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On the Use of Padé Approximation for Performance Evaluation of Maximal Ratio Combining Diversity over Weibull Fading Channels

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We use the Padé approximation (PA) technique to obtain closed-form approximate expressions for the moment-generating function (MGF) of the Weibull random variable. Unlike previously obtained closed-form exact expressions for the MGF, which are relatively complicated as being given in terms of the Meijer *G*-function, PA can be used to obtain simple rational expressions for the MGF, which can be easily used in further computations. We illustrate the accuracy of the PA technique by comparing its results to either the existing exact MGF or to that obtained via Monte Carlo simulations. Using the approximate expressions, we analyze the performance of digital modulation schemes over the single channel and the multichannels employing maximal ratio combining (MRC) under the Weibull fading assumption. Our results show excellent agreement with previously published results as well as with simulations.

1. INTRODUCTION

The use of the Weibull distribution as a statistical model that better describes the actual short term fading phenomenon over outdoor as well as indoor wireless channels has been proposed decades ago [1–3]. More recently, the appropriateness of the Weibull distribution has been further confirmed by experimental data collected in the cellular band by two independent groups in [4, 5]. Since then, the Weibull distribution has attracted much attention among the radio community. In particular, the performance of receive diversity systems over Weibull fading channels has been extensively studied in [6–13]. Also, a closed-form expression for the moment-generating function (MGF) of the Weibull random variable (RV) was obtained in [7] when the Weibull fading parameter (which will be defined in the sequel), usually denoted by m, assumes only integer values. Another expression for the MGF for arbitrary values of m was also derived in [8]. Both expressions were given in terms of the Meijer *G*-function and were used for evaluating the performance of digital modulation schemes over the single-channel reception and multichannel diversity reception assuming Weibull fading. Also, in [14], the second-order statistics and the capacity of the Weibull channel have been derived. Finally, we have analyzed the performance of cellular networks with composite Weibull-lognormal faded links as well as the performance of MRC diversity systems in Weibull fading in presence of cochannel interference (CCI) in terms of outage probability in [15, 16], respectively.

The closed-form expressions provided in [7, 8], despite being the first of their kind in the open literature and despite having a very elegant form, suffer from a major drawback. The expressions involve the Meijer *G*-function, which, although easy to evaluate by itself using the modern mathematical packages such as Mathematica and Maple, these packages fail to handle integrals involving this function and lead to numerical instabilities and erroneous results when m increases. This renders the expressions impractical from the ease of computation point of view. Hence, it is highly desirable to find alternative closed-form expressions for the MGF of the Weibull random variable (RV) that are simple to evaluate and in the same time can be used for arbitrary values of m.

Padé approximation (PA) is a well-known method that is used to approximate infinite power series that are either not guaranteed to converge, converge very slowly or for which a limited number of coefficients is known [17, 18]. This technique was recently used for outage probability calculation in diversity systems in Nakagami fading in [19]. The approximation is given in terms of a simple rational function of arbitrary numerator and denominator orders. In this paper, we illustrate how this technique can be used to obtain simple-to-evaluate approximate rational expressions for the MGF of the Weibull RV based on the knowledge of its moments. We then use these expressions to evaluate the performance of linear digital modulations over flat Weibull fading channels in the case of both single-channel reception and multichannel reception employing maximal ratio combining (MRC).

The rest of the paper is organized as follows. In Section 2, we give a brief overview of the Padé approximation technique. In Section 3, we apply this technique to the problem at hand. The performance of digital modulation systems over the Weibull fading channel is then revisited in Section 4. Examples and numerical results as well as comparisons with previously published results in the literature and Monte Carlo simulations are provided in Section 5 before the paper is finally concluded in Section 6.

2. PADÉ APPROXIMATION OVERVIEW

Let $g(z)$ be an unknown function given in terms of a power series in the variable $z \in \mathbb{C}$, the set of complex numbers, namely,

$$g(z) = \sum_{n=0}^{\infty} c_n z^n, \quad c_n \in \mathbb{R}, \tag{1}$$

where $\mathbb{R}$ is the set of real numbers. There are several reasons to look for a rational approximation for the series in (1). The series might be divergent or converging too slowly to be of any practical use. Also, it is possible that a compact rational form is needed in order to be used in later computations. Not to mention the fact that it might be possible that only few coefficients of $\{c_n\}$ are known [17]. The PA method is capable of dealing with all the problems mentioned above. In particular, it can capture the limiting behavior of a power series in a rational form.

The *one-point PA* of order $[N_p/N_q]$, $P^{[N_p/N_q]}(z)$, is defined from the series $g(z)$ as a rational function by [17, 18]

$$P^{[N_p/N_q]}(z) = \frac{\sum_{n=0}^{N_p} a_n z^n}{\sum_{n=0}^{N_q} b_n z^n}, \tag{2}$$

where the coefficients $\{a_n\}$ and $\{b_n\}$ are defined such that

$$\frac{\sum_{n=0}^{N_p} a_n z^n}{\sum_{n=0}^{N_q} b_n z^n} = \sum_{n=0}^{N_p+N_q} c_n z^n + \mathcal{O}\left(z^{N_p+N_q+1}\right), \tag{3}$$

with $\mathcal{O}(z^{N_p+N_q+1})$ representing the terms of order higher than $N_p + N_q$. It is straightforward to see that the coefficients $\{a_n\}$ and $\{b_n\}$ can be easily obtained by matching the coefficients of like powers on both sides of (3). Specifically, taking $b_0 = 1$, without loss of generality, one can find that

$$\sum_{n=0}^{N_q} b_n c_{N_p-n+j} = 0, \quad 1 \le j \le N_q, \tag{4}$$

or equivalently,

$$\sum_{n=1}^{N_q} b_n c_{N_p-n+j} = -c_{N_p+j}, \quad 1 \le j \le N_q. \tag{5}$$

The above equations form a system of N_q linear equations for the N_q unknown denominator coefficients. This system can be written in matrix form as

$$\mathbf{C}\mathbf{b} = -\mathbf{c}, \tag{6}$$

where

$$\begin{gathered}\mathbf{b} = \left(b_{N_q} \cdots b_k \cdots b_1\right)^T, \\ \mathbf{c} = \left(c_{N_p+1} \cdots c_{N_p+k+1} \cdots c_{N_p+N_q}\right)^T, \\ \mathbf{C} = \begin{pmatrix} c_{N_p-N_q+1} & c_{N_p-N_q+2} & \cdots & c_{N_p} \\ \vdots & \vdots & \vdots & \vdots \\ c_{N_p-N_q+k} & c_{N_p-N_q+k+1} & \cdots & c_{N_p+k-1} \\ \vdots & \vdots & \vdots & \vdots \\ c_{N_p} & c_{N_p+1} & \cdots & c_{N_p+N_q-1} \end{pmatrix},\end{gathered} \tag{7}$$

with $(\cdot)^T$ representing the transpose operation. After solving the matrix equation in (6), the set $\{a_n\}$ can be obtained by

$$a_j = c_j + \sum_{i=1}^{\min(N_q,j)} b_j c_{j-i}, \quad 0 \le j \le N_p. \tag{8}$$

An important remark is now in order. It might seem that the choice of the values of N_q and N_p is completely arbitrary. This, in fact, is not accurate. An insightful look at (6) reveals that in order to be able to *uniquely* solve such system of equations, it is necessary to have $|\mathbf{C}| \neq 0$, where $|\cdot|$ is the determinant. In [17], using what we refer to as the *rank-order plots*, it is shown that there exists a value of N_q above which the matrix $\mathbf{C}$ becomes rank deficient. This clearly represents an upper bound on the permissible values of N_q. Also, as mentioned in [20], N_p is chosen to be equal to $N_q - 1$ as this guarantees the convergence of the PA. In this paper, we take N_q such that it guarantees the uniqueness of the solution of (6) and $N_p = N_q - 1$.

3. APPLICATION TO THE WEIBULL MGF

The MGF of an RV $X > 0$ is defined as

$$\mathcal{M}_X(s) = \mathbb{E}\left(e^{-sX}\right) = \int_0^{\infty} e^{-sx} f_X(x)dx, \tag{9}$$

where $\mathbb{E}(\cdot)$ is the expectation operator and $f_X(x)$ is the probability density function (PDF) of X. The PDF of the Weibull

RV is given by

$$f_X(x) = \frac{mx^{m-1}}{\gamma} \exp\left(-\frac{x^m}{\gamma}\right), \quad x \geq 0, \tag{10}$$

where $m > 0$ is usually referred to as the Weibull distribution fading parameter and $\gamma > 0$ is a parameter related to the moments and the fading parameter of the distribution. As mentioned earlier, a closed-form expression available for $\mathcal{M}_X(s, m, \gamma)$, the MGF of the Weibull RV with parameters (m, γ), is provided in [8] and is restated here for convenience:

$$\mathcal{M}_X(s, m, \gamma) = \frac{m}{\gamma} \frac{(k/p)^{1/2}(p/s)^m}{(2\pi)^{(p+k)/2}} \times G^{k,p}_{p,k}\left(\frac{1}{\gamma^k s^p}\frac{p^p}{k^k} \,\middle|\, \begin{matrix}\Delta(p, 1-m)\\ \Delta(k, 0)\end{matrix}\right), \tag{11}$$

where p and k are the minimum integers chosen such that $m = p/k$, $\Delta(n, \zeta) = \zeta/n, (\zeta+1)/n, \ldots, (\zeta+n-1)/n$ and $G^{m,n}_{p,q}(\cdot)$ is the Meijer G-function [21, Equation (9.301)]. Based on the discussion presented in Section 1, it is required to find an alternative closed-form expression for the MGF which is simpler to use in computations and in the same time valid for any value of m. Towards that end, we use the PA technique as follows. It is interesting to note that the moments of the Weibull RV are known in closed-form and are given by [10]

$$\mathbb{E}(X^n) = \gamma^{n/m}\Gamma\left(1 + \frac{n}{m}\right), \tag{12}$$

where $\Gamma(\cdot)$ is the Gamma function. Using the Taylor series expansion of e^{-sX}, the MGF can be expressed in terms of a power series as

$$\mathcal{M}_X(s, m, \gamma) = \sum_{n=0}^{\infty} \frac{(-1)^n}{n!}\mathbb{E}(X^n)s^n = \sum_{n=0}^{\infty} c_n(m, \gamma)s^n, \tag{13}$$

where $c_n(m, \gamma) = ((-1)^n/n!)\gamma^{n/m}\Gamma(1 + n/m)$. The infinite series in (13) is not guaranteed to converge for all values of s. Furthermore, it is not possible to truncate the series since it is not clear what the truncation criterion is and again, convergence is not guaranteed. However, comparing (13) to (1), it is clear that a rational approximate expression for $\mathcal{M}_X(s, m, \gamma)$ can be obtained using the methodology outlined in Section 2. In the following, we will denote the approximate expression for the MGF of a Weibull RV with parameters (m, γ) having a denominator with order N_q by $P^{[N_q-1/N_q]}(s, m, \gamma)$.

4. PERFORMANCE OF DIGITAL MODULATIONS OVER THE WEIBULL FADING CHANNEL

In [7], based on the obtained closed-form expression for the Weibull MGF, and using the MGF approach [22], a comprehensive study of the performance of digital modulations over the Weibull slow flat-fading channel has been conducted. It is well known that, in general, the performance of any communication system, in terms of bit error rate (BER), symbol error rate (SER), or signal outage, will depend on the statistics of the signal-to-noise ratio (SNR). Assuming that both the average signal and noise powers are unity, then the SNR will be equal to the squared channel amplitude, X^2. One of the interesting properties of the Weibull RV with parameters (m, γ) is that raising it to the kth power results in another Weibull RV with parameters $(m/k, \gamma)$. Hence, for a fading channel having a Weibull distributed amplitude with parameters (m, γ), the SNR is clearly Weibull distributed with parameters $(m/2, \gamma)$. Due to the inapplicability of the MGF closed-form expression in [7] to the noninteger values of m, only results pertaining to integer values of $m/2$ (or, equivalently, to even integer values of m) were presented therein. Even if the expression in (11) is to be used, which is valid for arbitrary values of m, no software package will be able to handle the integrations involving the resulting high-order Meijer G-function [8]. Now, since the approximate expression obtained via the PA technique is very simple and does not have any restriction on the values of m, it is now possible to very easily obtain performance results for odd integer as well as noninteger values of m.

For convenience, we note here some of the key expressions presented in [7] that are relevant to our discussion. For an MRC system with L identical branches, the outage probability, $P_{\text{out,MRC}}(\zeta) \triangleq P(\text{SNR}_{\text{MRC}} < \zeta)$, is given by

$$P_{\text{out,MRC}}(\zeta) = \frac{1}{2\pi j}\int_{\epsilon-j\infty}^{\epsilon+j\infty} \frac{\left[\mathcal{M}_X(s, m/2, \gamma)\right]^L}{s} e^{s\zeta} ds, \tag{14}$$

where $\mathcal{M}_X(s, m/2, \gamma)$ is the MGF of the SNR per branch, ϵ is a properly chosen constant in the region of convergence in the complex s-plane, and SNR_{MRC} is the total SNR, which is equal to the sum of the branches SNRs. For the same system employing M-ary phase shift keying (M-PSK), the average SER can be found from

$$\text{SER}_{M-\text{PSK}} = \frac{1}{\pi}\int_0^{(M-1)\pi/M} \left[\mathcal{M}_X\left(\frac{g_{\text{PSK}}}{\sin^2\phi}, m/2, \gamma\right)\right]^L d\phi, \tag{15}$$

where $g_{\text{PSK}} = \sin^2(\pi/M)$. Finally, for M-ary quadrature amplitude modulation (M-QAM), the average SER is given by

$$\text{SER}_{M-\text{QAM}} = \frac{4}{\pi}\left(1 - \frac{1}{\sqrt{M}}\right) \times \left\{\int_0^{\pi/2}\left[\mathcal{M}_X\left(\frac{g_{\text{QAM}}}{\sin^2\phi}, m/2, \gamma\right)\right]^L d\phi - \int_0^{\pi/4}\left[\mathcal{M}_X\left(\frac{g_{\text{QAM}}}{\sin^2\phi}, m/2, \gamma\right)\right]^L d\phi\right\}, \tag{16}$$

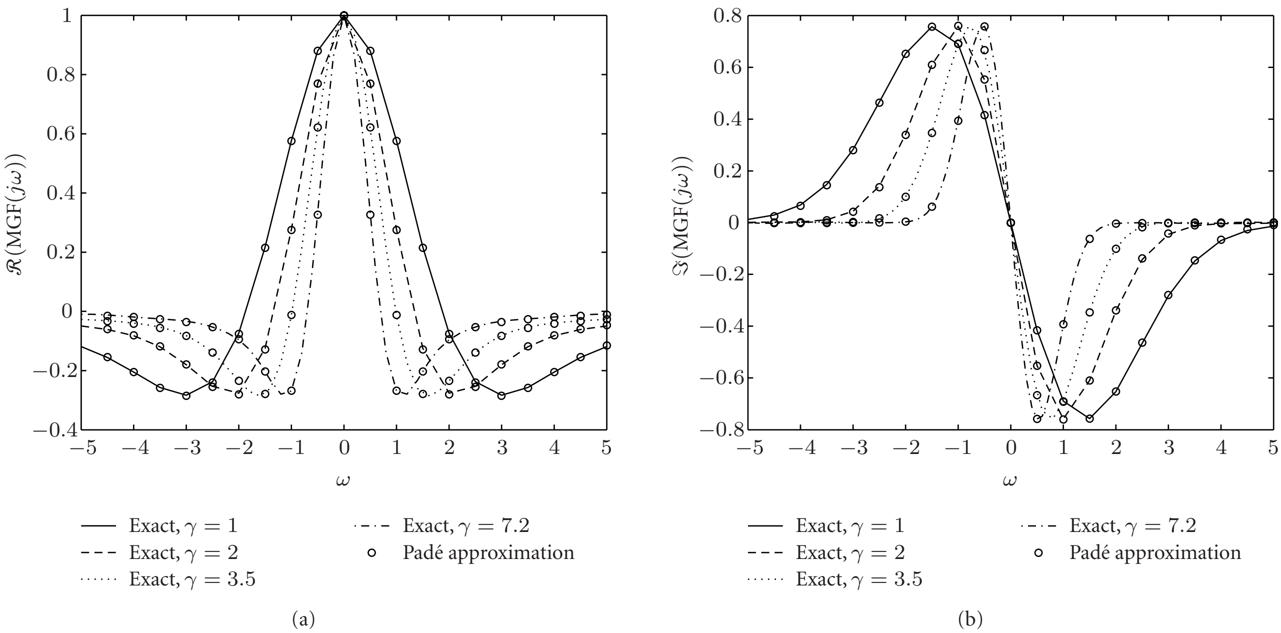


Figure 1: Padé approximation $P^{[4/5]}(j\omega, m, \gamma)$ and exact MGF using (11) for $m = 2$ and different values of γ: (a) real part and (b) imaginary part.

where $g_{\text{QAM}} = 3/2(M-1)$. Clearly, using the rational approximation for the MGF provided by the PA technique, all the integrals in (14) through (16) can be easily evaluated numerically and the result is guaranteed to be very stable. In fact some of the integrals, like the one in (14) can be found in closed form as it is equivalent to the problem of finding the inverse Laplace transform of a rational function, which can be easily solved using the partial fractions expansion.

5. EXAMPLES AND NUMERICAL RESULTS

5.1. Weibull MGF examples

In this section, we first illustrate through some examples the efficiency and accuracy of the PA technique when approximating the MGF of the Weibull RV.

Consider the interesting case of $m = 1$. In this case, it is easy to check that $\mathbf{C}$ is rank deficient except for $N_q = 1$. Hence, we choose $N_q = 1$ and $N_p = 0$. The only unknown, b_1, can now be easily found from $b_1 = -c_1(1,\gamma)/c_0(1,\gamma) = \gamma$. Also, $a_0 = c_0(1,\gamma) = 1$. The approximate MGF in this case is thus given by

$$P^{[0/1]}(s, 1, \gamma) = \frac{1}{1+\gamma s}. \quad (17)$$

Interestingly, in the special case of $m = 1$, the Weibull distribution reduces to the exponential distribution with parameter $1/\gamma$, which has an MGF, $\mathcal{M}_X(s, 1, \gamma) = 1/(1+\gamma s)$, which is exactly the same expression given in (17). Hence, the PA technique leads to an exact expression for the special case of $m = 1$.

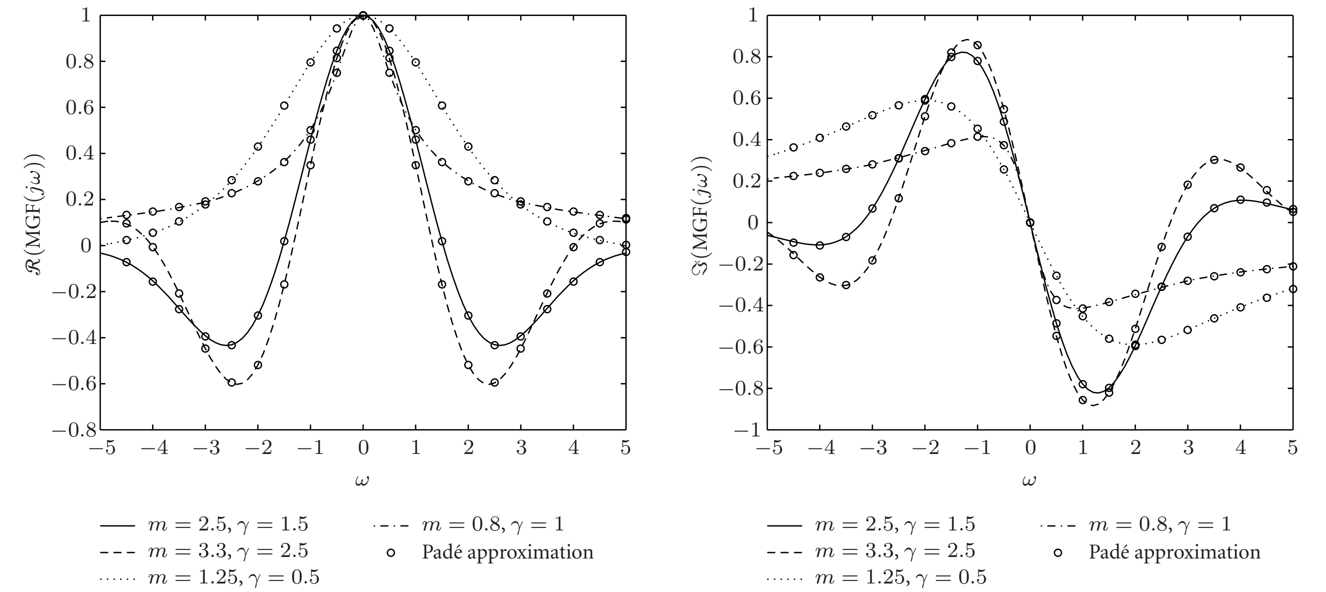
We now present some results for different combinations of m and γ. We use the PA with $N_q = 4$, that is, $P^{[4/5]}(s, m, \gamma)$ as an approximation for the MGF. For example, the PA for the MGF with $m = 2$ and $\gamma = 3.5$ is found to be

$$P^{[4/5]}(s, 2, 3.5) = \frac{1+0.328s+0.117s^2+7.119\times10^{-3}s^3+2.608\times10^{-4}s^4}{1+1.1986s+1.659s^2+0.734s^3+0.173s^4+0.018s^5}. \quad (18)$$

Figure 1 shows the real and imaginary parts of both the PA and the exact MGF using (11) versus ω, where $s = j\omega$, $j = \sqrt{-1}$, for $m = 2$ and different values of γ. Clearly, there is a perfect agreement between both expressions. It is now of interest to inspect the accuracy of the PA for *noninteger* values of m. For the sake of comparison, we revert to obtaining the MGF via Monte Carlo simulations this time. In Figure 2, we again plot the real and imaginary parts of the PA along with those of the MGF from simulations. From the plots, it is evident that the PA can be used to give a very accurate estimate of the MGF for arbitrary values of m and γ. Note that if the accuracy is not satisfactory for some cases, it is always possible to choose a higher value of N_q to enhance the accuracy as long as the matrix $\mathbf{C}$ is full rank.

5.2. Communication over the Weibull fading channel

Figure 3 shows the approximate outage probability curves for a dual-branch MRC system ($L = 2$) versus the average SNR per branch, $\mathbb{E}(X^2)$. For these curves, either $P^{[4/5]}(s, m, \gamma)$ or, if $|\mathbf{C}|$ is found to be 0, $P^{[3/4]}(s, m, \gamma)$ is used. For the even integer values of m, the outage probability obtained using the



(a) (b)

Figure 2: Padé approximation $P^{[4/5]}(j\omega, m, \gamma)$ and MGF obtained via Monte Carlo simulations for different combinations of *noninteger* m and γ: (a) real part and (b) imaginary part.

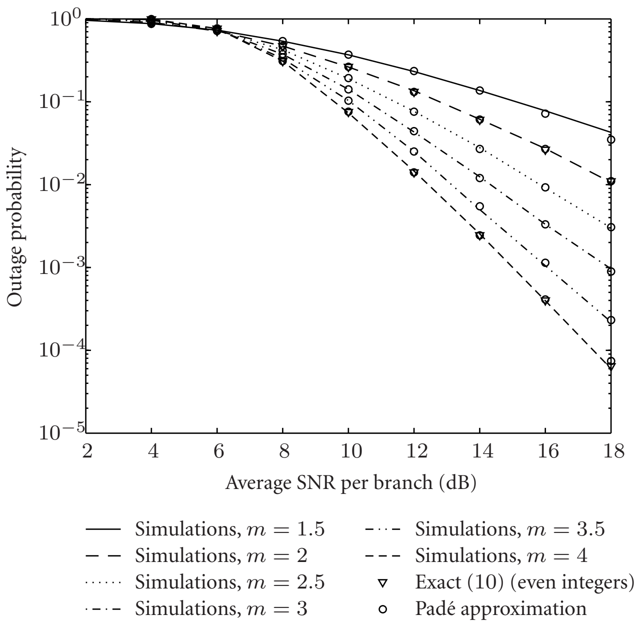


Figure 3: Simulated and PA outage probability for a dual-branch MRC system over Weibull fading channel for different values of m. The outage probability obtained using the exact expression is also shown for even integer values of m.

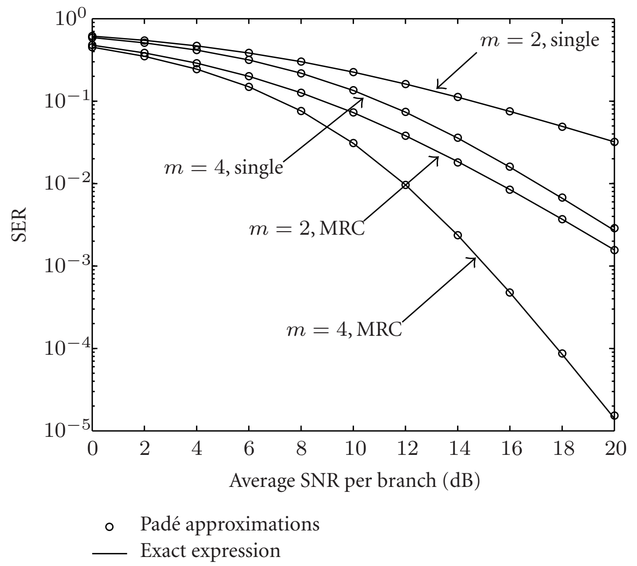


Figure 4: Exact and PA SER for 8-PSK with single- and dual-branch MRC channels for $m = 2$ and 4.

exact expression is also shown. Monte Carlo simulations are provided for all the cases as well. It is evident that the approximate results are in perfect agreement with the simulations and the exact expression.

The SER of an 8-PSK system is depicted in Figures 4 and 5. Comparison is first established with the exact SER for the two cases of $m = 2$ and $m = 4$. Again, perfect matching between the two curves is noticed. In Figure 5, the case of single-channel and dual-branch MRC system with odd and noninteger values of m is considered. Finally, similar results for the case of 16-QAM are presented in Figures 6 and 7.

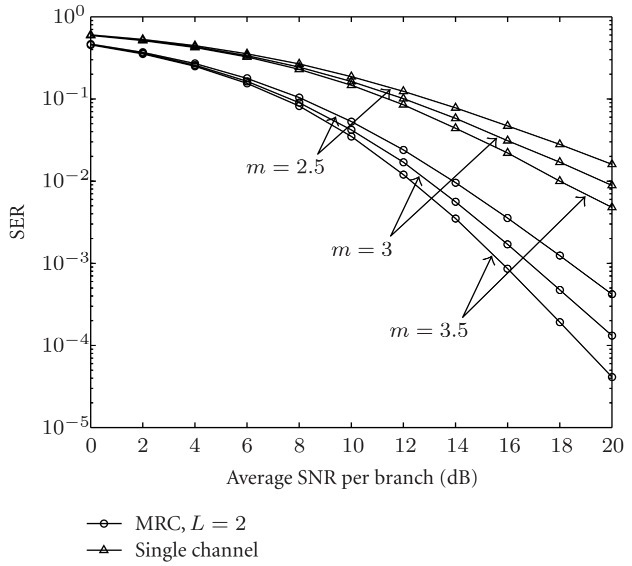


Figure 5: PA SER for 8-PSK with single- and dual-branch MRC channels for different *noninteger* and *odd* integer values of *m*.

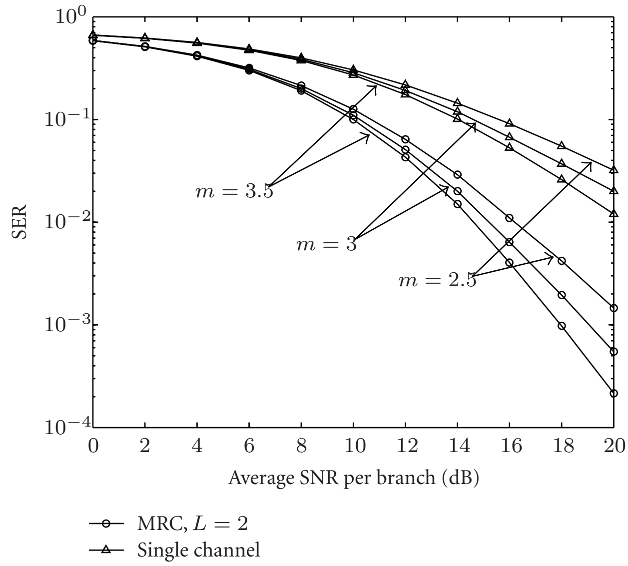


Figure 7: PA SER for 16-QAM with single- and dual-branch MRC channels for different *noninteger* and *odd* integer values of *m*.

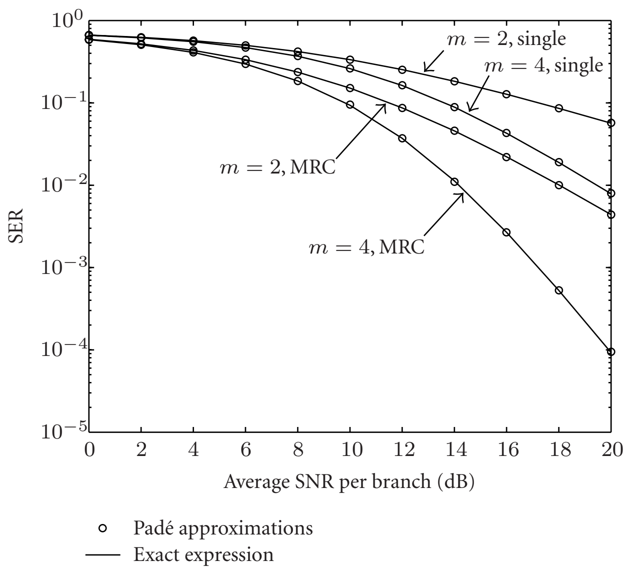


Figure 6: Exact and PA SER for 16-QAM with single- and dual-branch MRC channels for $m = 2$ and 4.

6. CONCLUSIONS

In this paper, we illustrated how the PA technique can be used to find simple closed-form approximate expressions for the MGF of the Weibull RV. Several examples have been presented, which show perfect agreement between the approximate technique and a previously published closed-form exact expression. When the exact expression is difficult to handle numerically, comparison with Monte Carlo simulations was performed. Using the PA technique, we also analyzed the performance of digital modulations over the Weibull fading channel with single- and multichannel MRC reception. We showed that the approximate results for the SER or outage probability match very well the exact results. We also presented a new set of results for the cases of odd and noninteger values of the Weibull fading parameter. The PA technique indeed proves to be an invaluable tool in the performance analysis of communications over the Weibull fading channels.

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