ($\overline{\gamma}_\ell = \overline{\gamma}$ and $\Omega_\ell = \Omega, \forall\ell$), using the binomial identity [16, eq. (1.111)], (13) can be simplified as [17, eq. (4)]

$$p_{\gamma_{sc}}(\gamma_{sc}) = \frac{\beta\, L\,\gamma_{sc}^{\beta/2-1}}{2\,(a\overline{\gamma})^{\beta/2}}\sum_{k=0}^{L-1}\binom{L-1}{k}(-1)^k \times \exp\left[-(k+1)\left(\frac{\gamma_{sc}}{a\,\overline{\gamma}}\right)^{\beta/2}\right] \tag{15}$$

where $\binom{L-1}{k} = (L-1)!/[k!\,(L-1-k)!]$.

III. Average Fade Duration (AFD) and Level Crossing Rate (LCR)

The average LCR and the AFD are two criteria which statistically characterize the fading communication channel. The average LCR is defined as the average number of times per unit duration that the envelope of a fading channel crosses a given value in the negative direction. The AFD corresponds to the average length of time the envelope remains under this value once it crosses it in the negative direction. Both reflect the correlation properties, and thus the second-order statistics, of the fading channel and they provide a dynamic representation of the channel [2].

The average LCR and the AFD are defined as

$$N(r) \triangleq \int_0^{\infty} \dot{r}\, p_{\dot{r},r}(\dot{r},r)\, d\dot{r} \tag{16}$$

and

$$\tau(r) \triangleq F_r(r)/N(r) \tag{17}$$

respectively, where $p_{\dot{r},r}(\dot{r},r)$ is the joint pdf of r and its time derivative $\dot{r}$. Using (2), the time derivative of r_ℓ is

$$\dot{r}_\ell = 2\, r_\ell^{1-\beta_\ell/2}\, \dot{x}_\ell/\beta_\ell \tag{18}$$

where $\dot{x}_\ell$ is the time derivative of x_ℓ. For isotropic scattering, $\dot{x}_\ell$ is Gaussian distributed with zero mean and variance [2]

$$\hat{\sigma}_\ell^2 = \sigma_\ell^2\, 2\pi^2 f_d^2. \tag{19}$$

From (18), the pdf of $\dot{r}_\ell$ conditioned on r_ℓ is also a zero mean Gaussian distribution, with standard deviation

$$\hat{\sigma}_{r_\ell} = 2\, r_\ell^{1-\beta_\ell/2}\, \hat{\sigma}_\ell/\beta_\ell. \tag{20}$$

Using (9), the time derivative of the envelope at the output of the SC receiver is

$$\dot{r} = \dot{r}_i,\ r_i = \max\{r_\ell\}. \tag{21}$$

From (18) and (21), it can be easily recognized that $\dot{r}$ conditioned on the r_ℓ is a zero mean Gaussian rv, with variance $\hat{\sigma}_r^2 = \hat{\sigma}_{r_\ell}^2$, if $(r_i = \max\{r_\ell\} \,|\, r_i = r)$ and pdf

$$p_{\dot{r}}(\dot{r}|r) = \exp\left(-0.5\,\dot{r}^2/\hat{\sigma}_{r_\ell}^2\right) / \left(\sqrt{2\pi}\,\hat{\sigma}_{r_\ell}\right). \tag{22}$$

Consequently, $\hat{\sigma}_r$ is a discrete rv with pdf

$$\begin{aligned} p_{\hat{\Sigma}_r}(\hat{\sigma}_r) &= \sum_{i=1}^{L} P(\hat{\sigma}_r = \hat{\sigma}_i)\, \delta(\hat{\sigma}_r - \hat{\sigma}_i) \\ &= \sum_{i=1}^{L} P(r_i = \max\{r_\ell\} \,|\, r_i = r)\, \delta(\hat{\sigma}_r - \hat{\sigma}_i). \end{aligned} \tag{23}$$

Using (16) and (22) and taking into account $p_{\dot{r},r}(\dot{r},r) = p_{\dot{r}}(\dot{r}|r)\, p_r(r)$, the average LCR conditional on $\hat{\sigma}_r$ is

$$N(r|\hat{\sigma}_r) = p_r(r)\, \hat{\sigma}_r/\sqrt{2\pi}. \tag{24}$$

By averaging (24) over the pdf of $\hat{\sigma}_r$, i.e., $N(r) = \int_0^{\infty} N(r|\hat{\sigma}_r)\, p_{\hat{\Sigma}_r}(\hat{\sigma}_r)\, d\hat{\sigma}_r$ and using (20) and (23), yields

$$N(r) = \sum_{i=1}^{L} p_{r_i}(r)\, \frac{2\, r^{1-\beta_\ell/2}\, \hat{\sigma}_\ell}{\beta_\ell\sqrt{2\pi}}\, P(r_i = \max\{r_\ell\} \,|\, r_i = r). \tag{25}$$

Taking into account the independence assumption between the input branches, $P(r_i = \max\{r_\ell\} \,|\, r_i = r) = \prod_{\substack{k=1\\k\neq i}}^{L} F_{r_k}(r)$ and by replacing, together with (3), (4) and (19) into (25), the average LCR of the SC operating in Weibull fading can be obtained in closed-form as

$$N(r) = \sqrt{2\pi} f_d \sum_{i=1}^{L} \frac{r^{\frac{\beta_i}{2}}}{\Omega_i}\, e^{-\frac{r^{\beta_i}}{\Omega_i}} \prod_{\substack{k=1\\k\neq i}}^{L} \left[1 - \exp\left(-\frac{r^{\beta_k}}{\Omega_k}\right)\right]. \tag{26}$$

Now, replacing (11) and (26) into (17), the AFD of the SC is also expressed in closed-form as

$$\tau(r) = \frac{\prod_{k=1}^{L}\left(1 - e^{-\frac{r^{\beta_k}}{\Omega_k}}\right)}{\sqrt{2\pi} f_d \sum_{i=1}^{L} \frac{r^{\frac{\beta_i}{2}}}{\Omega_i}\, e^{-\frac{r^{\beta_i}}{\Omega_i}} \prod_{\substack{k=1\\k\neq i}}^{L}\left[1 - \exp\left(-\frac{r^{\beta_k}}{\Omega_k}\right)\right]}. \tag{27}$$

For i.i.d. input paths, after normalizing the signals' levels to its root mean square (rms) value $\rho = r/r_{rms}$, with $r_{rms} = \sqrt{\overline{r^2}}$, (26) and (27) reduce to

$$\begin{aligned} N(\rho) =& L f_d \sqrt{2\pi}\, (\rho/\sqrt{a})^{\beta/2} \exp\left[-(\rho/\sqrt{a})^{\beta}\right] \\ &\times \left\{1 - \exp\left[-(\rho/\sqrt{a})^{\beta}\right]\right\}^{L-1} \end{aligned} \tag{28}$$

and

$$\tau(\rho) = \frac{1 - \exp\left[-(\rho/\sqrt{a})^{\beta}\right]}{L f_d \sqrt{2\pi}\, (\rho/\sqrt{a})^{\beta/2} \exp\left[-(\rho/\sqrt{a})^{\beta}\right]} \tag{29}$$

respectively. Note, that when $\beta = 2$, (26) and (27) reduce to previously published expressions for the average LCR and AFD of the well-known Rayleigh model [9]. For $L = 1$, (28) and (29) can be further reduced to [14, eq. (12)] and [14, eq. (13)], respectively.

The value which maximizes the average LCR can be derived as $\partial N(r)/\partial r|_{r=r_{\max}} = 0$. For $L = 1$, it can be shown that the average LCR is maximized at $\rho_{\max} = 2^{-1/\beta}\sqrt{a}$ as $N(\rho_{\max}) = f_d\sqrt{\pi/e}$, where $\rho_{max} = r_{max}/r_{rms}$. It is interesting to note that the severity of fading does not affect $N(\rho_{\max})$. However, for $L > 1$, $\rho_{\max}$ can not be analytically extracted and any of the well-known software mathematical packages such Mathematica and Maple can be used for numerical evaluation.

Using (28) and (29), Figs. 1 and 2 plot the normalized average LCR and AFD, respectively, for a dual branch SC with i.i.d. input branches SNRs as a function of ρ, for several values of β. As the fading severity increases, the normalized average LCR increases, meaning that fades occur more frequently. Furthermore, the lower the signal levels are, the less frequently that they are crossed, whereas higher signal level are crossed more frequently. Furthermore, in Figs. 3 and 4, the normalized average LCR and AFD, respectively, for an L-branch SC with i.i.d. input branches SNRs, is plotted as a function of ρ for $\beta = 2.5$ and different diversity orders. As L increases, the frequency at which the

$$
\begin{aligned}
\overline{SE} = & \frac{\beta\sqrt{\kappa}\,\mu^{-1}}{2\,\ln(2)\,(2\pi)^{\frac{\kappa+2\mu-3}{2}}} \sum_{n=1}^{L}(-1)^{n+1} \sum_{\lambda_1=1}^{L-n+1} \sum_{\lambda_2=\lambda_1+1}^{L-n+2} \cdots \sum_{\lambda_n=\lambda_{n-1}+1}^{L} \sum_{i=1}^{n} \left(a\,\overline{\gamma}_{\lambda_i}\right)^{-\frac{\beta}{2}} \\
& \left. \times\, \mathrm{G}_{2\mu,\,\kappa+2\mu}^{\kappa+2\mu,\,\mu} \left[\left[\frac{1}{\kappa} \sum_{j=1}^{n} \left(a\,\overline{\gamma}_{\lambda_j}\right)^{-\frac{\beta}{2}} \right]^{\kappa} \left(\frac{\mu}{B}\right)^{\mu} \,\middle|\, \begin{matrix} \Delta(\mu,-\frac{\beta}{2})\,,\,\Delta(\mu,1-\frac{\beta}{2}) \\ \Delta(\kappa,0)\,,\,\Delta(\mu,-\frac{\beta}{2})\,,\,\Delta(\mu,-\frac{\beta}{2}) \end{matrix} \right] \right\}
\end{aligned} \tag{31}
$$

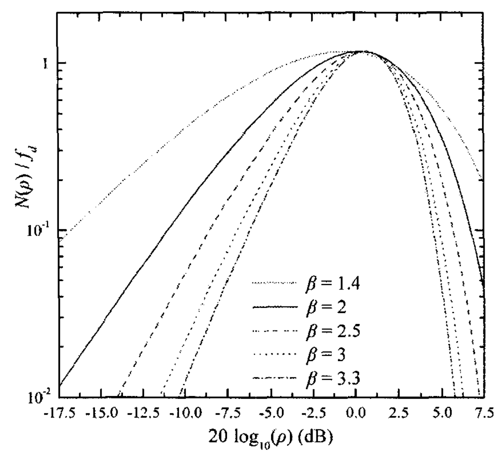

Fig. 1
Normalized average LCR vs. normalized envelope level for $L = 2$.

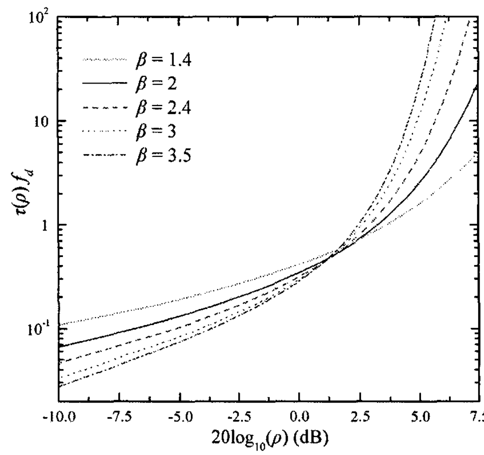

Fig. 2
Normalized AFD vs. normalized envelope level for $L = 2$.

received signal crosses high values (e.g. $\rho > 2.5$ dB) stays almost the same. Moreover, as L increases fades occur rarely.

IV. Average Spectral Efficiency (SE)

The SE, in Shannon's sense, is an important performance measure since it provides the maximum transmission rate which can be succeeded, in order to the errors be recoverable. The average SE is expressed as [3]

$$\overline{SE} = \int_0^\infty \log_2\left(1+\gamma\right)\, p_{\gamma_{sc}}(\gamma)\, d\gamma. \tag{30}$$

By replacing (14) into (30), it is required to evaluate integrals of the form $\int_0^\infty x^{\beta/2-1}\,\ln(1+x)\,\exp\left(-\xi\, x^{\beta/2}\right)dx$. This type of integral has been analytically solved in [14], using [18] and the average SE can be obtained in a closed-form expression as in (31) (top of this page), where G$[\cdot]$ is the tabulated Meijer's G-function [16, eq. (9.301)], available in most of the well-known mathematical software packages, such Maple and Mathematica and $\Delta(n,\xi) = \xi/n,\, (\xi+1)/n, \ldots, (\xi+n-1)/n$, with ξ an arbitrary real value and n a positive integer. Moreover, the values of integers κ and μ must be chosen, so that $\mu/\kappa = \beta/2$ holds (e.g. for $\beta = 3.4$ we have to choose $k = 10$ and $l = 17$). Note, that for the special case of β being integer, $k = 2$ and $l = \beta$. For i.d.d. input paths (31) reduces to (32) (top of the next page) and setting $L = 1$ in (32), leads to [14, eq. (17)].

V. Conclusions

Based on a useful formula extracted for the pdf of the SC output SNR, closed-form expressions for the average LCR, the AFD and the average SE were derived. Selected numerical examples were presented, supporting that the performance gain of SC gets more important as the fading gets less severe and the diversity order increases.

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$$\overline{SE} = \frac{L\,\beta}{2\,(a\overline{\gamma})^{\frac{\beta}{2}}\,\ln(2)}\frac{\sqrt{\kappa}\,\mu^{-1}}{(2\pi)^{\frac{\kappa+2\mu-3}{2}}}\sum_{n=0}^{L-1}\binom{L-1}{n}(-1)^n\,\mathrm{G}_{2\mu,\kappa+2\mu}^{\kappa+2\mu,\mu}\left[\frac{(n+1)^{\kappa}}{\kappa^{\kappa}\,(a\,\overline{\gamma})^{\frac{\kappa\beta}{2}}}\,\middle|\,\begin{matrix}\Delta(\mu,-\frac{\beta}{2})\,,\,\Delta(\mu,1-\frac{\beta}{2})\\ \Delta(\kappa,0)\,,\,\Delta(\mu,-\frac{\beta}{2})\,,\,\Delta(\mu,-\frac{\beta}{2})\end{matrix}\right] \quad (32)$$

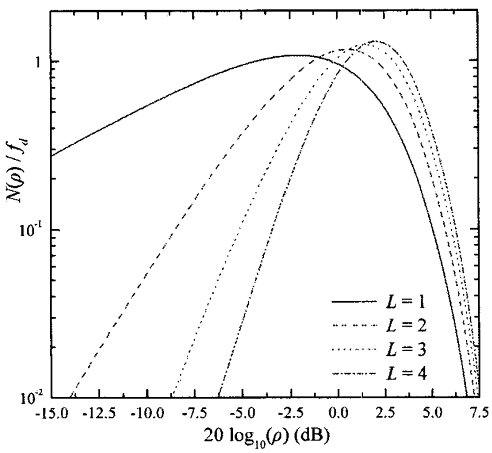

Fig. 3
Normalized average LCR vs. normalized envelope level for $\beta = 3.4$.

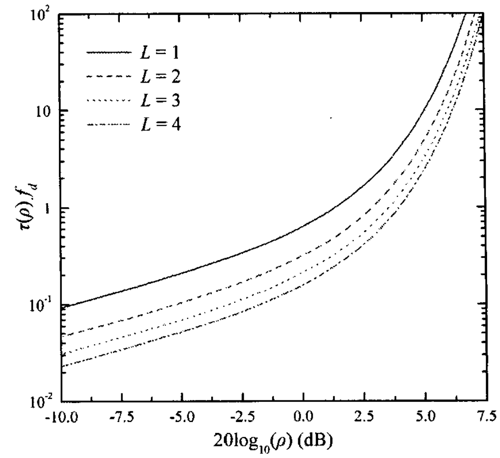

Fig. 4
Normalized average AFD vs. normalized envelope level for $\beta = 3.4$.

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