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Letter

Communication Theory

Capacity of dual-branch selection diversity receivers in correlative Weibull fading

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SUMMARY

An analysis for the Shannon channel capacity of dual-branch selection diversity receivers operating over correlative Weibull fading is presented under three adaptive policies: constant power with optimal rate adaptation, optimal power and rate adaptation and channel inversion with fixed rate. In this context, useful formulae for the average channel capacity with not necessarily identical fading statistics and arbitrary parameters for both the correlation coefficient and fading severity are derived in closed form. The analysis also includes the performance of single-branch receivers where special cases of the expressions agree with known results. Illustrative numerical examples are also presented, demonstrating the effects of the correlation coefficient, fading severity and signal-to-noise ratio unbalance on the receiver's performance. Copyright © 2005 AEIT.

1. INTRODUCTION

An effective method counteracting the negative effects of fading is to use one of the well-known diversity reception techniques, such as maximal-ratio combining (MRC), generalised-selection combining (GSC), equal-gain combining (EGC) and selection combining (SC). Among these techniques, SC requires the lowest implementation complexity at the expense of the worst performance providing, for example in terms of error and outage probability. Moreover, in contemporary wireless systems (e.g. handheld mobile terminals and indoor base-stations) the received signals are usually correlated due to insufficient antennae spacing [1, 2], resulting in a further performance degradation of SC [3]. Hence, the performance analysis of this type of receivers in a such environment is of great importance.

The Weibull distribution seems to be suitable for fading channel modeling since it has been found fitting empirical fading channel measurements, for both indoor [4, 5] and outdoor [6, 7] radio propagation environments but only recently it has gained some interest. In an early work concerning the Weibull model, an analysis for the performance evaluation of GSC receivers with independent and identical fading statistics has been presented [8]. Recently, the performance of SC and MRC receivers in independent Weibull fading has been studied [9]. In that work, useful closed-form expressions for the error performance have been derived in terms of the Meijer's G-function. Another work related to the Weibull model includes a detailed performance analysis of dual-branch SC receivers operating in correlated Weibull fading [10]. In that paper, an expression for the joint complementary cumulative distribution function (CDF) of Weibull distributed fading envelopes has been presented for the first time in telecommunications literature. Based on that expression, analytical formulae for the average output signal-to-noise ratio

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(SNR), amount of fading, outage probability and error performance have been studied. Very recently, the average output SNR has been studied for EGC receivers operating over Weibull fading channels with arbitrary correlation matrixes [11]. Further to the above mentioned performance metrics, another well-known metric, which provides an upper-bound for maximum errorless transmission rate in a given Gaussian environment, is the Shannon channel capacity (CC) [12–14]. This metric has been already studied for several channel models with independent or correlated fading statistics [15–20]. However, it has not been addressed yet with diversity receivers operating in correlated Weibull fading.

In this Letter, by taking into consideration the impact of correlated fading on practical wireless applications, we derive the Shannon CC, for dual-branch SC receivers operating in correlative Weibull fading under three adaptive policies: constant power with optimal rate adaptation (ORA), optimal power and rate adaptation (OPRA) and channel inversion with fixed rate (CIFR) [15–17]. The obtained expressions are quite general, including arbitrary values for the correlation coefficient and fading severity parameter, as well as non-identical fading statistics. The analysis also includes the performance of single-branch receivers as a special case. Selected numerical examples are provided, pointing out the effects of the Weibull severity parameter, correlation coefficient, and average SNRs unbalance on the receiver's performance.

The remainder of this paper is organised as follows. The next section presents the system and channel model. In Section 3, the outage and average CC are obtained in closed form under optimal rate adaptation with constant transmit power. In Section 4, the CC is studied under optimal simultaneous power and rate adaptation, while in Section 5, the same performance metric is analysed assuming channel inversion with fixed rate. The paper concludes with a summary given in Section 6.

2. SYSTEM AND CHANNEL MODEL

We consider a dual-branch SC receiver operating in a correlated Weibull fading environment. The marginal CDF of the instantaneous received SNR per symbol, γ_ℓ, in the ℓth ($\ell = 1$ and 2) input branch is [8, Equation (2)]

$$F_{\gamma_\ell}(\gamma) = 1 - \exp\left[-\left(\frac{\gamma}{a\,\overline{\gamma}_\ell}\right)^{\beta/2}\right] \quad (1)$$

where $\overline{\gamma}_\ell$ is the corresponding average SNR, $a = 1/\Gamma(1+2/\beta)$, with $\Gamma(\cdot)$ being the Gamma function [21, Equation (8.310/1)] and $\beta > 0$ is the Weibull fading parameter. As β increases, the severity of the fading decreases, while when $\beta = 2$, the well-known Rayleigh fading model is considered. The joint complementary CDF of γ_1 and γ_2 can be mathematically expressed in the form [10]

$$\tilde{F}_{\gamma_1,\gamma_2}(\gamma_1,\gamma_2) = \exp\left\{-\left[\left(\frac{\gamma_1}{a\,\overline{\gamma}_1}\right)^{\beta/(2\delta)} + \left(\frac{\gamma_2}{a\,\overline{\gamma}_2}\right)^{\beta/(2\delta)}\right]^{\delta}\right\} \quad (2)$$

where δ ($0 < \delta \leqslant 1$) is a parameter related to the correlation coefficient ρ ($0 \leqslant \rho < 1$) as

$$\rho = \frac{\Gamma^2(1+\delta/\beta) - a\,\Gamma^2(1+1/\beta)\,\Gamma(1+2\delta/\beta)}{\Gamma(1+2\delta/\beta)[1 - a\,\Gamma^2(1+1/\beta)]} \quad (3)$$

For $\delta \to 0$, $\rho \to 1$, while for $\delta = 1$, $\rho = 0$.

Using Equation (2), the CDF of SC output SNR per symbol

$$\gamma_{sc} = \max\{\gamma_1, \gamma_2\} \quad (4)$$

can be easily obtained as

$$F_{\gamma_{sc}}(\gamma) = \tilde{F}_{\gamma_1,\gamma_2}(\gamma,\gamma) + F_{\gamma_1}(\gamma) + F_{\gamma_2}(\gamma) - 1 \quad (5)$$

After taking the first derivative of this CDF and by performing some straightforward mathematical manipulations, the probability density function (PDF) of γ_{sc} can be compactly expressed as

$$f_{\gamma_{sc}}(\gamma) = \frac{\beta}{2}\,\gamma^{\beta/2-1}\sum_{i=1}^{3}\Xi_i \exp\left(-|\Xi_i|\,\gamma^{\beta/2}\right) \quad (6)$$

where for $\ell = 1$ and 2, Ξ_ℓ is defined as $\Xi_\ell = (a\,\overline{\gamma}_\ell)^{-\beta/2}$ while $\Xi_3 = -[(a\,\overline{\gamma}_1)^{-\beta/(2\delta)} + (a\,\overline{\gamma}_2)^{-\beta/(2\delta)}]^{\delta}$. For single-branch receivers we have to set $\Xi_1 = (a\,\overline{\gamma})^{-\beta/2}$ and $\Xi_2 = \Xi_3 = 0$, where $\overline{\gamma}$ is the average SNR per symbol measured at the input of the receiver.

3. OPTIMAL RATE ADAPTATION AND CONSTANT TRANSMIT POWER

In this section, we analyse the adaptive transmission scheme where ORA with constant transmit power is applied. This scheme entails variable-rate transmission relative to the channel, but is rather practical since the transmit power remains constant. Using the PDF expression given by Equation (6), the average and outage CC are obtained in closed form.

3.1. Average channel capacity

Considering a signal transmission of bandwidth B_w over the additive white Gaussian noise (AWGN) channel, the CC is given by [13, Equation (1)]

$$C_\mathrm{ora} = B_\mathrm{w} \log_2\left(1 + \gamma_\mathrm{awgn}\right) \tag{7}$$

where γ_awgn is the average symbols' energy to AWGN power spectral density ratio.

When the same signal is transmitted over the Weibull fading channel, the instantaneous CC, C_ora, can be considered as a random variable (RV). Using Equations (6) and (7), the PDF of C_ora can be derived following a standard method for RVs transformation as

$$f_{C_\mathrm{ora}}(c) = \frac{\ln(2)}{B_\mathrm{w}} 2^{c/B_\mathrm{w}} f_{\gamma_\mathrm{sc}}\left(2^{c/B_\mathrm{w}} - 1\right) \tag{8}$$

The average CC of SC can be obtained by averaging C_ora over the PDF of C_ora, i.e.

$$\bar{C}_\mathrm{ora} = \int_0^\infty c f_{C_\mathrm{ora}}(c)\,\mathrm{d}c \tag{9}$$

where by substituting Equation (8), interchanging the order of summations and integration, and after some mathematical transformations, some integrals of the form

$$I(\xi) = \int_0^\infty x^{\beta/2-1} \ln(1+x) \exp\left(-\xi x^{\beta/2}\right)\mathrm{d}x \tag{10}$$

appear, with $\xi > 0$. To the best of the author's knowledge, this type of integral is not included in classical reference books, such as in Reference [21]. The above type of integrals is analytically solved in the Appendix. Hence, $\bar{C}_\mathrm{ora}$ can be expressed in closed form as

$$\bar{C}_\mathrm{ora} = \frac{B_\mathrm{w}\,\beta\, l^{-1}\sqrt{k}}{2\ln(2)\left(\sqrt{2\pi}\right)^{2l+k-3}} \times \sum_{i=1}^{3} \Xi_i\, G_{2l,k+2l}^{k+2l,\,l}\left[\left(\frac{|\Xi_i|}{k}\right)^k \middle| \begin{matrix} \Delta(l,-\beta/2), \Delta(l, 1-\beta/2) \\ \Delta(k,0), \Delta(l,-\beta/2), \Delta(l,-\beta/2) \end{matrix}\right] \tag{11}$$

where $G[\cdot]$ is the Meijer's G-function* [21, Equation (9.301)] and $\Delta(\cdot,\cdot)$ is defined as $\Delta(\mu,h) = h/\mu, (h+1)/\mu, \ldots, (h+\mu-1)/\mu$, with μ being positive integer and h real constant. The k and l are positive integers such that

$$\frac{l}{k} = \frac{\beta}{2} \tag{12}$$

holds. Depending upon the value of β, a set with minimum values of l and k can be properly chosen in order (Equation 12) to be valid (e.g. for $\beta = 2.6$ we have to choose $k = 10$ and $l = 13$). Note that for single-branch receivers, Equation (11) reduces to an already known expression [12, Equation (17)].

3.2. Outage channel capacity

From Equations (5) and (7), the CDF of C_ora at the output of the SC can be obtained in closed form as

$$F_{C_\mathrm{ora}}(c) = F_{\gamma_\mathrm{sc}}\left(2^{c/B_\mathrm{w}} - 1\right) \tag{13}$$

The CDF at the output of a single-branch receiver can be obtained from Equation (13) as $F_{C_\mathrm{ora}}(c) = F_\gamma\left(2^{c/B_\mathrm{w}} - 1\right)$, where γ is the instantaneous SNR per symbol measured at the input of the receiver with $F_\gamma(\cdot)$ determined as in Equation (1).

The outage CC, P_out, which is considered as an important performance metric for cellular mobile networks, is defined as the probability that the instantaneous CC falls below a certain outage threshold, c_th. In case of SC receivers, this probability is the CDF of C_ora as determined by Equation (13) and thus, P_out can be obtained in closed form as

$$P_\mathrm{out}(c_\mathrm{th}) = F_{C_\mathrm{ora}}(c_\mathrm{th}) \tag{14}$$

3.3. Numerical results

With the aid of Equation (11), in Figure 1, $\bar{C}_\mathrm{ora}/B_w$ is plotted as a function of $\bar{\gamma}_1$ for both identically ($\bar{\gamma}_1 = \bar{\gamma}_2 = \bar{\gamma}_0$) and non-identically ($\bar{\gamma}_2 = 2\,\bar{\gamma}_1$) distributed average input SNRs, $\beta = 2.5$, and $\rho = 0$, 0.5, and 1. As expected, $\bar{C}_\mathrm{ora}/B_\mathrm{w}$ improves with an increase of $\bar{\gamma}_1$ and/or a decrease of ρ. Furthermore, $\bar{C}_\mathrm{ora}/B_\mathrm{w}$ decreases as the SNR unbalance increases. Note that for $\rho = 1$, the solid curve is common for both identical and non-identical cases.

Using Equation (14), in Figure 2, P_out is plotted as a function of $c_\mathrm{th}/B_\mathrm{w}$ (in dB values) for $\beta = 2.5$, identical fading statistics, and several values of ρ. As expected, the obtained results show, that for a given value of c_th, an increase of ρ leads to a respective increase of P_out, resulting in SC performance degradation. Note that the curve for $\rho = 1$ represents results for single-branch receivers.

*The Meijer's G-function is included as a built-in function in most of the well-known mathematical software packages.

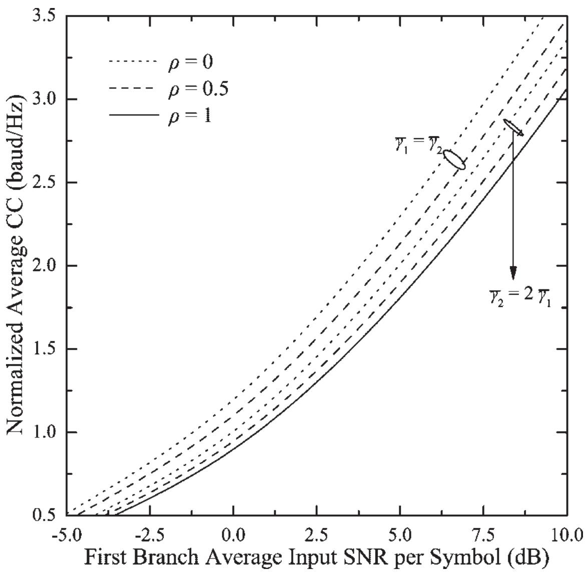

Figure 1. Normalised to bandwidth average CC against first branch average input SNR per symbol with equal and unequal Weibull fading statistics ($\beta = 2.5$) under constant transmit power with optimal rate adaptation.

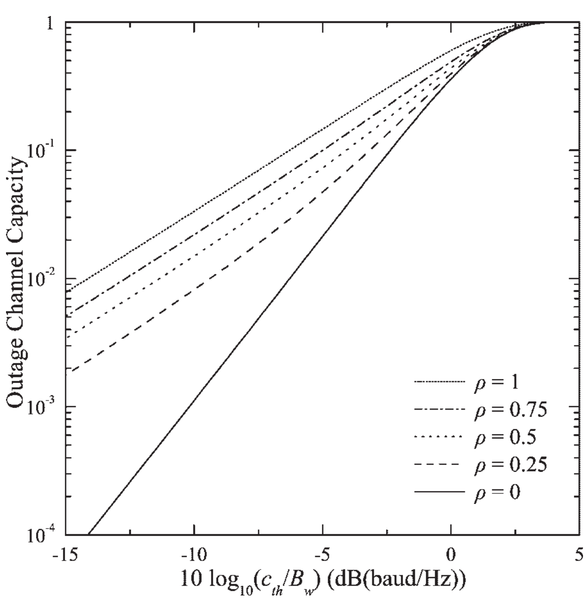

Figure 2. Outage capacity against outage threshold for identical Weibull fading statistics ($\beta = 2.5$) under constant transmit power with optimal rate adaptation.

4. OPTIMAL SIMULTANEOUS POWER AND RATE ADAPTATION

The OPRA scheme achieves the ergodic capacity of the system, which is the maximum achievable average rate under adaptive transmission. This average rate is achieved by varying the rate and power relative to the channel conditions and thus, it may not be appropriate for applications requiring a fixed rate. Given an average transmit power constraint, the channel capacity at the output of an SC receiver with OPRA is given by [16, Equation (7)]

$$\bar{C}_{\text{opra}} = B_{\text{w}} \int_{\gamma_0}^{\infty} \log_2\left(\frac{\gamma}{\gamma_0}\right) f_{\gamma_{\text{sc}}}(\gamma)\, \mathrm{d}\gamma \tag{15}$$

where γ_0 is the optimal cutoff SNR per symbol level below which data transmission is suspended.

4.1. *Optimal cutoff SNR*

The optimal cutoff SNR must satisfy the following condition

$$\int_{\gamma_0}^{\infty} \left(\frac{1}{\gamma_0} - \frac{1}{\gamma}\right) f_{\gamma_{\text{sc}}}(\gamma)\, \mathrm{d}\gamma = 1 \tag{16}$$

By substituting Equation (6) in the above equation, γ_0 must satisfy

$$\sum_{i=1}^{3} \operatorname{sign}(\Xi_i) \left[\frac{1}{\gamma_0} \exp\left(-|\Xi_i|\, \gamma_0^{\beta/2}\right) - |\Xi_i|^{2/\beta}\, \Gamma\left(1 - \frac{2}{\beta}, |\Xi_i|\, \gamma_0^{\beta/2}\right)\right] = 1 \tag{17}$$

with $\Gamma(\cdot,\cdot)$ being the upper incomplete Gamma function [21, Equation (8.350/2)] and $\operatorname{sign}(\cdot)$ being the sign function defined as $\operatorname{sign}(x) = 1$ if $x > 0$, $\operatorname{sign}(x) = 0$ if $x = 0$, and $\operatorname{sign}(x) = -1$ if $x < 0$. Since γ_0 in Equation (17) cannot be analytically solved in closed form, any of the well-known mathematical software packages may be used for its numerical evaluation. For single-branch receivers, γ_0 must satisfy $\exp\{-[\gamma_0/(a\,\bar{\gamma})]^{\beta/2}\}/\gamma_0 - \Gamma\{1 - 2/\beta, [\gamma_0/(a\,\bar{\gamma})]^{\beta/2}\}/(a\,\bar{\gamma}) = 1$ which for $\beta = 2$ reduces to [16, Equation (12)].

4.2. *Average channel capacity*

By substituting Equation (6) in Equation (15), interchanging the order of summations and integration, using [21, Equation (4.331/2)], and after some mathematical transformations, $\bar{C}_{\text{opra}}$ can be expressed in closed form as

$$\bar{C}_{\text{opra}} = -\frac{2\, B_{\text{w}}}{\beta\, \ln(2)} \sum_{i=1}^{3} \operatorname{sign}(\Xi_i)\, E_i\left(-|\Xi_i|\, \gamma_0^{\beta/2}\right) \tag{18}$$

where $E_i(\cdot)$ is the exponential integral function [21, Equation (8.211/1)]. For single-branch receivers, by using Equation (18), $\bar{C}_{\text{opra}}$ can be also derived as

$$\bar{C}_{\mathrm{opra}} = -\frac{2\,B_{\mathrm{w}}}{\beta\,\ln(2)}\,E_i\left[-\left(\frac{\gamma_0}{a\,\bar{\gamma}}\right)^{-\beta/2}\right] \tag{19}$$

Note that for $\beta = 2$, Equation (19) reduces to [16, Equation (16)].

To achieve the capacity given by Equations (18) or (19), the channel fade level must be tracked at both the receiver and transmitter, and the transmitter has to adapt its power and rate accordingly, allocating high power levels and rates for good channel conditions (γ_{sc} large), and lower power levels and rates for unfavourable channel conditions (γ_{sc} small). Since no data is sent when $\gamma_{\mathrm{sc}} < \gamma_0$, the optimal policy suffers a probability of outage equal to the probability of no transmission, given by $P_{\mathrm{out}}(\gamma_0) = \int_0^{\gamma_0} f_{\gamma_{\mathrm{sc}}}(\gamma)\,\mathrm{d}\gamma$. By the definition of the CDF of γ_{sc} and using Equation (5), P_{out} can be obtained in closed form as

$$P_{\mathrm{out}}(\gamma_0) = F_{\gamma_{\mathrm{sc}}}(\gamma_0) \tag{20}$$

For single-branch receivers, Equation (20) simplifies to $P_{\mathrm{out}}(\gamma_0) = F_{\gamma}(\gamma_0)$.

4.3. Numerical results

Based on Equation (18), in Figure 3, $\bar{C}_{\mathrm{opra}}/B_{\mathrm{w}}$ is plotted as a function of ρ for non-identically ($\bar{\gamma}_1 = 2\,\bar{\gamma}_2$) distributed average input SNRs, $\beta = 2$, 2.5 and 3.75, and $\bar{\gamma}_1 = 5$, 7.5 and 10 dB. Similar conclusions as in Figure 1 can be obtained for the effect of β, $\bar{\gamma}_1$ and ρ on $\bar{C}_{\mathrm{opra}}/B_{\mathrm{w}}$. In the same figure, results are also included for single-branch receivers for $\rho = 1$ which has been verified using Equation (19).

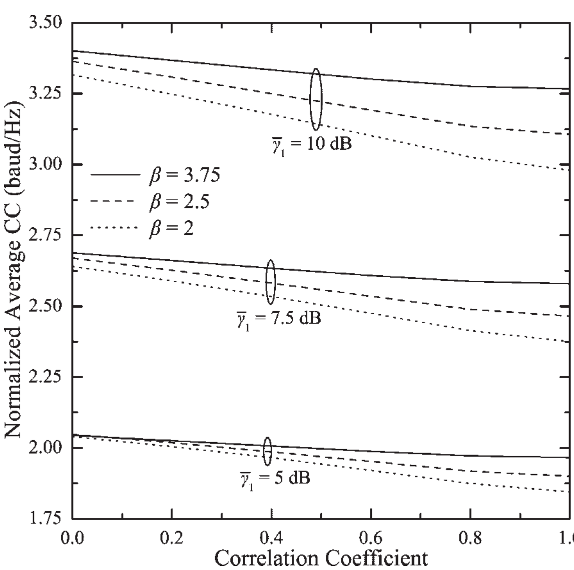

Figure 3. Normalized to bandwidth average CC against first branch average input SNR per symbol ($\bar{\gamma}_1 = 2\,\bar{\gamma}_2$).

5. CHANNEL INVERSION WITH FIXED RATE AND ITS TRUNCATED VERSION

In case where the transmitter adapts its power to maintain a constant SNR at the receiver, i.e. inverts the channel fading, the channel capacity has been investigated in several works [15]. This technique uses fixed-rate modulation and a fixed code design, since the channel after channel inversion appears as a time-invariant AWGN channel.

5.1. Channel inversion with fixed rate

Channel inversion with fixed rate is the least complex technique to implement, assuming good channel estimates are available at the transmitter and receiver. The channel capacity with this technique is given by [16, Equation (46)]

$$\bar{C}_{\mathrm{cifr}} = B_{\mathrm{w}}\log_2\left[1 + \frac{1}{\int_0^{\infty}\gamma^{-1} f_{\gamma_{\mathrm{sc}}}(\gamma)\,\mathrm{d}\gamma}\right] \tag{21}$$

By substituting Equation (6) in the above equation and after some mathematical transformations, $\bar{C}_{\mathrm{cifr}}$ can be expressed in closed form as

$$\bar{C}_{\mathrm{cifr}} = B_{\mathrm{w}}\log_2\left[1 + \frac{1}{\sum_{i=1}^{3}\mathrm{sign}(\Xi_i)\,|\Xi_i|^{2/\beta}\,\Gamma(1-2/\beta)}\right] \tag{22}$$

Moreover, for single-branch receivers, Equation (22) simplifies to

$$\bar{C}_{\mathrm{cifr}} = B_{\mathrm{w}}\log_2\left[1 + \frac{a\,\bar{\gamma}}{\Gamma(1-2/\beta)}\right] \tag{23}$$

Interestingly enough, Equation (23) includes the case of $\beta \to 2^+$ where $\bar{C}_{\mathrm{cifr}} \to 0^+$ [16, Section 5.1].

5.2. Truncated channel inversion with fixed rate (TCIFR)

Channel inversion with fixed rate suffers a large capacity penalty relative to the other techniques, since a large amount of the transmitted power is required to compensate for the deep channel fades. A better approach is to use a modified inversion policy which inverts the channel fading only above a fixed cutoff fade depth γ_0, which we shall refer to as TCIFR. The capacity with this truncated channel inversion and fixed rate policy is given by [16, Equation (47)]

$$\bar{C}_{\rm tcifr} = B_{\rm w}\,[1 - P_{\rm out}(\gamma_0)]\,\log_2\left[1 + \frac{1}{\int_{\gamma_0}^{\infty}\gamma^{-1} f_{\gamma_{\rm sc}}(\gamma)\,{\rm d}\gamma}\right] \quad (24)$$

where $P_{\rm out}$ is given by Equation (20). By substituting Equation (6) in the above equation and after some mathematical transformations, $\bar{C}_{\rm tcifr}$ can be expressed in closed form as

$$\bar{C}_{\rm tcifr} = B_{\rm w}\,[1 - P_{\rm out}(\gamma_0)] \times \log_2\left[1 + \frac{1}{\sum_{i=1}^{3}\left(\operatorname{sign}(\Xi_i)/|\Xi_i|^{-2/\beta}\right)\Gamma\left(1 - 2/\beta, |\Xi_i|\,\gamma_0^{\beta/2}\right)}\right] \quad (25)$$

Moreover, for single-branch receivers, Equation (25) simplifies to

$$\bar{C}_{\rm tcifr} = B_{\rm w}\,[1 - P_{\rm out}(\gamma_0)] \times \log_2\left\{1 + \frac{a\,\bar{\gamma}}{\Gamma\left[1 - 2/\beta, (\gamma_0/(a\,\bar{\gamma}))^{\beta/2}\right]}\right\} \quad (26)$$

Note that for $\beta = 2$, Equation (26) reduces to [16, Equation (48)].

5.3. Numerical results

By using Equation (25), in Figure 4, $\bar{C}_{\rm tcifr}/B_{\rm w}$ is plotted as a function of γ_0 for non-identically distributed average input SNRs ($\bar{\gamma}_2 = 2\,\bar{\gamma}_1$), $\beta = 2$ and 2.5, and $\rho = 0.25$ and 0.5. It can be easily recognised that $\bar{C}_{\rm tcifr}/B_{\rm w}$ is maximised for a certain value of γ_0. Furthermore, $\bar{C}_{\rm tcifr}/B_{\rm w}$ increases as ρ decreases and/or β increases.

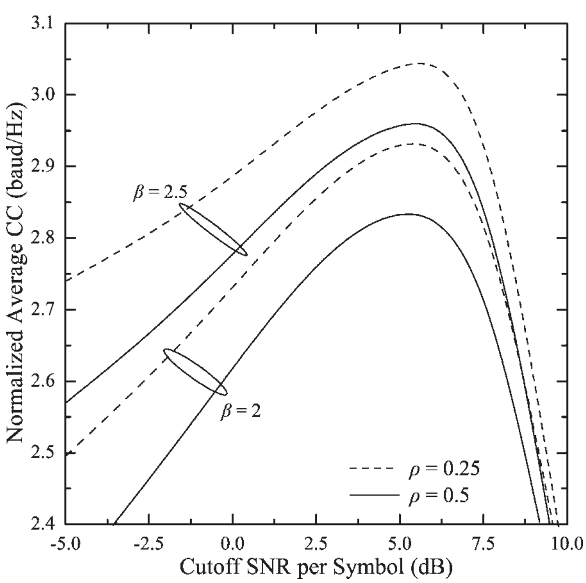

Figure 4. Normalised to bandwidth average CC under truncated channel inversion policy against cut-off SNR with unequal Weibull fading statistics ($\bar{\gamma}_2 = 2\,\bar{\gamma}_1$).

6. CONCLUSIONS

Novel closed-form expressions for the Shannon CC of dual-branch SC receivers operating in correlative Weibull fading were obtained under three adaptive policies: constant power with ORA, OPRA and CIFR. The derived formulae are quite general, including identical and non-identical fading statistics and arbitrary values for the fading parameter and the correlation coefficient. Moreover, the performance analysis of single-branch receivers was also studied as a special case. Selected numerical examples were presented, illustrating the performance degradation of SC receivers when operating in correlated fading environments.

A. APPENDIX: DERIVATION OF EQUATION (10)

The integral in Equation (10) can be evaluated in closed form using [22]. By expressing the logarithmic and exponential functions in terms of Meijer's G-functions [22, Equation (11)], i.e.

$$\ln(1 + x) = G_{2,2}^{1,2}\left[x\,\middle|\,\begin{matrix}1,1\\1,0\end{matrix}\right] \quad (A1)$$

and

$$\exp\left(-\xi x^{\beta/2}\right) = G_{0,1}^{1,0}\left[\xi x^{\beta/2}\,\middle|\,\begin{matrix}-\\0\end{matrix}\right] \quad (A2)$$

respectively, Equation (10) can be rewritten as

$$I(\xi) = \int_0^{\infty} x^{\beta/2-1}\,G_{2,2}^{1,2}\left[x\,\middle|\,\begin{matrix}1,1\\1,0\end{matrix}\right] G_{0,1}^{1,0}\left[\xi x^{\beta/2}\,\middle|\,\begin{matrix}-\\0\end{matrix}\right]{\rm d}x \quad (A3)$$

By using [22, Equation (21)], the above integral can be expressed in closed form as

$$I(\xi) = \frac{\sqrt{k}\,l^{-1}}{(\sqrt{2\pi})^{k+2l-3}} \times G_{2l,k+2l}^{k+2l,l}\left[\left(\frac{\xi}{k}\right)^k\,\middle|\,\begin{matrix}\Delta(l,-\beta/2),\Delta(l,1-\beta/2)\\\Delta(k,0),\Delta(l,-\beta/2),\Delta(l,-\beta/2)\end{matrix}\right] \quad (A4)$$

where k and l are chosen so that Equation (12) holds.

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AUTHOR'S BIOGRAPHY

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