PERFORMANCE ANALYSIS OF FULLY JOINT DIVERSITY COMBINING, ADAPTIVE MODULATION, AND POWER CONTROL SCHEMES

A Thesis

by

ZIED BOUIDA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2009

Major Subject: Electrical Engineering

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Approved by:

Co-Chairs of Committee,	Khalid A. Qaraqe
	Jean-Francois Chamberland
Committee Members,	Mohamed-Slim Alouini
	Mahmoud M. El-Halwagi
	Srinivas Shakkottai
Head of Department,	Costas Georghiades

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ABSTRACT

Performance Analysis of Fully Joint Diversity Combining, Adaptive Modulation, and Power Control Schemes. (August 2009)

Zied Bouida, B.S., École Supérieure des Communications de Tunis

Co–Chairs of Advisory Committee: Dr. Khalid A. Qaraqe
Dr. Jean-Francois Chamberland

Adaptive modulation and diversity combining represent very important adaptive solutions for future generations of wireless communication systems. Indeed, to improve the performance and the efficiency of these systems, these two techniques recently have been used jointly in new schemes named joint adaptive modulation and diversity combining (JAMDC) schemes. Considering the problem of finding low-complexity, bandwidth-efficient, and processing-power efficient transmission schemes for a downlink scenario and capitalizing on some of these recently proposed JAMDC schemes, we propose and analyze three fully joint adaptive modulation, diversity combining, and power control (FJAMDC) schemes. More specifically, the modulation constellation size, the number of combined diversity paths, and the needed power level are determined jointly to achieve the highest spectral efficiency with the lowest possible combining complexity, given the fading channel conditions and the required bit error rate (BER) performance. The performance of these three FJAMDC schemes is analyzed in terms of their spectral efficiency, processing power consumption, and error-rate performance. Selected numerical examples show that these schemes considerably increase the spectral efficiency of the existing JAMDC schemes with a slight increase in the average number of combined paths for the low signal to noise ratio range while maintaining compliance with the BER performance and a low radiated power resulting in a substantial decrease in interference to co-existing systems/users.

To

My Mother & My Father,

My Wife & My Daughter,

My Brothers & My Sister.

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Paula Evans and Tammy Carda, we are so privileged at the ECE department to have people like you helping all the students. Thanks for all your valuable emails, reminders, and your continuous help that started before I joined TAMU.

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CHAPTER I

INTRODUCTION

More and more importance is accorded to adaptive modulation [1], [2], adaptive diversity combining techniques [3, 4, 5, 6], and power control [7], [8]. Many reasons are behind the use of these key adaptive solutions. Indeed, future wireless communication systems which will provide multimedia services to the power/size limited mobile terminals are characterized by limited bandwidth and power resources. These systems should be able to support high spectral efficiency with good link reliability. This need for higher bandwidth efficiency motivates further optimization of the use of wireless resources. Due to user mobility and highly time-variant propagation environments, resource management in wireless communications becomes a difficult task. In order to facilitate the management of these resources, adaptive techniques seem to be one of the best solutions.

Based on multiple thresholds, adaptive modulation can achieve high spectral efficiency over wireless channels. The key idea of adaptive modulation is to adapt the modulation parameters, such as constellation size, to fading channel conditions while respecting the bit error rate (BER) requirements. Adaptive diversity combining, on the other hand, improves the reliability of wireless fading channels by adapting the combiner structure to fading channel conditions. Adaptive power control schemes, unlike schemes using a constant-power variable-rate setup, adapt the transmitted power to fading channels conditions while fulfilling the BER constraint. These schemes reduce the radiated power, and thus the potential interference to other systems/users which implies a significant network capacity improvements.

This thesis follows the style of *IEEE Transactions on Wireless Communications*

Diversity combining is a classical concept which has been used for the past half century to combat the effects of fading on wireless systems. Over the last decade, low-complexity diversity combining schemes operating in a diversity rich environment received a great deal of attention. Among these schemes, generalized selection combining (GSC), also known as hybrid selection/maximum ratio combining (H-S/MRC), was the first to be proposed (e.g. [9, 10, 11, 12]). Minimum selection GSC (MS-GSC) is an adaptive diversity combining technique that was proposed in [3] as a power-saving implementation of GSC and further studied and analyzed in [4, 5, 6]. With MS-GSC the receiver ranks the SNR of all available paths and then combines the minimum number of branches in order to make the combined SNR exceed a certain predetermined threshold. On average, MS-GSC combines less branches and hence uses less processing power [3, 6], making it ideal for a downlink scenario where the mobile unit is power and size limited.

These adaptive solutions have been originally studied separately. Recently, joint adaptive solutions have been proposed and studied. For instance, while joint adaptive modulation and diversity combining (JAMDC) schemes were introduced in [13, 14], joint adaptive combining and power control were studied for constant-rate transmission in [15, 16]. In addition, in [17] and for the purpose of interference reduction, Gjendemsjø *et al.* extended the schemes discussed in [13, 14, 15, 16] by looking at joint adaptive modulation, diversity combining, and post-combining power control. Capitalizing on this recent work and on the work done in [14], and in order to have better spectral efficiency, better BER performance, and less radiated power, we offer in this thesis a generalization of the existing schemes by proposing three fully joint adaptive modulation, diversity combining, and power control (FJAMDC) schemes, namely (i) a processing power efficient (PES-FJAMDC) scheme, (ii) a bandwidth efficient (BES-FJAMDC) scheme, and (iii) a bandwidth efficient with finger deactivation (BES-FD-FJAMDC) scheme. We analyze these newly proposed schemes in term of average spectral efficiency (ASE) (in bits/s/Hz), average BER, diversity combining complexity, and transmit power gain and compare their performance to that of the PES-JAMDC and the BES-JAMDC schemes proposed in [17] and to that of the bandwidth-efficient and power-greedy scheme proposed in [14]. Selected numerical examples, obtained by Monte-Carlo simulations and confirmed by analytical results, show that the proposed FJAMDC schemes (i) have better ASE with a slight increase in the average number of combined paths, (ii) improve the BER performance, and (iii) maintain a low average radiated power yielding to a substantial decrease in interference to co-existing systems/users.

The remainder of this thesis is organized as follows. In chapter II, we first present the system and channel models, then we give the details behind the adaptive transmission system and the underlying power control mechanism. In chapter III, we start by presenting the details behind the mode of operation of each of the proposed FJAMDC schemes, then we derive the statistics of their output SNR before power control. While we analyze in chapter IV the performance of the proposed schemes, we offer in chapter V some selected numerical examples illustrating this performance and comparing it to that of existing schemes. Finally, chapter VI concludes the thesis.

CHAPTER II

SYSTEM AND CHANNEL MODELS

In this second chapter, we make some assumptions concerning the system and channel models. More specifically, we give the details behind the adaptive transmission system, the diversity system, and the underlying power control mechanism used during our study of the proposed FJAMDC schemes.

A. System Model

We consider a generic diversity system with L available diversity paths. This includes, for example, RAKE receivers which are used in wideband CDMA systems to combine the available resolvable multipaths. For hardware complexity considerations, we assume that up to L_c branches can be combined at the receiver side (i.e., the number of fingers of the RAKE receiver is limited to L_c). We also assume that the proposed FJAMDC schemes have a reliable feedback path between the receiver and the transmitter and are implemented in a discrete-time fashion. More specifically, and as shown in Fig. 1, short guard periods are periodically inserted into the transmitted signal. During these guard periods, the receiver performs a series of operation, including (i) path estimation, (ii) combined SNR comparison with respect to the predetermined SNR threshold, and (iii) when needed request to the transmitter high power amplifier (HPA) to increase or decrease its gain by a specific amount. Once the suitable paths for combining and the suitable modulation mode are selected and once the appropriate transmitted power is reached, the combiner (at the receiver end) and the HPA (at the transmitter) are configured accordingly, and this transmitter and receiver settings are used throughout the subsequent data burst.

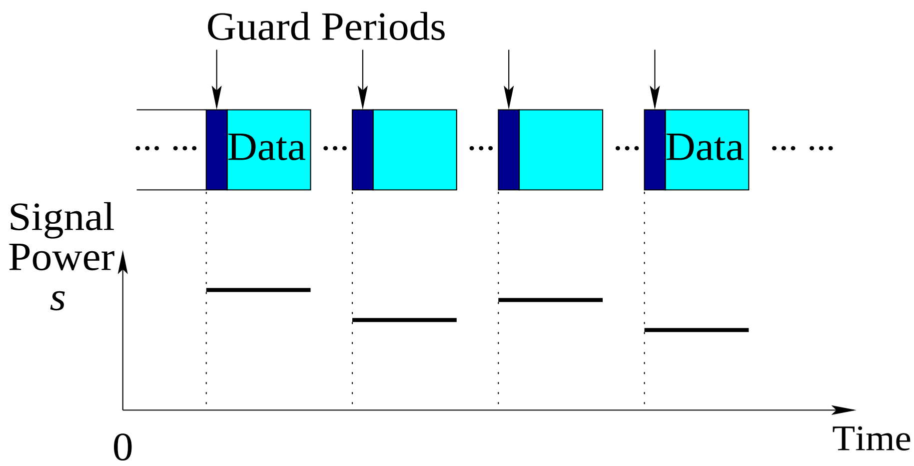


Fig. 1. Block fading channel model.

B. Channel Model

We denote by γ_l ($l = 1, 2, \ldots, L$), the received SNR of the lth diversity path under nominal transmitted power from the BS[1] and, as illustrated in Fig. 1, we adopt a block flat fading channel model. More specifically, assuming slowly-varying fading conditions, the different diversity paths experience roughly the same fading conditions (or equivalently the same SNR) during the data burst and its preceding guard period. In addition, the fading conditions are assumed to (i) be independent across the diversity paths and between different guard period and data burst pairs, and (ii) follow anyone of the popular fading models such as Rayleigh, Rice, or Nakagami-m.

For our study, we assume that the multipath envelop of each path follows the Rayleigh fading model. We also assume that the fading signal envelops on all diversity branches are mutually independent and identically distributed (i.i.d.). The PDF $f_\gamma(x)$

[1]The BS nominal transmitted power is assumed to correspond to an initial level of output power that is adjusted/set to minimize the average outer cell interference in a particular deployment.

and CDF $F_\gamma(x)$ of the faded SNR $\gamma_i,\ i = 1, \ldots, L$ for a diversity path for Rayleigh fading model are given by

$$f_{\gamma_i}(x) = \frac{1}{\overline{\gamma}} \exp\left(-\frac{x}{\overline{\gamma}}\right), \quad x \geq 0 \tag{2.1}$$

and

$$F_{\gamma_i}(x) = 1 - \exp\left(-\frac{x}{\overline{\gamma}}\right), \quad x \geq 0, \tag{2.2}$$

respectively, where $\overline{\gamma}$ is the common average faded SNR.

C. Adaptive Transmission System

We consider the constant-power variable-rate M-ary QAM [1] as the adaptive modulation system of choice for our proposed adaptive transceiver. With this adaptive modulator, the SNR range is divided into $N+1$ fading regions and the constellation size $M = 2^n$ (where n is the number of bits per symbol) is assigned to the nth region ($n = 0, 1, \ldots, N$). The selection of a constellation size is based on the fading channel state. Specifically, we partition the range of the SNR after diversity combining into $N+1$ regions, which are defined by the switching thresholds $\{\gamma_{T_n}\}_{n=1}^{N}$, and transmit using constellation n if the combined SNR is in the interval $[\gamma_{T_n}/G_{\max}, \gamma_{T_{n+1}}/G_{\max})$, where $G_{\max}$ is the transmitter gain at saturation.

The BER of 2^n-QAM constellations with SNR of γ is given in [1] by

$$\mathrm{BER}_n(\gamma) = \frac{1}{5} \exp\left(\frac{-3\gamma}{2(2^n - 1)}\right). \tag{2.3}$$

Given a target instantaneous BER equal to BER_0, the region boundaries (or adaptive modulator switching thresholds) γ_{T_n} for $n = 0, 1, \ldots N$ are given in this case by

$$\gamma_{T_n} = -\frac{2}{3} \ln(\mathrm{BER}_0)(2^n - 1)\,;\ n = 0, 1, \ldots N. \tag{2.4}$$

The adaptive modulator switching thresholds are given for the case of $N = 4$ and $\text{BER}_0 = 10^{-3}$ by the following table.

Table I. M-QAM SWITCHING THRESHOLDS (dB)

$\gamma_{T_1}^{\text{dB}}$	$\gamma_{T_2}^{\text{dB}}$	$\gamma_{T_3}^{\text{dB}}$	$\gamma_{T_4}^{\text{dB}}$
5.48	10.25	13.93	17.24

D. Power Control

In an ideal adaptive power control system, we can assume that the transmitter power can be varied continuously to accurately follow channel variations. In the FJAMDC schemes, in addition to the continuous power adaptation, we also consider power control adaptations accounting for practical implementation constraints including discrete power levels (G_δ) and a transmitter gain saturation ($G_{\max}$).

In the beginning of each data burst the transmitter dB gain G_{dB} is initially set to 0 dB with respect to the nominal transmitted power. The combined SNR after power control is defined by $\Gamma' = \frac{\Gamma}{G}$, where Γ is the combined SNR before power control and G is the value of the gain. We assume that the maximal value of the additional gain, $G_{\max\text{dB}}$, is a multiple of the power control step size ($G_{\delta\text{dB}}$) (i.e. $G_{\max\text{dB}} = k * G_{\delta\text{dB}}$ where $k \in \mathbb{Z}$). While for continuous adaptation $G \in [1/G_{\max}, \infty)$, for the discrete power adaptation there are $M + k$ power parameters:
$\{\beta_{-k} = 1/G_{\max} < \beta_{-k+1} < \ldots \beta_{-1} = 1/G_\delta < \beta_0 = 1 < \beta_1 = G_\delta < \ldots < \beta_{M-1}\}$, where, for practical power control settings, we have

$$\beta_m = \Big(G_\delta\Big)^m \qquad \text{for } m \in [-k, M-1], \tag{2.5}$$

If the modulation mode n is selected and the mobile requests the base station to increase or decrease its power then the SNR after continuous power control will reach the threshold γ_{T_n}. For the discrete adaptation, the SNR will be varied by β_m. In order to respect the error rate constraint, the maximum power control parameter $M-1$ is given by

$$M - 1 \quad = \quad \min_{1 \leq n \leq N} \left\lfloor \frac{\gamma_{T_{n+1}\mathrm{dB}} - G_{\max\mathrm{dB}} - \gamma_{T_n\mathrm{dB}}}{G_{\delta\mathrm{dB}}} \right\rfloor . \tag{2.6}$$

CHAPTER III

MODE OF OPERATION OF THE FJAMDC SCHEMES

A. Processing-Power Efficient FJAMDC Scheme

1. Mode of Operation

The PES-FJAMDC scheme represents a generalization of the PES-JAMDC scheme proposed and analyzed in [17]. The aim of our first scheme is to reduce the processing power consumption, by combining the fewest branches possible, while improving the spectral efficiency of the PES-JAMDC scheme. The mode of operation of the PES-FJAMDC scheme is summarized in a flowchart given in Fig. 2. In the beginning of each data burst, the base station transmits a training sequence using the nominal power level β_{nom}. After estimating and ranking the L available paths, the combiner in the mobile's side tries to increase the output SNR above the threshold for the lowest constellation size by performing MS-GSC with γ_{T1} as output threshold. Whenever the combined SNR Γ is larger than γ_{T1}, the mobile stops combining and determines the highest feasible constellation index n for the given Γ by comparing the combined SNR to different switching thresholds $\{\gamma_{Tn}/G_{\max}\}_{n=1}^{N}$. The modulation mode n (2^n-QAM) is selected if Γ is greater than $\gamma_{Tn}/G_{\max}$ but smaller than $\gamma_{Tn+1}/G_{\max}$. If $\Gamma \in [\gamma_{Tn}/G_{\max},\ \gamma_{Tn})$ then the mobile asks the base station to increase its power in order to reach the constellation size n. If, on the other hand, $\Gamma \in [\gamma_{Tn},\ \gamma_{Tn+1}/G_{\max})$ then the base station reduces its power level such that the modulation mode n is still usable. If, even after combining all L paths, the lowest constellation size is not reached (i.e $\Gamma < \gamma_{T1}/G_{\max}$), the base station buffers the data and does not transmit for the next time interval. In the particular case of $G_{\max} = 1$, the PES-FJAMDC scheme reduces to the PES-JAMDC scheme.

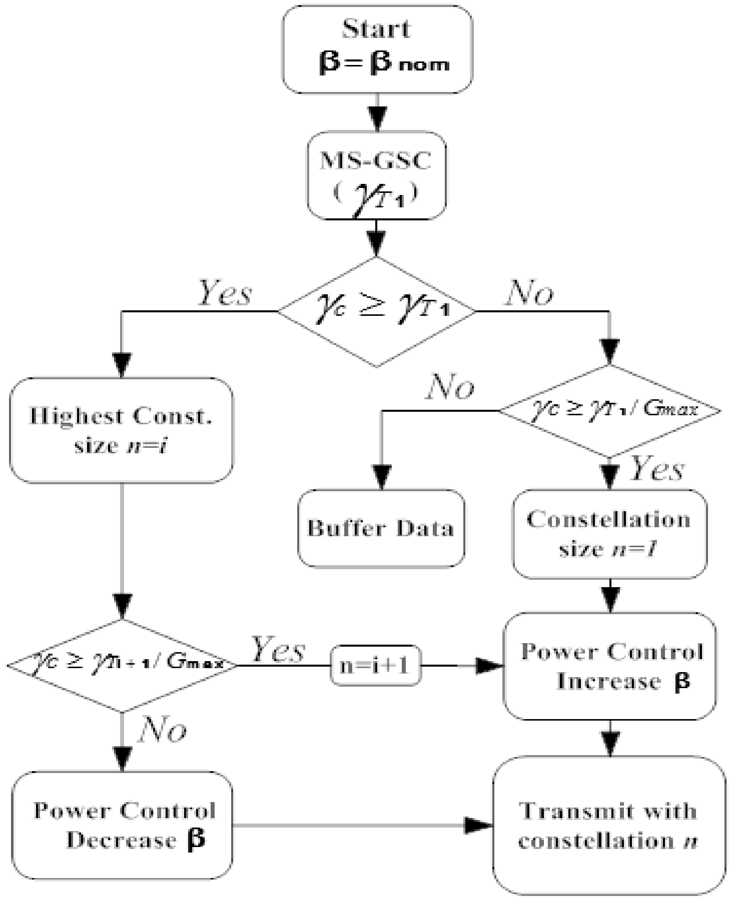


Fig. 2. Mode of operation of the PES-FJAMDC scheme.

2. Statistics of the Output SNR Before Power Control

The statistics of the combined SNR Γ with the PES-FJAMDC scheme can be easily obtained based on the mode of operation of the scheme described above. We can see that Γ is the same as the combined SNR of MS-GSC with γ_{T_1} as the output threshold. The CDF of the received SNR, $F_\Gamma(\cdot)$, of the PES-FJAMDC based on MS-GSC is then given by

$$F_\Gamma(\gamma) = \begin{cases} F_{\gamma_c}^{MSC(\gamma_{T1})}(\gamma), & \gamma > \gamma_{T1}/G_{\max}; \\ F_{\gamma_c}^{MSC(\gamma_{T1})}(\gamma_{T1}/G_{\max}), & 0 < \gamma \leq \gamma_{T1}/G_{\max}; \end{cases} \tag{3.1}$$

where $F_{\gamma_c}^{MSC(\gamma_{T1})}(\cdot)$ denotes the CDF of the combined SNR with L-branch MS-GSC and using an output threshold equal to γ_{T1}, and which is given for the i.i.d. Rayleigh fading environment in [6, Eq. (24)].

Correspondingly, the expression of the PDF of the combined SNR with PES-FJAMDC, $f_\Gamma(\cdot)$, is given by

$$\begin{aligned} f_\Gamma(\gamma) &= f_{\gamma_c}^{MSC(\gamma_{T1})}(\gamma)\,\mathcal{U}(\gamma - \gamma_{T1}/G_{\max}) \\ &\quad + f_{\gamma_c}^{MSC(\gamma_{T1})}(\gamma_{T1}/G_{\max})\,\delta(\gamma), \end{aligned} \tag{3.2}$$

where $\mathcal{U}(\cdot)$ and $\delta(\cdot)$ are the unit step function and the delta function, respectively. In (3.2), $f_{\gamma_c}^{MSC(\gamma_{T1})}(\cdot)$ denotes the PDF of the combined SNR with L-branch MS-GSC and using an output threshold equal to γ_{T1}, and which is given for the i.i.d. Rayleigh fading environment in [6, Eq. (26)].

B. Bandwidth Efficient FJAMDC Scheme

1. Mode of Operation

The BES-FJAMDC scheme represents a generalization of the BES-JAMDC scheme proposed and analyzed in [17]. Our second proposed scheme is designed to maximize the spectral efficiency by: (i) performing all the the necessary diversity combining aiming for the highest signal constellation, and (ii) increasing the power level that both allows to reach the next constellation and obeys to the power constraint.

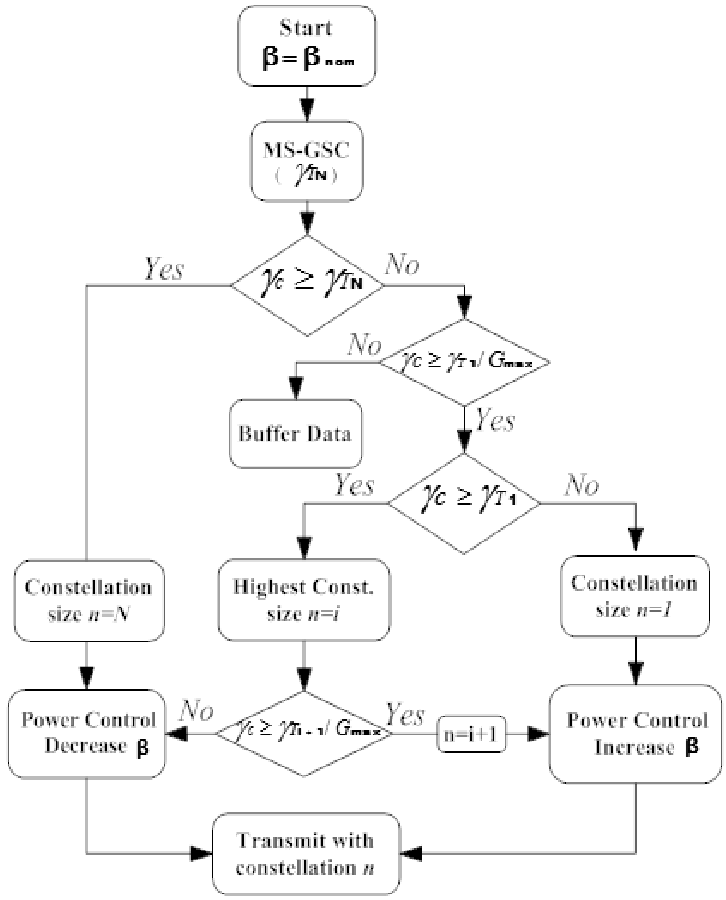


Fig. 3. Mode of operation of the BES-FJAMDC scheme.

The mode of operation of the BES-FJAMDC is summarized in a flowchart given in Fig. 3. In the beginning of each data burst, the base station transmits a training sequence using the nominal power level β_{nom}. After estimating and ranking the L available paths, the combiner in the mobile's side tries to increase the output SNR above the threshold for the highest constellation size by performing MS-GSC with γ_{T_N} as output threshold. Whenever the combined SNR is larger than γ_{T_N}, the receiver selects the highest constellation size (N) and asks the transmitter to use the lowest possible power level such that the highest modulation mode (2^N-QAM) is still usable. If the combined SNR of all available branches is still below γ_{TN}, the mobile determines the highest feasible constellation size. The modulation mode n is selected by the mobile if the combined SNR is smaller than $\gamma_{Tn+1}/G_{\max}$ but greater than $\gamma_{Tn}/G_{\max}$. If even the lowest constellation size is not feasible, data is buffered, and there is no transmission for the next time interval. In the particular case of $G_{\max} = 1$, the BES-FJAMDC scheme reduces to the BES-JAMDC scheme.

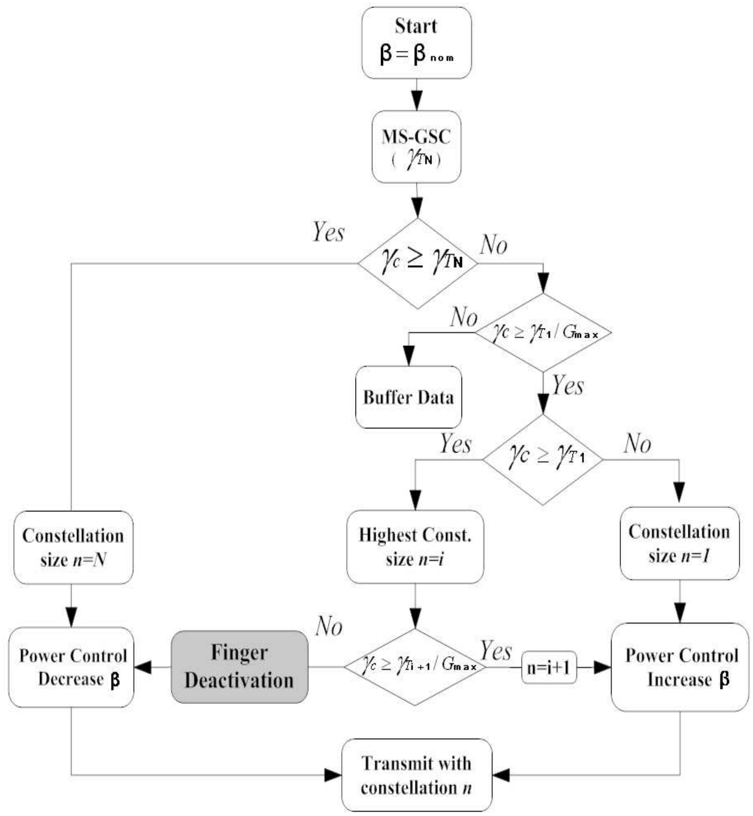
2. Statistics of the Output SNR Before Power Control

The statistics of the combined SNR Γ with the BES-FJAMDC scheme can easily be obtained based on the mode of operation of the scheme described above. We can see that Γ is the same as the combined SNR of MS-GSC with γ_{TN} as the output threshold. The CDF of the received SNR, $F_{\Gamma}(\cdot)$, of the BES-FJAMDC based on MS-GSC is given by

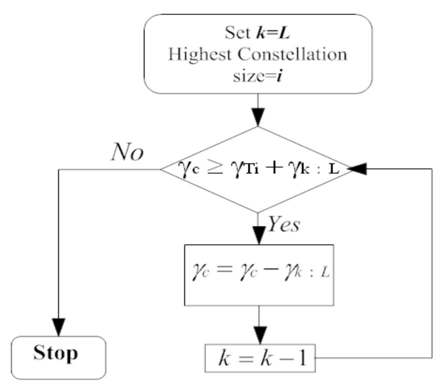
$$F_{\Gamma}(\gamma) = \begin{cases} F_{\gamma_c}^{MSC(\gamma_{TN})}(\gamma), & \gamma > \gamma_{T1}/G_{\max}; \\ F_{\gamma_c}^{MSC(\gamma_{TN})}(\gamma_{T1}/G_{\max}), & 0 < \gamma \leq \gamma_{T1}/G_{\max}. \end{cases} \tag{3.3}$$

Correspondingly, the expression of the PDF of the combined SNR with PES-FJAMDC, $f_{\Gamma}(\cdot)$, is given by

$$\begin{aligned} f_{\Gamma}(\gamma) &= f_{\gamma_c}^{MSC(\gamma_{TN})}(\gamma)\,\mathcal{U}(\gamma - \gamma_{TN}/G_{\max}) \\ &\quad + f_{\gamma_c}^{MSC(\gamma_{TN})}(\gamma_{T1}/G_{\max})\,\delta(\gamma). \end{aligned} \tag{3.4}$$



(a) Flowchart of BES-FD-FJAMDC.



(b) Finger deactivation process.

Fig. 4. Mode of operation of the BES-FD-FJAMDC scheme.

C. Bandwidth Efficient with Finger Deactivation FJAMDC Scheme

1. Mode of Operation

The BES-FD-FJAMDC scheme represents a generalization of the BES-FD-JAMDC scheme proposed in [18]. Our third proposed scheme allows better processing power efficiency at the cost of a slightly higher transmit power and BER. The aim of the BES-FD-FJAMDC scheme is to combine the least number of diversity branches that give the highest bandwidth efficiency (or equivalently the highest constellation size) while satisfying the instantaneous BER requirement. The mode of operation of the BES-FD-FJAMDC scheme is summarized in a flowchart given in Fig. 4. After the modulation mode n is selected by the mobile, the BES-FD-FJAMDC scheme will start the finger deactivation process summarized in Fig. 4(b). If the combined SNR is smaller than $\gamma_{T n+1}/G_{\max}$ but greater than γ_{T_n} then the mobile selects the minimum number of paths that are needed such that the output SNR remains greater than γ_{T_n} (i.e. turning off the weakest branches while conserving the same modulation mode). The deactivation process is continued until turning off another diversity path leads to an output SNR below γ_{T_n}. After this, the base station reduces its power level such that the selected constellation is still usable. If even the lowest constellation size is not feasible, data is buffered, and there is no transmission for the next time interval. In the particular case of $G_{\max} = 1$, the BES-FD-FJAMDC scheme reduces to the BES-FD-JAMDC scheme.

2. Statistics of the Output SNR Before Power Control

Based on the mode of operation described above and using the expression of the CDF of the combined SNR of the bandwidth efficient and power greedy scheme proposed in [14], we give the expression of the CDF of the combined SNR before power control of the BES-FD-FJAMDC scheme as

$$F_{\Gamma}(x) = \tag{3.5}$$
$$\begin{cases} F_{\gamma_c}^{MSC(\gamma_{T N})}(x), & x \geq \gamma_{T N} \text{ or} \\ & \gamma_{Tn}/G_{\max} \leq x < \gamma_{Tn}; \\ F_{\gamma_c}^{L-MRC}(\gamma_{Tn}) + \int_{\gamma_{Tn}}^{x} \int_{0}^{\gamma_{Tn+1}/G_{\max}-\gamma} p_{\gamma_{1:L},z_1}(\gamma, z)\, dz\, d\gamma & \\ + \sum_{l=2}^{L-1} \int_{0}^{\gamma_{Tn}} \int_{\gamma_{Tn}-y}^{\min[y/(l-1),x-y]} & \\ \int_{0}^{\gamma_{Tn+1}/G_{\max}-y-\gamma} p_{y_l,\gamma_{l:L},z_l}(y,\gamma,z)\, dz\, d\gamma\, dy & \\ + \int_{0}^{\gamma_{Tn}} \int_{\gamma_{Tn}-y}^{\min[y/(L-1),x-y]} p_{y_L,\gamma_{L:L}}(y,\gamma) d\gamma\, dy, & \\ & \gamma_{Tn} \leq x < \gamma_{Tn+1}/G_{\max}; \\ F_{\gamma_c}^{L-MRC}(\gamma_{T1}/G_{\max}), & 0 < x < \gamma_{T1}/G_{\max}, \end{cases}$$

where $F_{\gamma_c}^{L-MRC}(\cdot)$ is the CDF of the combined SNR with L-branch MRC scheme and is given in closed form for i.i.d. Rayleigh fading in [11, Eq. (25)] by

$$F_{\gamma_c}^{L-MRC}(x) = 1 - e^{-(x/\overline{\gamma})} \sum_{l=0}^{L-1} \frac{\left(\frac{x}{\overline{\gamma}}\right)^l}{l!}. \tag{3.6}$$

The closed-form expressions of the joint PDFs $p_{\gamma_{1:L},z_1}(\gamma, z)$ and $p_{y_L,\gamma_{L:L}}(y,\gamma)$ can be easily obtained as marginals of the joint PDF $p_{y_l,\gamma_{l:L},z_l}(y,\gamma,z)$ given in closed-form for i.i.d. Rayleigh fading in [19, Eq. (20)] by

$$\begin{aligned} p_{y_l,\gamma_{l:L},z_l}(y,\gamma,z) &= \frac{L!}{(L-1)!\,(l-1)\,\overline{\gamma}^L} \frac{[y-(l-1)\,\gamma]^{l-2}}{(l-2)!\,(L-l-1)!} e^{-\frac{y+\gamma+z}{\overline{\gamma}}} \mathcal{U}\big(y-(l-1)\gamma\big) \\ &\quad \times \sum_{i=0}^{L-l} \binom{L-l}{i} (-1)^i (z-i\gamma)^{L-l-1} \mathcal{U}\big(z-i\gamma\big), \\ &\quad \gamma > 0,\ y > (l-1)\gamma,\ z < (L-l)\gamma. \end{aligned} \tag{3.7}$$

After differentiating $F_\Gamma(x)$ with respect to x, a generic formula for the PDF of the output SNR with BES-FD-FJAMDC can be found as

$$f_\Gamma(x) = \tag{3.8}$$
$$\begin{cases} f_{\gamma_c}^{MSC(\gamma_{TN})}(x), & x \geq \gamma_{TN} \text{ or} \\ & \gamma_{Tn}/G_{\max} \leq x < \gamma_{Tn}; \\ \int_0^{\gamma_{T\,n+1}/G_{\max}-x} p_{\gamma_{1:L},z_1}(x,z)\,dz & \\ +\sum_{l=2}^{L-1}\left(\int_{\frac{l-1}{l}x}^{\gamma_{Tn}}\int_0^{\gamma_{T\,n+1}/G_{\max}-x} p_{y_l,\gamma_{l:L},z_l}(y,x-y,z)\,dz\,dy\right. & \\ \left.\times\big(\mathcal{U}(x-\gamma_{Tn})-\mathcal{U}(x-\tfrac{l}{l-1}\gamma_{Tn})\big)\right) & \\ +\int_{\frac{L-1}{L}x}^{\gamma_{Tn}} p_{y_L,\gamma_{L:L}}(y,x-y)\,dy & \\ \times\big(\mathcal{U}(x-\gamma_{Tn})-\mathcal{U}(x-\tfrac{L}{L-1}\gamma_{Tn})\big), & \\ & \gamma_{Tn} \leq x < \gamma_{T\,n+1}/G_{\max}; \\ \delta(x)F_{\gamma_c}^{L-MRC}(\gamma_{T1}/G_{\max}), & 0 < x < \gamma_{T1}/G_{\max}. \end{cases}$$

CHAPTER IV

PERFORMANCE ANALYSIS

A. Transmit Power Gain

While in the JAMDC schemes, the transmitter starts sending using its maximal power, in the proposed FJAMDC schemes the transmitter starts sending using its nominal power. Based on this nominal initial power transmitted and on the MS-GSC diversity combining, we assume that we have a combined SNR of Γ and that we reached the constellation size n. The transmitter will then vary its power depending on the value of Γ.

1. Continuous Power Control

The case of continuous power adaptation will allow us to reach exactly the value of γ_{T_n}. If the combined SNR before power control Γ verifies $\gamma_{T_n}/G_{\max} < \Gamma \leq \gamma_{T_n}$ then transmitter will increase its power by γ_{T_n}/Γ. If on the other hand $\gamma_{T_n} < \Gamma \leq \gamma_{T_{n+1}}/G_{\max}$, the transmitter will reduce its power by Γ/γ_{T_n}. In both these cases the transmit power gain is given by $G = \Gamma/\gamma_{T_n}$. Hence, the average transmit power gain, in decibels, $\overline{G}_{\text{dB}}$, is given by

$$\begin{aligned}
\overline{G}_{\text{dB}} &= \sum_{n=1}^{N} \int_{\gamma_{T_n}/G_{\max}}^{\gamma_{T_{n+1}}/G_{\max}} 10 \log_{10}\left(\frac{\gamma_c}{\gamma_{T_n}}\right) f_{\Gamma}(\gamma_c)\, d\gamma_c \\
&= \sum_{n=1}^{N} \int_{\gamma_{T_n}/G_{\max}}^{\gamma_{T_{n+1}}/G_{\max}} 10 \log_{10}(\gamma_c)\; f_{\Gamma}(\gamma_c)\, d\gamma_c \\
&\quad - \sum_{n=1}^{N} 10 \log_{10}(\gamma_{T_n}) \Big(F_{\Gamma}\left(\gamma_{T_{n+1}}/G_{\max}\right) - F_{\Gamma}\left(\gamma_{T_n}/G_{\max}\right) \Big),
\end{aligned} \tag{4.1}$$

where we define $\gamma_{T_{N+1}} = \infty$.

2. Discrete Power Control

Let us start by summarizing the choice of the power parameter β for the discrete power adaptation. For $\gamma_{Tn}/G_{\max} < \Gamma \leq \gamma_{Tn+1}/G_{\max}$, $n \geq 1$, and $-k \leq m \leq M-1$

$$\begin{aligned}
\beta = \beta_{M-1}, &\quad \text{iff} \quad \frac{\Gamma}{\gamma_{Tn}} \geq \beta_{M-1} \\
&\quad\vdots \\
\beta = \beta_{m-1}, &\quad \text{iff} \quad \beta_{m-1} \leq \frac{\Gamma}{\gamma_{Tn}} < \beta_m \\
&\quad\vdots \\
\beta = \beta_0 = 1, &\quad \text{iff} \quad \beta_0 \leq \frac{\Gamma}{\gamma_{Tn}} < \beta_1 \\
&\quad\vdots \\
\beta = \beta_{-m+1}, &\quad \text{iff} \quad \beta_{-m+1} \leq \frac{\Gamma}{\gamma_{Tn}} < \beta_{-m} \\
&\quad\vdots \\
\beta = \beta_{-k} = \frac{1}{G_{\max}}, &\quad \text{iff} \quad \beta_{-k} \leq \frac{\Gamma}{\gamma_{Tn}} < \beta_{-k+1}
\end{aligned} \tag{4.2}$$

The average transmit dB power gain is then given by

$$\begin{aligned}
\overline{G}_{\text{dB}} &= \sum_{n=1}^{N} \int_{\gamma_{Tn}/G_{\max}}^{\gamma_{Tn+1}/G_{\max}} 10 \log_{10}\left(\frac{\gamma_c}{\gamma_c/\beta}\right) f_\Gamma(\gamma_c)\, d\gamma_c \\
&= \sum_{n=1}^{N} \int_{\gamma_{Tn}/G_{\max}}^{\gamma_{Tn+1}/G_{\max}} 10 \log_{10}(\beta)\; f_\Gamma(\gamma_c)\, d\gamma_c \\
&= \sum_{n=1}^{N} \sum_{m=-k}^{M-1} 10 \log_{10}(\beta_m) \Big(F_\Gamma(\gamma_{Tn}\beta_{m+1}) - F_\Gamma(\gamma_{Tn}\beta_m) \Big),
\end{aligned} \tag{4.3}$$

where $\gamma_{Tn}\beta_M = \gamma_{Tn+1}/G_{\max}$.

B. Average Number of Combined Paths

We quantify the power consumption for diversity combining in terms of the average number of combined paths. For the PES-FJAMDC scheme, it can be shown that the average number of combined paths is given by

$$\overline{N}_c = 1 + \sum_{i=1}^{L-1} F_{\gamma_c}^{L/i-\mathrm{GSC}}(\gamma_{T1}) - L F_{\gamma_c}^{L-\mathrm{MRC}}(\gamma_{T1}/G_{\max}), \tag{4.4}$$

where $F_{\gamma_c}^{L/i-GSC}(\cdot)$ is the CDF of the combined SNR with L/i-GSC scheme and is given in closed-form for i.i.d. Rayleigh fading in [20] by

$$F_{\gamma_c}^{L/i-GSC}(\gamma) = 1 - \sum_{l=0}^{i-1} \frac{A_l\, \gamma^l\, e^{-\gamma/\overline{\gamma}}}{\overline{\gamma}^l\, l!} + \sum_{k=1}^{L-i} B_k\, e^{-(1+k/i)\,\gamma/\overline{\gamma}}, \quad \gamma \geq 0, \tag{4.5}$$

where

$$A_l = \sum_{j=0}^{i-l-1} a_{l+j} = a_l + A_{l+1}, \quad \text{with } A_{-1} = 0, \tag{4.6}$$

where

$$a_{i-1-l} = \binom{L}{i} \sum_{k=1}^{L-i} \binom{L-i}{k} \frac{(-1)^{k+l+1}\, i^l}{k^l}, \tag{4.7}$$

and

$$B_k = \frac{i\, b_k}{k+i}, \tag{4.8}$$

where

$$b_k = \binom{L}{i} \binom{L-i}{k} \frac{(-1)^{i+k}\, i^{\,i-1}}{k^{\,i-1}}. \tag{4.9}$$

Using Eqs. (3.6) and (4.5), we obtain the average number of combined paths of the PES-FJAMDC scheme in closed form as

$$\overline{N}_c = \sum_{i=1}^{L-1}\Big[\sum_{k=1}^{L-i} B_k\, e^{-(1+k/i)\,\gamma_{T1}/\overline{\gamma}} - \sum_{l=0}^{i-1}\frac{A_l\,{\gamma_{T1}}^l\, e^{-\gamma_{T1}/\overline{\gamma}}}{\overline{\gamma}^l\, l!}\Big] + L\, e^{-\frac{\gamma_{T1}}{\overline{\gamma}\, G_{\max}}}\sum_{l=0}^{L-1}\frac{\left(\frac{\gamma_{T1}}{\overline{\gamma}\, G_{\max}}\right)^l}{l!} \tag{4.10}$$

Similarly, it can be shown that the average number of combined paths for the BES-FJAMDC scheme is given by

$$\overline{N}_c = 1 + \sum_{i=1}^{L-1} F_{\gamma_c}^{L/i-\mathrm{GSC}}(\gamma_{TN}) - L F_{\gamma_c}^{L-\mathrm{MRC}}(\gamma_{T1}/G_{\max}). \tag{4.11}$$

which is also given in closed form by

$$\overline{N}_c = \sum_{i=1}^{L-1}\Big[\sum_{k=1}^{L-i} B_k\, e^{-(1+k/i)\,\gamma_{TN}/\overline{\gamma}} - \sum_{l=0}^{i-1}\frac{A_l\,{\gamma_{TN}}^l\, e^{-\gamma_{TN}/\overline{\gamma}}}{\overline{\gamma}^l\, l!}\Big] + L\, e^{-\frac{\gamma_{T1}}{\overline{\gamma}\, G_{\max}}}\sum_{l=0}^{L-1}\frac{\left(\frac{\gamma_{T1}}{\overline{\gamma}\, G_{\max}}\right)^l}{l!}. \tag{4.12}$$

The average number of combined paths for the BES-FD-FJAMDC can be calculated as [14, Eq. (24), Option 2]

$$\overline{N}_c = \sum_{l=1}^{L}\sum_{n=1}^{N} l\, P_{l,n}, \tag{4.13}$$

where $P_{l,n}$ denotes the probability that mode n is used with l combined branches.

Based on the mode of operation of the BES-FD-FJAMDC, the expression of $P_{l,n}$ is given, for $n = N$, by

$$
\begin{aligned}
&P_{l,N} \\
&= \begin{cases} 1 - F_{\gamma_c}^{L/1-\mathrm{GSC}}\left(\gamma_{T\,N}/G_{\max}\right), & l = 1; \\ F_{\gamma_c}^{L/(l-1)-\mathrm{GSC}}\left(\gamma_{T\,N}/G_{\max}\right) - F_{\gamma_c}^{L/l-\mathrm{GSC}}\left(\gamma_{T\,N}/G_{\max}\right), & 1 < l \leq L; \end{cases} \qquad (4.14) \\
&= \begin{cases} \sum_{k=1}^{L-1} L \binom{L-1}{k} \frac{(-1)^k}{k+1} e^{-(k+1)\frac{\gamma_{T\,N}}{\overline{\gamma}\,G_{\max}}}, & l = 1; \\ F_{\gamma_c}^{L/(l-1)-\mathrm{GSC}}\left(\gamma_{T\,N}/G_{\max}\right) - F_{\gamma_c}^{L/l-\mathrm{GSC}}\left(\gamma_{T\,N}/G_{\max}\right), & 1 < l \leq L; \end{cases} \qquad (4.15)
\end{aligned}
$$

and for $n < N$ by

$$
\begin{aligned}
&P_{l,n} \qquad (4.16) \\
&= \begin{cases} \Pr\Big[\gamma_{T\,n} \leq \gamma_{1:L} \,\&\, \sum_{j=1}^{L} \gamma_{j:L} < \gamma_{T\,n+1}/G_{\max}\Big], & l = 1; \\ \Pr\Big[\sum_{j=1}^{l-1} \gamma_{j:L} < \gamma_{T\,n} \leq \sum_{j=1}^{l} \gamma_{j:L} \,\&\, \sum_{j=1}^{L} \gamma_{j:L} < \gamma_{T\,n+1}/G_{\max}\Big], & 1 < l < L; \\ \Pr\Big[\sum_{j=1}^{L-1} \gamma_{j:L} < \gamma_{T\,n} \leq \sum_{j=1}^{L} \gamma_{j:L} < \gamma_{T\,n+1}/G_{\max}\Big] & \\ +\Pr\Big[\gamma_{T\,n}/G_{\max} \leq \sum_{j=1}^{L} \gamma_{j:L} < \gamma_{T\,n}\Big], & l = L; \end{cases}
\end{aligned}
$$

Using the same steps and the definitions of the joint PDF's of y_l, $\gamma_{l:L}$, and z_l as in [14], and taking $G_{\max}$ into consideration, (4.16) can be calculated as

$$P_{l,n} = \begin{cases} \int_{\gamma_{T_n}}^{\frac{\gamma_{T_{n+1}}}{G_{\max}}} \int_0^{\frac{\gamma_{T_{n+1}}}{G_{\max}}-\gamma} p_{\gamma_{1:L},z_1}(\gamma,z)\,dz\,d\gamma, & l=1; \\ \int_{\frac{l-1}{l}\gamma_{T_n}}^{\frac{l-1}{l}\frac{\gamma_{T_{n+1}}}{G_{\max}}} \int_{\gamma_{T_n}-y}^{\frac{y}{l-1}} \int_0^{\frac{\gamma_{T_{n+1}}}{G_{\max}}-y-\gamma} p_{y_l,\gamma_{l:L},z_1}(y,\gamma,z)\,dz\,d\gamma\,dy \\ + \int_{\frac{l-1}{l}\frac{\gamma_{T_{n+1}}}{G_{\max}}}^{\gamma_{T_n}} \int_{\gamma_{T_n}-y}^{\frac{\gamma_{T_{n+1}}}{G_{\max}}-y} \int_0^{\frac{\gamma_{T_{n+1}}}{G_{\max}}-y-\gamma} p_{y_l,\gamma_{l:L},z_1}(y,\gamma,z)\,dz\,d\gamma\,dy, & 1<l<L; \\ \int_{\frac{L-1}{L}\gamma_{T_n}}^{\frac{L-1}{L}\frac{\gamma_{T_{n+1}}}{G_{\max}}} \int_{\gamma_{T_n}-y}^{\frac{y}{L-1}} p_{y_L,\gamma_{L:L}}(y,\gamma)\,d\gamma\,dy \\ + \int_{\frac{L-1}{L}\frac{\gamma_{T_{n+1}}}{G_{\max}}}^{\gamma_{T_n}} \int_{\gamma_{T_n}-y}^{\frac{\gamma_{T_{n+1}}}{G_{\max}}-y} p_{y_L,\gamma_{L:L}}(y,\gamma)\,d\gamma\,dy \\ +\Big(F_\Gamma(\gamma_{T_n}) - F_\Gamma(\gamma_{T_n}/G_{\max})\Big), & l=L; \end{cases} \tag{4.17}$$

where $F_\Gamma(\cdot)$ is the CDF of the combined SNR with BES-FD-FJAMDC and it is given in (3.5).

C. Average Spectral Efficiency

A general expression of the average spectral efficiency of an adaptive modulation system is given in [1, Eq. (33)] by

$$\eta = \sum_{i=1}^{N} n\, p_n, \tag{4.18}$$

where p_n denotes the probability that the nth constellation is used. The expression of this probability is given for the PES-FJAMDC scheme by

$$p_n = F_{\gamma_c}^{MSC(\gamma_{T1})}\left(\gamma_{T_{n+1}}/G_{\max}\right) - F_{\gamma_c}^{MSC(\gamma_{T1})}\left(\gamma_{T_n}/G_{\max}\right). \tag{4.19}$$

Using the above expression of p_n and (4.18), we obtain the following expression of the average spectral efficiency of the PES-FJAMDC scheme

$$\eta = N - \sum_{n=1}^{N} F_{\gamma_c}^{MSC(\gamma_{T1})} \left(\gamma_{Tn}/G_{\max}\right). \tag{4.20}$$

Similarly, the expression of p_n for the BES-FJAMDC, which is equal to that of the BES-FD-FJAMDC scheme, can be shown to be given by

$$p_n = F_{\gamma_c}^{MSC(\gamma_{TN})} \left(\gamma_{Tn+1}/G_{\max}\right) - F_{\gamma_c}^{MSC(\gamma_{TN})} \left(\gamma_{Tn}/G_{\max}\right). \tag{4.21}$$

Then the BES-FJAMDC and the BES-FD-FJAMDC schemes have the same spectral efficiency given by

$$\eta = N - \sum_{n=1}^{N} F_{\gamma_c}^{MSC(\gamma_{TN})} \left(\gamma_{Tn}/G_{\max}\right). \tag{4.22}$$

D. Statistics of the Output SNR After Power Control

In order to analyze the bit error rate performance of the three proposed schemes, a statistical characterization of the combined SNR after power control is needed. Based on the mode of operation of the FJAMDC schemes, described in chapter III, we give in what follows the expressions of the PDF and the CDF of the combined SNR after power control for both continuous and discrete adaptations.

1. Continuous Power Control

Assuming that the modulation mode n has been chosen, the combined SNR after continuous power control, Γ', will be set to γ_{Tn}. The expression of the PMF is then given, for $0 \leq n \leq N$, by

$$f_{\Gamma'}(\gamma'_c) = \begin{cases} F_\Gamma(\gamma_{T\,n+1}/G_{\max}) - F_\Gamma(\gamma_{T\,n}/G_{\max}), & \gamma'_c = \gamma_{T\,n}; \\ 0, & \text{otherwise}; \end{cases} \tag{4.23}$$

where we define $\gamma_{T\,0} = 0$, and $\gamma_{T\,N+1} = \infty$.

The expression of the CDF is then given, for $0 \le n \le N$, by

$$F_{\Gamma'}(\gamma'_c) = \begin{cases} F_\Gamma(\gamma_{T\,n+1}/G_{\max}), & \gamma_{T\,n}/G_{\max} \le \gamma'_c < \gamma_{T\,n+1}/G_{\max}; \\ 0, & \gamma'_c < 0; \end{cases} \tag{4.24}$$

2. Discrete Power Control

If the combined SNR before power control falls between $\gamma_{T\,n}/G_{\max}$ and $\gamma_{T\,n+1}/G_{\max}$, then the transmitter will vary its power in order to use the constellation size n with a minimum amount of transmitted power. Starting from the mode of operation of the proposed schemes, constraining on the length of $[\gamma_{T\,n},\ \gamma_{T\,n+1}/G_{\max}]$, and using the same steps as in [17], we give a simplified expression for the PDF of the combined SNR after power control as

$$f_{\Gamma'}(\gamma'_c) = \begin{cases} \sum_{j=-k}^{M-2} \beta_j\, f_\Gamma(\beta_j\, \gamma'_c) \\ +\beta_{M-1}\, f_\Gamma(\beta_{M-1}\, \gamma'_c)\, \mathcal{U}\left(\frac{\gamma_{T\,n+1}}{\beta_{M-1}\, G_{\max}} - \gamma'_c\right), & \gamma_{T\,n} \le \gamma'_c < \gamma_{T\,n}\, \beta_1; \\ \beta_{M-1}\, f_\Gamma(\beta_{M-1}\, \gamma'_c), & \gamma_{T\,n}\, \beta_1 \le \gamma'_c < \frac{\gamma_{T\,n+1}}{\beta_{M-1}\, G_{\max}} \\ & \&\gamma_{T\,n}\, \beta_{M-1}\, G_\delta \le \frac{\gamma_{T\,n+1}}{G_{\max}}; \\ 0, & \text{otherwise}; \end{cases} \tag{4.25}$$

E. Average Error Rate

The general expression of the average BER for an adaptive modulation system is given in [1, Eq. (35)] as

$$\overline{\mathrm{BER}} = \frac{1}{\eta} \sum_{n=1}^{N} n \, \overline{\mathrm{BER}}_n, \tag{4.26}$$

where $\overline{\mathrm{BER}}_n$ is the average BER for constellation size n, and is given, using (2.3), by

$$\overline{\mathrm{BER}}_n = \int_{\gamma_{T\,n}/G_{\max}}^{\gamma_{T\,n+1}/G_{\max}} \mathrm{BER}_n\left(\gamma'\right) \, f_{\Gamma'}\left(\gamma'\right) \, d\gamma'. \tag{4.27}$$

Using Eq. (4.27) in Eq. (4.26), we can write

$$\overline{\mathrm{BER}} = \frac{\sum_{n=1}^{N} n \int_{\gamma_{T\,n}/G_{\max}}^{\gamma_{T\,n+1}/G_{\max}} \mathrm{BER}_n\left(\gamma'\right) \, f_{\Gamma'}\left(\gamma'\right) \, d\gamma'}{\eta}. \tag{4.28}$$

CHAPTER V

NUMERICAL EXAMPLES

The performance of the FJAMDC schemes is illustrated in this chapter with some selected numerical results. For these examples we set the number of available diversity branches $L = 3$, the number of signal constellations $N = 4$, the maximum value of the dB additional gain $G_{\mathrm{maxdB}} = 1\,\mathrm{dB}$, and the bit error rate constraint as $\mathrm{BER}_0 = 10^{-3}$.

In the particular case of $G_{\max} = 1$ (i.e. $G_{\mathrm{maxdB}} = 0$), the performance of our proposed schemes will reduce to that of the JAMDC schemes that we use in this chapter as comparison with the FJAMDC schemes.

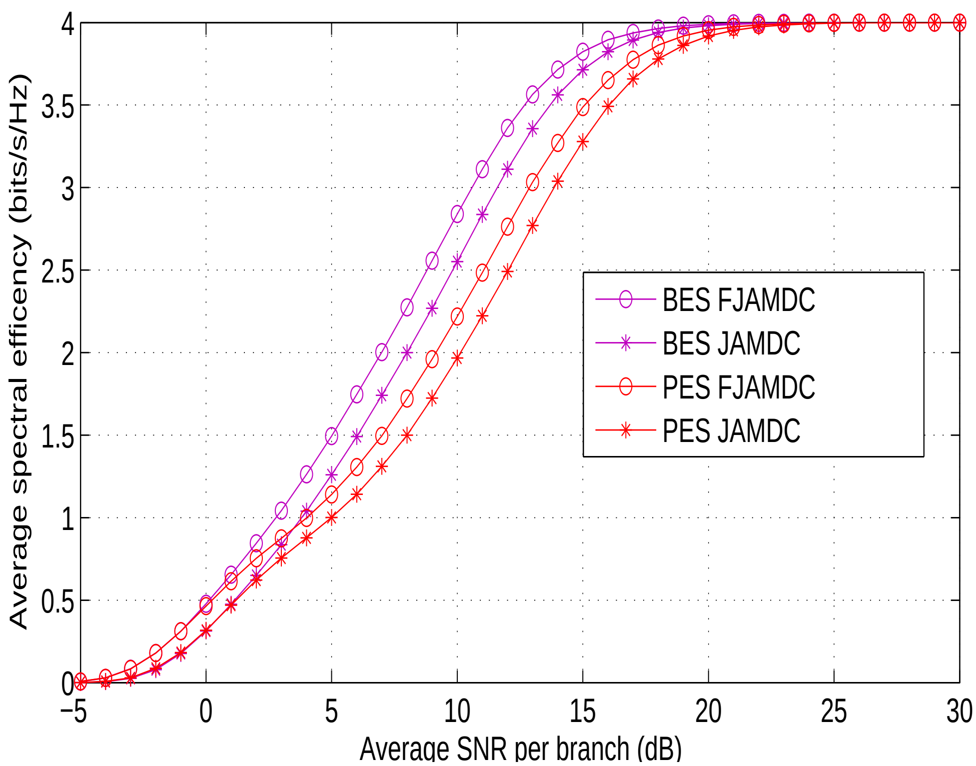


Fig. 5. Average spectral efficiency versus the average SNR per branch, $\overline{\gamma}$, comparison between the JAMDC and FJAMDC schemes.

A. Average Spectral Efficiency and Number of Combined Paths

Fig. 5 illustrates the spectral efficiency improvement that is offered by the the proposed FJAMDC schemes over the JAMDC schemes. This improvement comes at the expense of a higher number of combined paths in the low SNR range as shown in Fig. 6.

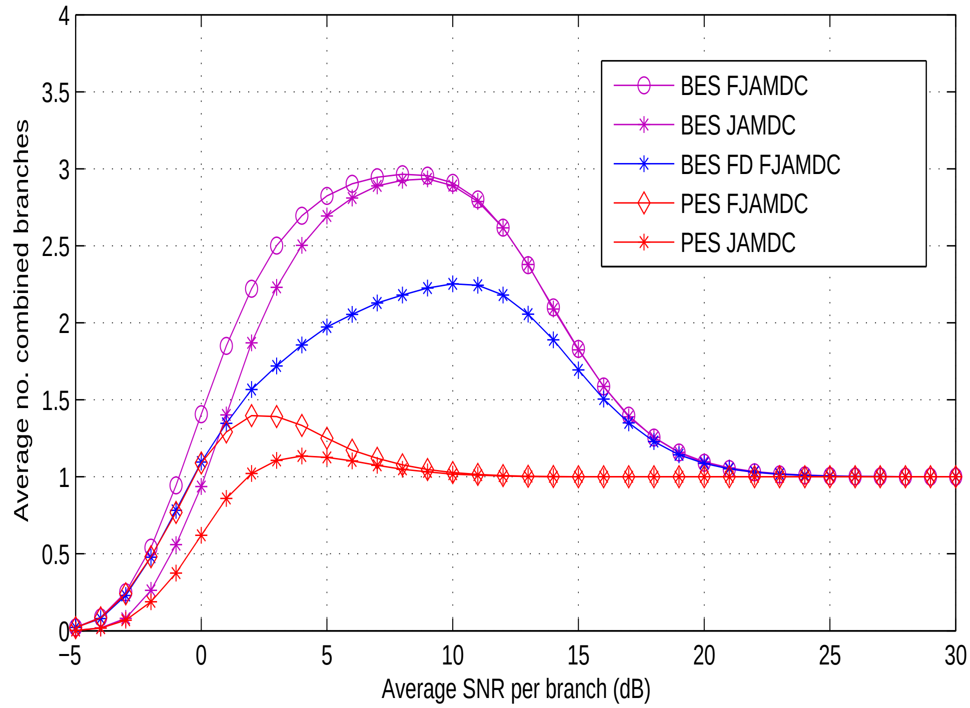


Fig. 6. Average number of combined paths versus the average SNR per branch, $\overline{\gamma}$, comparison between the JAMDC and FJAMDC schemes.

These results are explained by the fact that the transmitter in the JAMDC schemes used to buffer the data whenever the combined SNR does not reach the lowest constellation size after combining all the available L paths, but in the FJAMDC schemes if the combined SNR Γ is lower than γ_{T1} but higher than $\gamma_{T1}/G_{\max}$, the transmitter will send using the lowest constellation size and combining all the L available paths. For an average SNR above 20 dB, we can see that for both JAMDC and FJAMDC schemes one diversity path is enough to utilize the highest constellation size (i.e. $16-$QAM modulation).

We can also see from Fig. 6 that, thanks to the finger deactivation process, the BES-FD-FJAMDC scheme has better processing power performance than the BES-FJAMDC while keeping the same spectral efficiency.

B. Transmit Power Gain

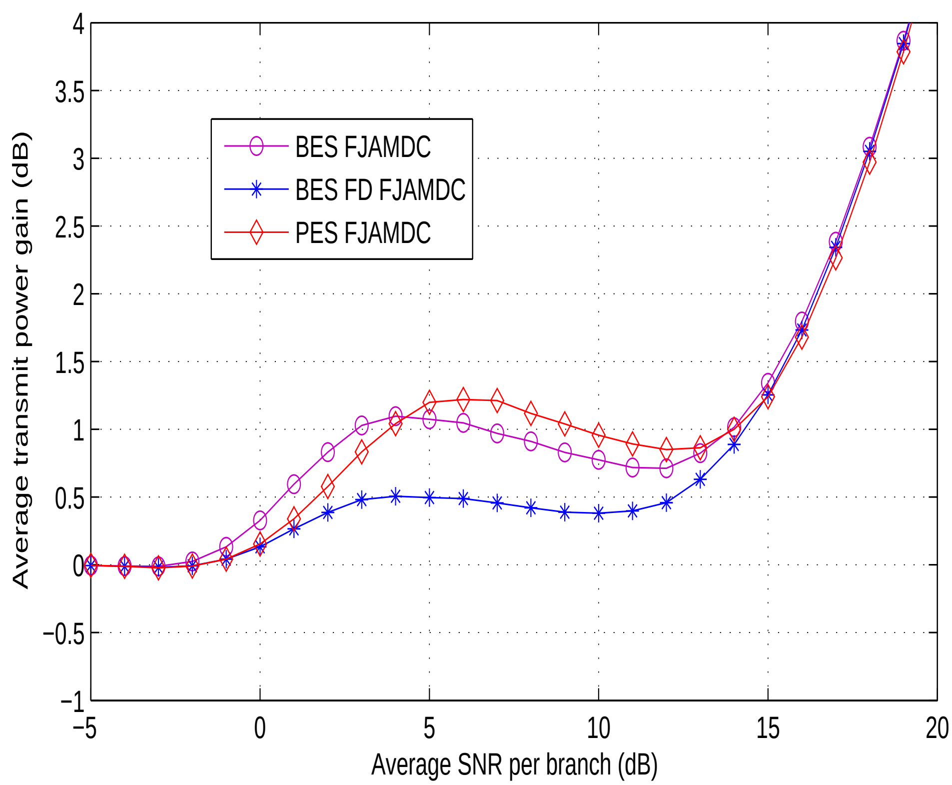


Fig. 7. Average transmit power for continuous adaptation versus the average SNR per branch, $\overline{\gamma}$, for the three proposed schemes.

Fig. 7 compares the average transmitted power gain of our three proposed schemes. We can clearly see from this figure that the BES-FD-FJAMDC scheme has the lowest average transmit dB gain. This is explained by the fact that the finger deactivation process will turn off all the weakest branches while conserving the same modulation mode. We can also see from this figure that for the low SNR range the BES-FJAMDC scheme has higher average transmit gain than the PES-FJAMDC, or equivalently lower average radiated power, since the processing power efficient scheme will stop combining as soon as $\Gamma \geq \gamma_{T1}$ while the BES-FJAMDC continue the combining process allowing to reach higher SNR and higher power gain.

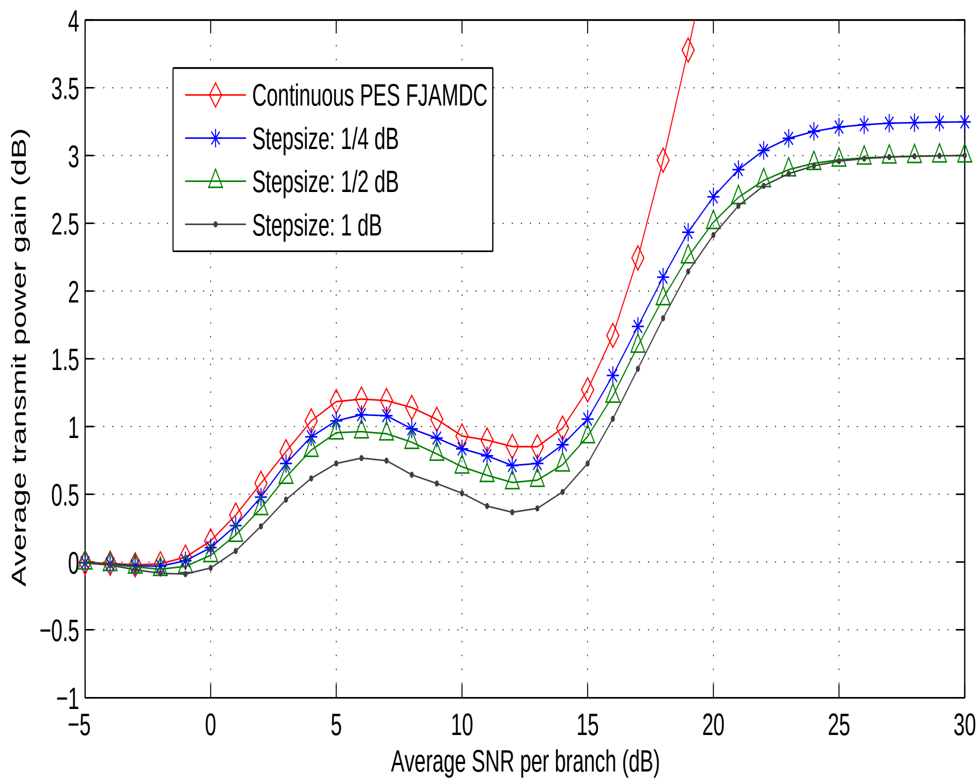


Fig. 8. Average transmit power for the PES-FJAMDC scheme versus the average SNR per branch, $\overline{\gamma}$.

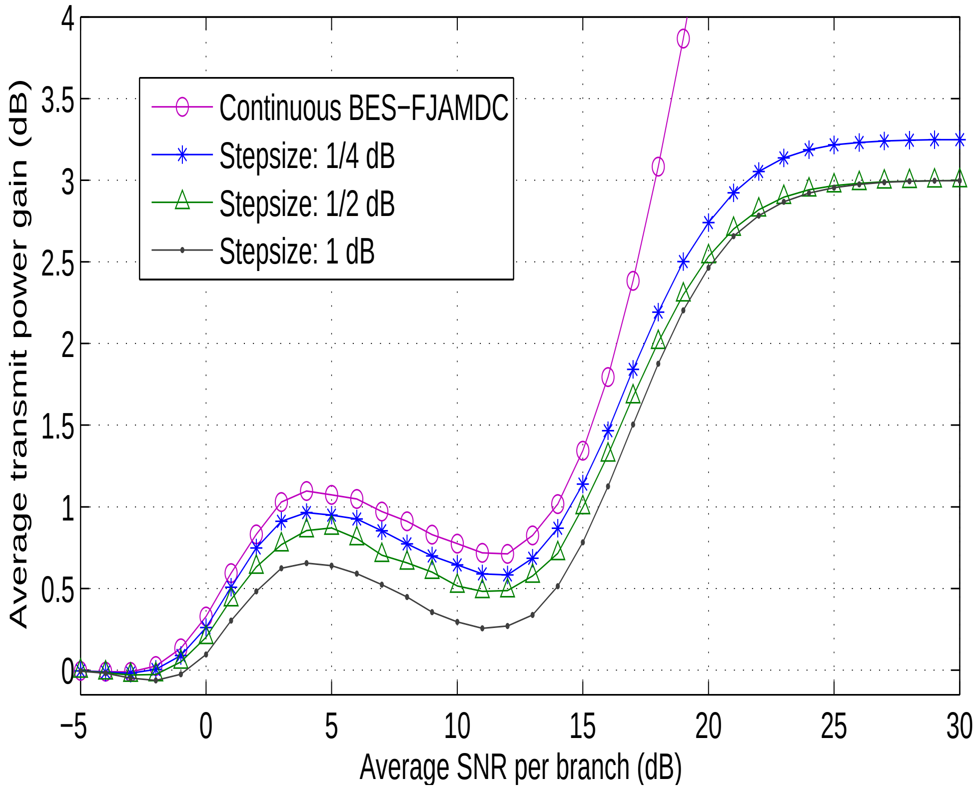


Fig. 9. Average transmit power for the BES-FJAMDC scheme versus the average SNR per branch, $\overline{\gamma}$.

We depict in Figs. 8 and 9 the average transmit power gain versus the average SNR per branch for the PES-FJAMDC and the BES-FJAMDC schemes for both, continuous and discrete adaptations. These figures confirm that the introduction of power control reduces significantly the average radiated power. We also see from these figures that the lower is the power control step size, the higher is the power gain, and then the lower is the average radiated power.

The shape of the graphs in Figs. 8 and 9 can be explained as follows. As seen from Fig. 5, at very low SNR data is buffered, hence no transmit power gain is possible. Increasing the branch SNR up to the intermediate range, we observe a steady increase in transmit power gain. In the intermediate range, we see a slight decrease in the power gain, due to a combination of that i) the increased branch SNRs are used to facilitate larger constellations, and ii) the two intermediate intervals for constellations $n = 2, 3$ are shorter than the interval for $n = 1$, as seen from Table I. At high SNR the maximum reduction for discrete level transmit power control is limited by the length of the shortest interval according to the expression of $M - 1$ given in (2.6) and to the values of the switching thresholds given by Table I. This explains why the average transmit power gain saturates in different values depending on the used power control step size. This is not the case for the continuous power adaptation since for the high SNR range the gain with continuous power control is unbounded.

C. BER Performance

In Fig. 10, we show the BER of the FJAMDC proposed schemes. For reference, we also compare the BER performances of the BES-FJAMDC, the PES-FJAMDC, and the BES-FD-FJAMDC schemes using constant full power.

For continuous power control adaptation, the three proposed schemes have the same BER performance. For this case, the BER is constant and is equal to BER_0, since the combined SNR after continuous power control will be set to the switching threshold corresponding to the used constellation. For discrete power control adaptation, we show that the BES-FJAMDC scheme has slightly better error performance than the PES-FJAMDC scheme. The reason behind this is that in the low SNR range the BES-FJAMDC scheme needs to combine more branches than the PES-FJAMDC. We also show from this figure that the BES-FD-FJAMDC has a slightly higher BER than the two other schemes. The reason behind this is the finger deactivation process which decreases the average number of combined paths while keeping a higher transmitted power.

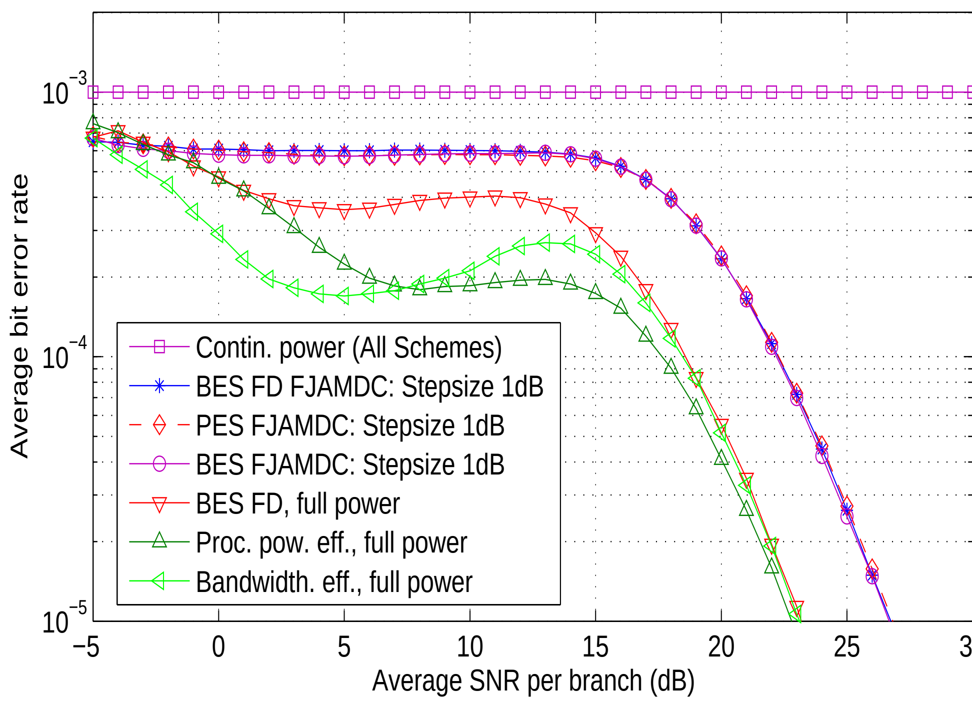


Fig. 10. Average bit error rate versus the average SNR per branch, $\overline{\gamma}$, when $L = 3$, $N = 4$, and with a BER constraint $\text{BER}_0 = 10^{-3}$.

CHAPTER VI

CONCLUSION

Future wireless communication systems, which will provide multimedia services to the power/size limited mobile terminals, are characterized by limited bandwidth and power resources. These systems should be able to support high spectral efficiency with good link reliability. This need for higher bandwidth efficiency motivates further optimization of the use of wireless resources. Due to user mobility and highly time-variant propagation environments, resource management in wireless communications becomes a difficult task. In order to facilitate the management of these resources, adaptive techniques seem to be one of the best solutions. These adaptive solutions include adaptive modulation, adaptive diversity combining, and power control.

Capitalizing on some recently proposed schemes using these three techniques jointly, and in order to have better spectral efficiency, better BER performance, and less radiated power, we offered in this thesis a generalization of the existing schemes by proposing three fully joint adaptive modulation, diversity combining, and power control FJAMDC schemes. These schemes can be viewed as general variants of some existent joint adaptive modulation and diversity combining schemes using post combining power control, by the introduction of a joint power control process that can both increase and decrease the power level.

In this thesis, we gave the modes of operation of the proposed schemes and analyzed their performance in terms of average spectral efficiency, average BER, diversity combining complexity, and transmit power gain and compared this performance to that of the PES-JAMDC and the BES-JAMDC schemes proposed in [17] and the bandwidth-efficient and power-greedy scheme proposed in [14]. Selected numerical examples show that the newly proposed schemes considerably increase the spectral efficiency with a slight increase in the average number of combined path for the low SNR range while maintaining compliance with the BER performance and a low radiated power which leads to a substantial decrease in interference to co-existing systems/users.

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VITA

Zied Bouida received the B.S. degree in electrical engineering from École Supérieure des Communications de Tunis, Tunis, Tunisia, in June 2006. He joined Texas A&M University at Qatar (TAMUQ), Doha, Qatar, for the spring 2006 and the spring 2007 semesters, where he worked on Qatar Telecom (QTEL) projects. He received his Master of Science degree in electrical engineering at Texas A&M University (TAMU), College Station, TX, USA in August 2009. His research interests include wireless communications, diversity techniques, system performance evaluation, and delay-sensitive applications.

Mr. Bouida may be reached at 1100 Hensel Dr. Apt Y1K, College Station, TX 77840. His email is bouidazied@tamu.edu.