# Increasing Power Efficiency in Transmitter Diversity Systems under Error Performance Constraints

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***Abstract*—Motivated by combinatorial optimization theory, we propose an algorithmic power allocation method that minimizes the total transmitting power in transmitter diversity systems, provided that the instantaneous Bit-Error-Rate (BER) is not greater than a predetermined value. This method applies to many practical applications where the power transmitted by each antenna is constrained. We also provide closed-form expressions for the average total transmitted power for the case of two transmitting antennas operating in Rayleigh fading, and the average number of active antennas at the transmitter assuming Nakagami-$m$ fading channels. Simulations and numerical results show that, compared to the conventional equi-power scheme, the proposed model offers a considerable reduction in the total transmitting power and the average number of active antennas, without loss in error performance.**

***Index Terms*—Bit error rate (BER), fading channels, multiple-input-single-output (MISO) systems, transmitter diversity.**

## I. Introduction

TRANSMITTER diversity offers diversity gains in cases where multiple transmitting antennas and a single antenna at the receiver are employed [1]- [3]. Its operation is based upon the separation of the transmitting signals using Code Division Multiple Access (CDMA) spreading or space-time codes, or by simply exploiting the multiple paths, partially or fully uncorrelated, between the transmitting paths and the receiver. The multiple replicas are then appropriately combined at the receiver, resulting in the same or similar performance as that of receive diversity. Thus, in cases where it is practically difficult to employ multiple antennas at the receiver, the beneficial effects of diversity can still be achieved; the cost is higher complexity, since this requires channel-state knowledge by the transmitter.

Several works have been published in the past concerning the concept of optimizing transmitter diversity systems. In [4], Cavers presented an optimal power allocation method, aiming at the minimization of the average bit-error-rate (ABER) under power constraints, when the system is operating over independent or correlated Rayleigh fading channels. This work was extended in [5], considering Nakagami-$m$ fading channels, taking into account the effect of imperfect channel estimation at the transmitter; this concept was also employed in [6], where the optimization was held in terms of the outage probability.

In this letter, we propose an algorithmic solution to the dual power allocation problem, which minimizes and optimally allocates the total transmitting power provided that the instantaneous BER does not exceed a predetermined threshold. In fact, the transmitter utilizes its knowledge on the amplitude of each individual channel between a transmitting antenna and the receiver, in order to activate the minimum number of branches and to save as much energy as possible. The power allocation problem is formulated as a special case of the well-known fractional minimization Knapsack problems [7], and applies to many practical applications where the power transmitted by each antenna is constrained. Its exact algorithmic solution is computed within a relatively short amount of time, ensuring that no extra delay in packet transmission is induced. Moreover, the rate that the proposed power allocation procedure is repeated depends on the channels' fading coherence time, since the channel state in the time interval between two consecutive procedure repetitions needs to remain unchanged.

## II. System Model

We consider a typical Multiple-Input-Single-Output (MISO) system, consisting of an $L$-antenna transmitter and a single-antenna receiver. The receiver is equipped with a maximal ratio combiner (MRC), together with an appropriate path-resolving mechanism in order to separate the signals incident from different antennas, e.g. a despreading matched filter if the multiple signals are separated using CDMA spreading codes. Additionally, we assume that each antenna is equipped with its own power amplifier (see e.g., [8]- [9]), and thus *the power transmitted by each antenna is constrained*, due to the linearity of the corresponding amplifiers. It is also assumed that the channel amplitudes are known at the transmitter; moreover, each of the individual channels is considered independent, but not necessarily identically distributed. In the following, the term branch will denote the individual channel between a transmitting antenna and the receiver.

Let $g_i$, $P_i$ represent respectively the instantaneous squared channel gain, including the path-loss and fading attenuation, and the normalized transmitting power with respect to 1 W, corresponding to the $i$th branch with $i = 1, ..., L$. The maximum power that each antenna can transmit is denoted by $P_{\max}$. Then, $P_i$ can be expressed as

$$P_i = P_{\max} x_i, \quad (1)$$

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where $x_i \in [0,1]$. Let $N_0$ represent the additive white Gaussian noise (AWGN) power and $G_i$ denote the ratio of the instantaneous squared channel gain of the $i$th branch over the noise power, i.e.,

$$G_i = \frac{g_i}{N_0}. \tag{2}$$

Then, the instantaneous signal to noise ratio (SNR), $\gamma_i$, of the $i$th branch can be expressed as

$$\gamma_i = P_i G_i. \tag{3}$$

Moreover, the receiver is assumed to have perfect channel state information as well, so that the SNR at the combiner output, namely $\gamma_{out}$, can be expressed as

$$\gamma_{out} = \sum_{i=1}^{L} \gamma_i. \tag{4}$$

## III. Optimal Power Allocation

The well-known zero-one minimization Knapsack problem is defined as follows [7]: Given a bound $B$, and a set of $n$ items with profits $p_j > 0$ and weights $w_j > 0$, $j = 1, ..., n$, select the subset leading to the minimum profit summation provided that the weight summation is not smaller than $B$. In cases where a fraction of each item is eligible for selection (and not necessarily the whole part of it), the resulting problem is known as *fractional minimization Knapsack* [7]; as it is shown later, the power allocation problem studied in this paper represents a special case of this kind of problems.

Let us assume that the power allocation procedure is repeated in a rate ensuring constant fading characteristics in each channel during the selection interval; this implies that the selection repetition rate is greater than or equal to $1/T_c$, where $T_c$ stands for the channel coherence time. Considering this, the problem of minimizing the total transmitting power provided that the instantaneous BER does not exceed a specified target BER, denoted by $BER_t$, reduces to the problem of minimizing the transmitting power under the constraint that the overall received SNR is greater than or equal to a given value $\gamma_t$, i.e.,

$$\begin{aligned} &\textit{minimize} \ \sum_{i=1}^{L} P_{\max} x_i \\ &\textit{subject to} \ \sum_{i=1}^{L} G_i P_{\max} x_i \geq \gamma_t \\ &x_i \in [0,1], \quad i = 1, ..., L. \end{aligned} \tag{5}$$

In a BPSK application, for example, $\gamma_t$ is related with $BER_t$ through

$$\gamma_t = \left[\mathrm{erfc}^{-1}\left(2BER_t\right)\right]^2, \tag{6}$$

where $\mathrm{erfc}^{-1}(\cdot)$ is the inverse function of the $\mathrm{erfc}(\cdot)$, which can be efficiently evaluated with desired accuracy, using the approximations given in [10]. Also, note that $\mathrm{erfc}^{-1}(\cdot)$ is a standard built-in function in most of the well-known mathematical software packages, such as MAPLE, MATHEMATICA and MATLAB.

| |
|---|
| Sort the branches in decreasing order of |
| $G_i$ (e.g., $x_1 = \max[x_i]$) |
| $j = 1$; $x_i = 0 : i = 2, ..., L$ |
| † $x_j = 1$ |
| if $\gamma_{out} > \gamma_t$ |
| modify $x_j$ such that $\gamma_{out} = \gamma_t$; break |
| else |
| if $j \neq L$ |
| $j = j + 1$ |
| go to † |
| break |

Fig. 1. The proposed power allocation algorithm.

In fact, the problem in (5) represents a special case of the so-called fractional minimization Knapsack problem as it was described above. Its peculiarity lies in the equal profit values $(p_j)$ of each selected item, which correspond to the maximum power $P_{\max}$ that can be transmitted by each antenna. For this reason, *the exact optimal solution of the problem in (5) coincides with the one provided via the Greedy-Split algorithm* [7], a computer-implemented description of which is given in Fig. 1. More specifically, the transmitter first sorts the available branches in decreasing order of $G_i$; following this order, it allocates full power to each branch successively, until the SNR of the combiner output exceeds $\gamma_t$. Then, the power allocated to the latterly accessed branch is modified so as $\gamma_{out}$ meets the desired level. Consequently, the above policy allocates full power to the strongest branches, and a part of the full power to a single branch in order to achieve precisely the desired BER, if this is possible. All the other branches remain inactive as long as their fading conditions are relatively weak. Apparently, the algorithm described above is a polynomial-time one, since its running time grows linearly with $L$.

Nonetheless, it must be noted that it may be impossible to achieve the desired $BER_t$ in each repetition of the proposed algorithm. In such case, $P_{\max}$ is allocated to all the available antennas and $\gamma_{out}$ is still below $\gamma_t$. Then, similarly to the typical cellular systems, the system administrator can determine the certain number of successive failures of achieving $BER_t$ that lead to an outage. Hence, the outage probability defined above is identical with the outage probability of the conventional MRC diversity scheme, when the SNR threshold equals $\gamma_t$. An extensive study of this probability for Nakagami-$m$ fading channels can be found in [11]- [12].

We should also note that the proposed power allocation method resembles a transmitter-implemented concept of the minimum-selection generalized selection combining (MS-GSC) scheme (see for example [13]- [14]). The difference between these two allocation techniques lies in the fact that the power of the weakest active branch in the proposed method is adjusted so that the desired BER is precisely achieved; this adjustment is not included in the transmitter-implemented MS-GSC concept.

## IV. Power Efficiency of the Proposed Scheme

### A. Average Total Transmitted Power in independent and identically distributed (i.i.d.) Rayleigh Fading for $L = 2$

Next, a closed-form expression for the average total transmitted power for the special case of two transmitting antennas, when operating over i.i.d Rayleigh fading channels, is derived. Suppose that $G_1^{'} \geq G_2^{'}$ represent the order statistics of $G_1$ and $G_2$, i.e. $G_1^{'} = \max(G_1, G_2)$ and $G_2^{'} = \min(G_1, G_2)$. Denoting as $f_G(\cdot)$ the probability density function (PDF), and as $F_G(\cdot)$ the cumulative density function (CDF) of the random variables (RVs) $G_1$ and $G_2$, the PDF of $G_1^{'}$ can be expressed as [15, eq. (6-55), (6-58)]

$$f_{G_1^{'}}(G_1^{'}) = 2 f_G(G_1^{'}) F_G(G_1^{'}). \tag{7}$$

The average total transmitted power, namely $P_{av}$, can be evaluated by taking into account the following two cases:

- if $P_{\max} G_1^{'} \geq \gamma_t$, only a single antenna transmits at a certain power level, which is appropriately adjusted so that the SNR meets the threshold $\gamma_t$
- if $P_{\max} G_1^{'} < \gamma_t$, the antenna corresponding to the strongest channel transmits at full power while the power allocated to the remaining antenna is the power required to attain $\gamma_t$; if $\gamma_t$ cannot be achieved, then this power equals to $P_{\max}$.

Considering the above, $P_{av}$ can be written as

$$\begin{aligned} P_{av} &= P_{\max} E\left[x_1 + x_2\right] \\ &= P_{\max} E\left[\frac{A}{G_1^{'}} \middle| G_1^{'} \geq A\right] \Pr\left\{G_1^{'} \geq A\right\} \\ &+ P_{\max}\left(1 + E\left[\min\left(1, \frac{A - G_1^{'}}{G_2^{'}}\right) \middle| G_1^{'} < A\right]\right) \\ &\times \Pr\left\{G_1^{'} < A\right\} \\ &= P_{\max} \int_A^{\infty} \frac{A}{G_1^{'}} f_{G_1^{'}}(G_1^{'}) dG_1^{'} \\ &+ P_{\max}\left(\int_0^A f_{G_1^{'}}(G_1^{'}) dG_1^{'}\right. \\ &\left.+ \int_0^A \int_0^{G_1^{'}} \Theta\left(G_1^{'}, G_2^{'}\right) f_{G_1^{'} G_2^{'}}(G_1^{'}, G_2^{'}) dG_2^{'} dG_1^{'}\right), \end{aligned} \tag{8}$$

where $f_{G_1^{'} G_2^{'}}(\cdot,\cdot)$ represents the joint PDF of $G_1^{'}$ and $G_2^{'}$, $E[\cdot]$ denotes expectation, $E[B\,|\mathcal{B}]$ stands for the expectation value of $B$ conditioned on the random event $\mathcal{B}$, $A = \gamma_t / P_{\max}$ and

$$\Theta\left(G_1^{'}, G_2^{'}\right) = \begin{cases} 1, & G_2^{'} \leq A - G_1^{'} \\ \frac{A - G_1^{'}}{G_2^{'}}, & G_2^{'} > A - G_1^{'} \end{cases}. \tag{9}$$

Therefore, using (9) and simplifying $f_{G_1^{'} G_2^{'}}(\cdot,\cdot)$ using the order statistics theory [16, eq. (2.2.1)], (8) yields

$$\begin{aligned} P_{av} &= P_{\max}\left[\int_A^{\infty} \frac{A}{G_1^{'}} f_{G_1^{'}}(G_1^{'}) dG_1^{'} + \int_0^A f_{G_1^{'}}(G_1^{'}) dG_1^{'}\right. \\ &+ 2 \int_0^{\frac{A}{2}} \int_0^{G_1^{'}} f_G(G_1^{'}) f_G(G_2^{'}) dG_2^{'} dG_1^{'} \\ &+ 2 \int_{\frac{A}{2}}^{A} \int_0^{A - G_1^{'}} f_G(G_1^{'}) f_G(G_2^{'}) dG_2^{'} dG_1^{'} \\ &\left.+ 2 \int_{\frac{A}{2}}^{A} \int_{A - G_1^{'}}^{G_1^{'}} \frac{A - G_1^{'}}{G_2^{'}} f_G(G_1^{'}) f_G(G_2^{'}) dG_2^{'} dG_1^{'}\right] \\ &= P_{\max}\left(\mathcal{I}_1 + \mathcal{I}_2 + \mathcal{I}_3 + \mathcal{I}_4 + \mathcal{I}_5\right). \end{aligned} \tag{10}$$

If $G_1$ and $G_2$ are i.i.d exponential RVs with scale parameter $1/\overline{G}$, using trivial integral simplifications and the non-trivial one given in [17, eq. (2.325)], the integrals in (10) can be written as

$$\mathcal{I}_1 = \frac{2A}{\overline{G}}\left(\mathrm{Ei}\left[-\frac{2A}{\overline{G}}\right] - \mathrm{Ei}\left[-\frac{A}{\overline{G}}\right]\right) \tag{11}$$

$$\mathcal{I}_2 = e^{-\frac{2A}{\overline{G}}}\left(e^{\frac{A}{\overline{G}}} - 1\right)^2 \tag{12}$$

$$\mathcal{I}_3 = 2 e^{-\frac{A}{\overline{G}}}\left(e^{\frac{A}{2\overline{G}}} - \frac{A}{2\overline{G}} - 1\right) \tag{13}$$

$$\mathcal{I}_4 = e^{-\frac{A}{\overline{G}}}\left(e^{\frac{A}{2\overline{G}}} - 1\right)^2 \tag{14}$$

$$\begin{aligned} \mathcal{I}_5 = e^{-\frac{A}{\overline{G}}}&\left[e^{-\frac{A}{\overline{G}}} - 2\mathcal{E} + \frac{A}{\overline{G}} - 2e^{\frac{A}{\overline{G}}}\left(1 - \frac{A}{\overline{G}}\right)\mathrm{Ei}\left[-\frac{2A}{\overline{G}}\right]\right. \\ &+2\left(1 + e^{\frac{A}{\overline{G}}} - \frac{A e^{\frac{A}{\overline{G}}}}{\overline{G}}\right)\mathrm{Ei}\left[-\frac{A}{\overline{G}}\right] \\ &\left.+\ln(4) - 2\ln\left(\frac{A}{\overline{G}}\right) - 1\right] \end{aligned} \tag{15}$$

where $\mathrm{Ei}[\cdot]$ denotes the exponential integral function defined in [17, eq. (8.211)] and $\mathcal{E}$ the Euler's constant with numerical value $\mathcal{E} \simeq 0.57721$. Hence, the average total transmitted power can be derived in closed form by substituting (11)-(15) into (10). We note that the validity of eq. (10) was verified by simulations; however, a schematic comparison between the analytical and the simulation results is omitted for the sake of brevity.

### B. Average Number of Active Antennas

The power saving of the proposed scheme can be also quantified by the average number of active antennas at the transmitter. By optimally allocating the transmitted power, not all the available antennas are used to achieve the desired BER. We note, however, that this number of used antennas (in an average perspective) does not correspond exactly to the average transmitted power, since not all the antennas transmit equal amount of power.

By following a similar analysis as that in [14], where the Generalized Selection Combining (GSC) and MRC with an output threshold were studied, the average number of active

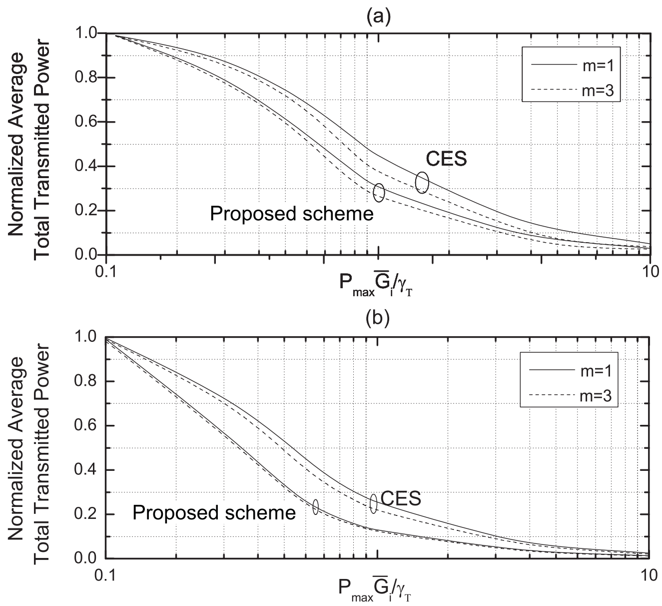


Fig. 2. Average total transmitting power versus $P_{\max}\overline{G}_i/\gamma_t$, for the conventional equi-power scheme (CES) and the proposed scheme in i.i.d. Nakagami-$m$ fading for (a) $L = 3$ and (b) $L = 5$.

antennas at the transmitter is given by

$$N = 1 + \sum_{i=1}^{L-1} F^{(L/i)}(\gamma_t). \tag{16}$$

where $F^{(L/i)}(\cdot)$ is the CDF of the combined output SNR, of a receiver that uses the $i$ strongest branches out of the $L$ available ones. Fortunately, the desired CDF is the CDF of a GSC receiver that uses the $i$ strongest branches out of the $L$ available ones, and has been extensively studied in the literature (see e.g., [18]- [19]). For the case of i.i.d and independent but not necessarily identically distributed (i.n.i.d.) Nakagami-$m$ fading channels, the desired CDF was given in [18] and [19] respectively; for the case of i.i.d. Rayleigh fading channels, a compact formula can be found in [14].

## V. Simulations and Numerical Examples

In this section, we provide simulations and numerical results[1] demonstrating the considerable reduction in transmitting power that the proposed model offers, compared to the classic equi-power transmitter diversity system. In the latter scheme, all the available branches are considered to transmit with equal power, in a fashion that limits the total transmitted power to the minimum required to achieve a predetermined ABER, if possible. The simulation was conducted on the system model described in Section II, employing BPSK modulation with three or five transmitting antennas and operating over i.i.d. or i.n.i.d. Nakagami-$m$ fading environments.

In Fig. 2, we compare the conventional equi-power scheme (CES) with the proposed one, in terms of the normalized average total transmitted power (normalized with respect to its maximum value), assuming three and five transmitting antennas (Fig 2 (a) and 2 (b), respectively), and two different i.i.d. Nakagami-$m$ fading environments. In order to provide a fair comparison, we assume that the amount of power transmitted by the CES leads to the same ABER as that achieved by the proposed model. Fig. 2 (b) shows that the proposed scheme offers a considerable reduction in transmitting power, for a given value of $P_{\max}\overline{G}_i/\gamma_t$, where $\overline{G}_i$ denotes the expectation of $G_i$ (which is identical for all the available branches due to the i.i.d assumption). Moreover, this power is nearly the same for both fading environments ($m = 1$ and $m = 3$), under the condition that there is available power at the transmitter. This important characteristic of the system seems to diminish as the number of antennas reduces ($L = 3$), as it is evident from Fig. 2 (a). Although the total transmitted power is considerably reduced (compared to the CES), the algorithm can hardly maintain the transmitted power at a constant level as the fading conditions worsen. This behavior is explained intuitively, considering that any reduction in the available paths between the transmitter and the receiver entails a reduction in the number of the alternative power allocation options among the antennas.

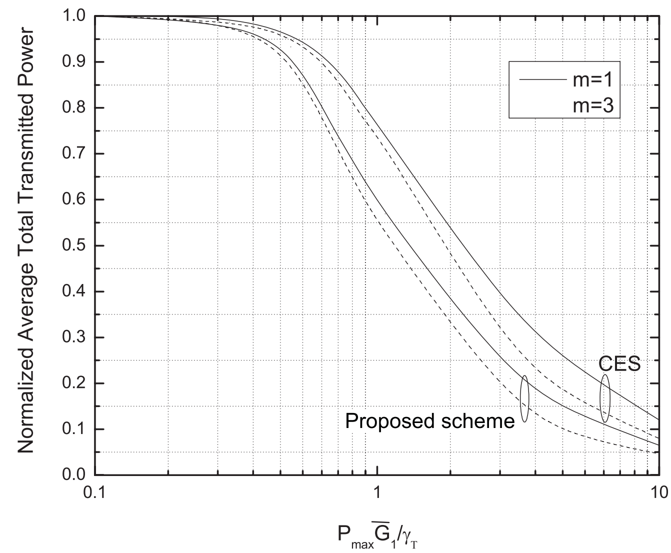


Fig. 3. Average total transmitting power versus $P_{\max}\overline{G}_1/\gamma_t$, for the conventional equi-power scheme (CES) and the proposed scheme in i.n.i.d. Nakagami-$m$ fading with exponential power profile, for $L = 3$.

The performance of the proposed power allocation methodology compared to the equivalent CES is depicted in Fig. 3, when operating over i.n.i.d. Nakagami-$m$ fading channels and $L = 3$. In this figure, the average SNRs corresponding to the individual system branches are assumed to follow an exponential profile with unitary power decay factor, and initial value denoted by $\overline{G}_1$, i.e., $\overline{G}_i = \overline{G}_1 e^{-i}$.

The power saving of the proposed scheme can be also illustrated through the average number of active antennas at the transmitter. In Fig. 4, two MISO systems with three and five transmitting antennas respectively are assumed, operating over Rayleigh fading channels. As it was expected, the more the available transmitting antennas the less the active ones (in an average perspective), since the number of alternative power allocation options increases with $L$.

[1]The results concerning the average transmitted power (Figs. 2 and 3) were derived using simulations; the results concerning the average transmitting antennas (Fig. 4) were derived numerically, using (16).

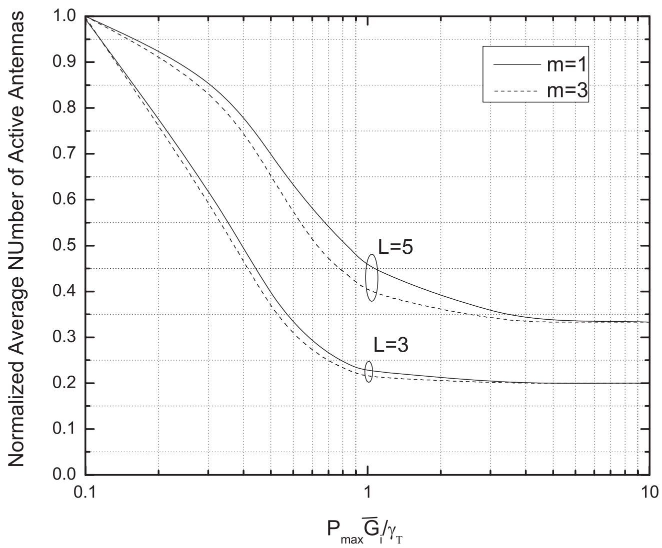


Fig. 4. Average number of active antennas in Nakagami-$m$ fading.

## REFERENCES

[1] J. H. Winters, "The diversity gain of transmit diversity in wireless systems with Rayleigh fading," *IEEE Trans. Veh. Technol.*, vol. 47, pp. 119–123, Feb. 1998.

[2] P. A. Dighe, R. K. Mallik, and S. S. Jamuar, "Analysis of K-transmit dual-receive diversity with cochannel interferers over a Rayleigh fading channel," *Wireless Personal Communications*, vol. 25, pp. 87–100, May 2003.

[3] ——, "Analysis of transmit-receive diversity in Rayleigh fading," *IEEE Trans. Commun.*, vol. 51, pp. 694–703, Apr. 2003.

[4] J. K. Cavers, "Optimized use of diversity modes in transmitter diversity systems," in *Proc. of IEEE Vehicular Technology Conf. VTC'99*, Apr. 1999, pp. 1768–1773.

[5] Y.-Ko and M.-S. Alouini, "Estimation of Nakagami-$m$ fading channel parameters with application to optimized transmitter diversity systems," *IEEE Trans. Wir. Commun.*, vol. 2, pp. 250–259, Mar. 2003.

[6] Y. Xie, C. N. Georghiades, and A. Arapostathis, "Minimum outage probability transmission with imperfect feedback for MISO fading channels," *IEEE Trans. Wireless Commun.*, vol. 4, pp. 1084–1091, May 2005.

[7] H. Kellerer, U. Pferschy, and D. Pisinger, *Knapsack Problems*, 1st ed. Berlin: Springer, 2004.

[8] W. Yu, "Uplink - downlink duality via minimax duality," *IEEE Trans. Inform. Theory*, vol. 52, pp. 361–374, Feb. 2006.

[9] W. Yu and T. Lan, "Transmitter optimization for the multi-antenna downlink with per-antenna power constraints," *IEEE Trans. Signal Processing*, to appear.

[10] Wolfram. (2006) The Wolfram functions site. Internet. [Online]. Available: http://functions.wolfram.com/06.31.06.0001.01

[11] M.-S. Alouini, A. Abdi, and M. Kaveh, "Sum of gamma variates and performance of wireless communication systems over Nakagami-fading channels," *IEEE Trans. Veh. Technol.*, vol. 50, pp. 1471–1480, Nov. 2001.

[12] G. K. Karagiannidis, N. C. Sagias, and T. A. Tsiftsis, "Closed-form statistics for the sum of squared Nakagami-$m$ variates and its applications," *IEEE Trans. Commun.*, to appear.

[13] R. K. Mallik, P. Gupta, and Q. T. Zhang, "Minimum selection GSC in independent Rayleigh fading," *IEEE Trans. Veh. Technol.*, vol. 54, pp. 1013–1021, May 2005.

[14] H.-C. Yang and M.-S. Alouini, "MRC and GSC Diversity Combining With an Output Threshold," *IEEE Trans. Veh. Technol.*, vol. 54, no. 3, pp. 1081–1090, May 2005.

[15] A. Papoulis, *Probability, Random Variables, and Stochastic Procceses*, 3rd ed. McGraw-Hill, 1991.

[16] H. A. David and H. N. Nagaraja, *Order Statistics*, 3rd ed. New York, NY: John Wiley, 2003.

[17] I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series, and Products*, 6th ed. New York: Academic, 2000.

[18] A. Annamalai and C. Tellambura, "A new approach to performance evaluation of generalized selection diversity receivers in wireless channels," *IEEE Vehicular Technology Conf.*, vol. 4, pp. 2309–2313, Oct. 2001.

[19] A. Annamalai, G. K. Deora, and C. Tellambura, "Theoretical Diversity Improvement in GSC(N, L) Receiver With Nonidentical Fading Statistics," *IEEE Trans. Commun.*, vol. 53, no. 6, pp. 1027–1035, Jun. 2005.