Fully Joint Diversity Combining, Adaptive Modulation, and Power Control*

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***Abstract*—Adaptive modulation and diversity combining represent very important adaptive solutions for the future generations of communication systems. In order to improve the performance and the efficiency of wireless communication systems these two techniques have been recently 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 one of these recently proposed JAMDC schemes, we propose and analyze in this paper two 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 jointly determined to achieve the highest spectral efficiency with the lowest possible combining complexity, given the fading channel conditions and the required error rate performance. 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 signal to noise ratio (SNR) range while maintaining compliance with the bit error rate (BER) performance and a low radiated power which yields to a substantial decrease in interference to co-existing systems/users.**

***Index Terms*—Diversity Techniques, Adaptive Modulation, and Power Control.**

I. INTRODUCTION

More and more importance is accorded to adaptive modulation [1], [2], adaptive diversity combining techniques [3], [4], and power control [5], [6]. 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 solution.

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. 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 considerably reduce the radiated power, and thus the potential interference to other systems/users which implies a significant network capacity improvements.

Generalized selection combining (GSC) is one of diversity combining schemes that received a great deal of attention over the last decade (e.g. [7]–[9]). Minimum selection GSC (MS-GSC) was proposed in [3] as a power-saving implementation of GSC. 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], [4], 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 combining schemes were introduced in [10], [11], joint adaptive combining and power control were studied for constant-rate transmission in [12], [13]. In addition, in [14] and for the purpose of interference reduction, Gjendemsjø *et. al.* extended the schemes discussed in [10]–[13] by looking at joint adaptive modulation, diversity combining, and post-combining power control (JAMDC). Capitalizing on this recent work, and in order to have better spectral efficiency, better bit error rate performance, and less radiated power, we propose in this paper two fully joint adaptive modulation, diversity combining, and power control (FJAMDC) schemes, namely (i) a processing power efficient (PES-FJAMDC) scheme and (ii) a bandwidth efficient (BES-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 [14]. Selected numerical examples, obtained by Monte-Carlo simulations and confirmed by analytical results, show

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that both FJAMDC schemes increase the ASE with a slight increase in the average number of combined paths, improve the bit error rate performance, and maintain a low average radiated power.

The remainder of the paper is organized as follows. Section II presents first the system and channel models then gives the details behind the adaptive transmission system, the mode of operation of the proposed schemes, and power control. While section III analyzes the spectral and the processing power performance of the proposed schemes, section IV offers some selected numerical examples illustrating this performance and comparing it to that of the JAMDC schemes. Finally, section V concludes the paper.

II. MODELS AND MODE OF OPERATION

A. System and Channel Model

We consider a generic diversity system with L available diversity paths and we 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, 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) decision on a diversity structure and signal constellation, and (iii) selection of the power to be used for transmission. Once the suitable paths for combining and constellation size are selected and once the appropriate transmitted power is fixed, the combiner and the demodulator (at the receiver end) and the high power amplifier (HPA) and the modulator (at the transmitter) are configured accordingly and these settings are used throughout the subsequent data burst. Under the assumption of frequency flat fading, we use a block-fading model assuming that different diversity paths experience roughly the same fading conditions (or equivalently the same SNR) during the data burst and its preceding guard period. For our study, we assume that the received signal on each diversity branch experiences independent identically distributed (i.i.d.) Rayleigh fading. As such, the faded SNR, denoted by γ_l $(l = 1, 2, \ldots, L)$, follows an exponential distribution, with common probability density function (PDF) and cumulative distribution function (CDF) given by

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

and

$$F_{\gamma_i}(x) = 1 - \exp\left(-\frac{x}{\overline{\gamma}}\right), \quad x \geq 0, \tag{2}$$

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

B. Adaptive Transmission System

We consider the constant-power variable-rate M-ary QAM [1] as an adaptive modulation system 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 $[\gamma_{T\,n}, \gamma_{T\,n+1})$.

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

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

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

$$\gamma_{T\,n} = -\frac{2}{3} \ln(\mathrm{BER}_0)(2^n - 1)\,;\; n = 0, 1, \ldots N. \tag{4}$$

C. Processing-Power Efficient FJAMDC Scheme

The aim of the PES-FJAMDC 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. 1. 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 $\gamma_{T\,1}$ as output threshold. Whenever the combined SNR γ_c is larger than $\gamma_{T\,1}$, the mobile stops combining and determines the highest feasible constellation index n for the given γ_c by comparing the combined SNR to different switching thresholds $\{\gamma_{T\,n}\}_{n=1}^{N}$. If γ_c is greater than $\gamma_{T\,n}$ but smaller than $\gamma_{T\,n+1}/G_{\max}$, where $G_{\max}$ is the transmitter gain saturation, the mobile selects the constellation size n (2^n-QAM) and asks the base station to use the lowest possible power level such that the modulation mode n is still usable. If, on the other hand, γ_c is greater than $\gamma_{T\,n+1}/G_{\max}$ then the base station increases its power till reaching the constellation size $n+1$ (2^{n+1}-QAM). If, even after combining all L paths, the lowest constellation size is not reached (i.e $\gamma_c < \gamma_{T\,1}/G_{\max}$), the base station buffers the data and will not transmit for the next time interval.

D. Bandwidth Efficient FJAMDC Scheme

The BES-FJAMDC 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. The mode of operation of the BES-FJAMDC is summarized in a flowchart given in Fig. 2. In the beginning of each data burst, the base station transmits a training sequence using he 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 $\gamma_{T\,N}$ as output threshold. Whenever the combined SNR is larger than $\gamma_{T\,N}$, 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 $\gamma_{T\,N}$, the mobile determines the highest feasible constellation size. The modulation mode n is selected by the mobile if the combined SNR is smaller than $\gamma_{T\,n+1}/G_{\max}$ but greater than $\gamma_{T\,n}/G_{\max}$. If even the lowest constellation size is not feasible, data is buffered, and there is no transmission for the next time interval.

E. Power Control

In an ideal adaptive power control system, we can assume that the transmitter power can be varied continuously to accurately follow the 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 $G_{\max\mathrm{dB}}$ is a multiple of the power control step size ($G_{\delta\mathrm{dB}}$) (i.e, $G_{\max\mathrm{dB}} = k * G_{\delta\mathrm{dB}}$ 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:
$\{\beta_{-k} = 1/G_{\max} < \beta_{-k+1} < \beta_{-1} < \ldots \beta_0 = 1 < \beta_1 < \ldots < \beta_{M-1}\}$.

If the modulation mode n is selected and the mobile requests the base station to reduce its power then the SNR after continuous power control is reduced to $\gamma_{T\,n}$. For the discrete adaptation the SNR will be reduced by β_i, where β_{M-1} must verify the constraint given in [14] by

$$\beta_{M-1} \leq \min_{1 \leq n \leq N} \frac{\gamma_{T\,n+1}}{\gamma_{T\,n}}. \tag{5}$$

III. PROCESSING POWER AND SPECTRAL ANALYSIS

A. 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

$$\overline{N}_c = 1 + \sum_{i=1}^{L-1} F_{\gamma_c}^{L/i-\mathrm{GSC}}(\gamma_{T\,1}) - L F_{\gamma_c}^{L-\mathrm{MRC}}(\gamma_{T\,1}/G_{\max}), \tag{6}$$

where $F_{\gamma_c}^{L/i-GSC}(.)$ is the CDF of the combined SNR with L/i-GSC scheme (which is given in closed-form for i.i.d. Rayleigh fading as [9, Eq. (24)].) and $F_{\gamma_c}^{L-\mathrm{MRC}}(.)$ is the CDF of the combined SNR with L-branch maximum ratio combining (MRC) scheme (which is given in closed-form for i.i.d. Rayleigh fading as [9, Eq. (25)].)

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

$$\overline{N}_c = 1 + \sum_{i=1}^{L-1} F_{\gamma_c}^{L/i-\mathrm{GSC}}(\gamma_{T\,N}) - L F_{\gamma_c}^{L-\mathrm{MRC}}(\gamma_{T\,1}/G_{\max}), \tag{7}$$

B. Average Spectral Efficiency

The probability that the nth constellation is used for the proposed schemes based on MS-GSC is given by

$$p_n = \begin{cases} F_{\gamma_c}^{MSC(\gamma_{T\,1})}\left(\gamma_{T\,n+1}/G_{\max}\right) - F_{\gamma_c}^{MSC(\gamma_{T\,1})}\left(\gamma_{T\,n}/G_{\max}\right), \\ \mathrm{PES-FJAMDC}; \\ F_{\gamma_c}^{MSC(\gamma_{T\,N})}\left(\gamma_{T\,n+1}/G_{\max}\right) - F_{\gamma_c}^{MSC(\gamma_{T\,N})}\left(\gamma_{T\,n}/G_{\max}\right), \\ \mathrm{BES-FJAMDC}; \end{cases} \tag{8}$$

where $F_{\gamma_c}^{MSC(\gamma_{T\,1})}(.)$ and $F_{\gamma_c}^{MSC(\gamma_{T\,N})}(.)$ denote the CDF's of the combined SNR with L-branch MS-GSC and using $\gamma_{T\,1}$ and $\gamma_{T\,N}$ as output thresholds, respectively, and which are given for the i.i.d. Rayleigh fading environment in [4, Eq. (24)].

Using the above expressions of p_n and [1, Eq. (33)] we obtain the following expressions of the average spectral efficiency of both proposed schemes

$$\eta = \begin{cases} N - \sum_{n=1}^{N} F_{\gamma_c}^{MSC(\gamma_{T\,1})}\left(\gamma_{T\,n}/G_{\max}\right), \mathrm{PES-FJAMDC}; \\ N - \sum_{n=1}^{N} F_{\gamma_c}^{MSC(\gamma_{T\,N})}\left(\gamma_{T\,n}/G_{\max}\right), \mathrm{BES-FJAMDC}; \end{cases} \tag{9}$$

In the particular case of $G_{\max} = 1$, the spectral and the processing power performance of the FJAMDC schemes studied in this section reduces to the performance of the JAMDC schemes given by Yang *et. al.* in [11].

IV. NUMERICAL EXAMPLES

The performance of the FJAMDC schemes is illustrated in this section 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 $G_{\max dB} = 1\,\mathrm{dB}$, and the bit error rate constraint as $BER_0 = 10^{-3}$.

Fig. 3 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. 4. 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 is higher than $\gamma_{T\,1}/G_{\max}$ the transmitter will transmit 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).

Fig. 5 compares the average transmitted power gain for BES-JAMDC and BES-FJAMDC for different values of $G_{\max\mathrm{dB}}$. We can see from this figure that when we set $G_{\max\mathrm{dB}} = 0\,\mathrm{dB}$ the FJAMDC schemes reduce to the case of JAMDC schemes. When $G_{\max\mathrm{dB}}$ increases we obtain lower average transmit power gain, or equivalently higher average radiated power. The negative values of the gain are explained by the fact that the transmitter is sending with a higher level than its nominal power.

In Figs. 6 and 7, we depict 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. We can see from these figures that reducing the power control step size reduces the average radiated power by increasing the power gain. According to the constraint given in (5), the maximum reduction for discrete level transmit power control is limited by the length of the shortest interval. This explains why the average transmit power gain saturates in different values depending on the used power control step size.

In Fig. 8 we show the bit error performance of the proposed schemes. For continuous power control adaptation both 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. For reference, we also compare the BER performances of the BES-FJAMDC and the PES-FJAMDC schemes using constant full power.

V. CONCLUSION

We have proposed in this paper, two new schemes using a fully joint adaptive modulation, diversity combining, and downlink power control. These schemes can be viewed as a general variant of the existent JAMDC schemes by the introduction of a joint power control process that can both increase and decrease the power level. 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 yields to a substantial decrease in interference to co-existing systems/users.

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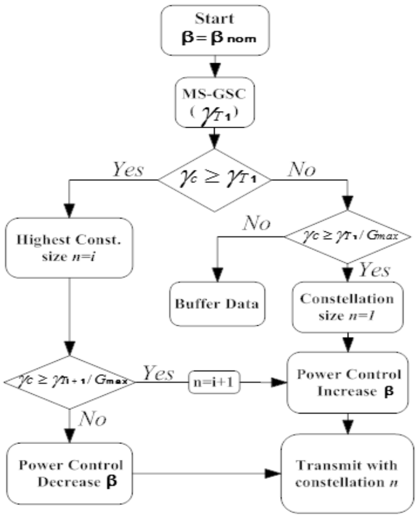

Fig. 1. Mode of operation of the PES-FJAMDC scheme.

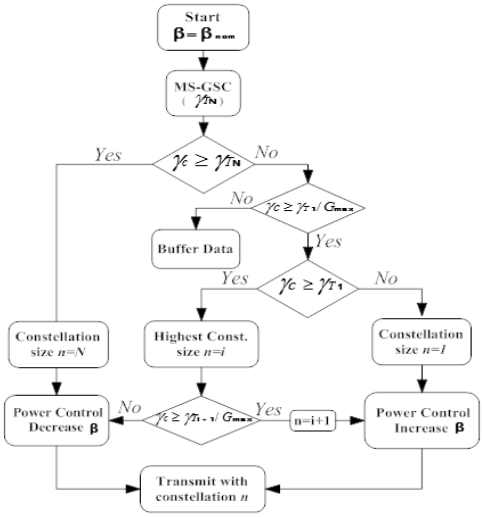

Fig. 2. Mode of operation of the BES-FJAMDC scheme.

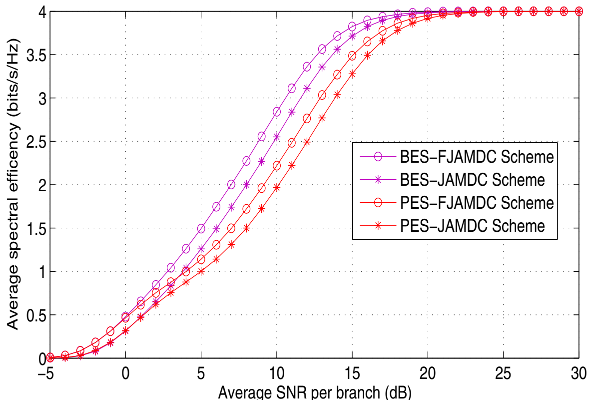

Fig. 3. Average spectral efficiency versus the average SNR per branch, $\overline{\gamma}$, comparison between the JAMDC and FJAMDC schemes.

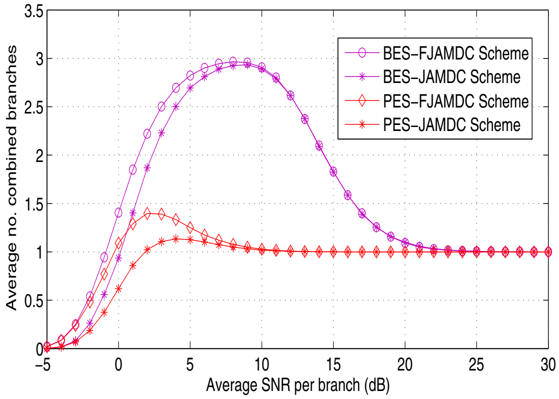

Fig. 4. Average number of combined paths versus the average SNR per branch, $\overline{\gamma}$, comparison between the JAMDC and FJAMDC schemes.

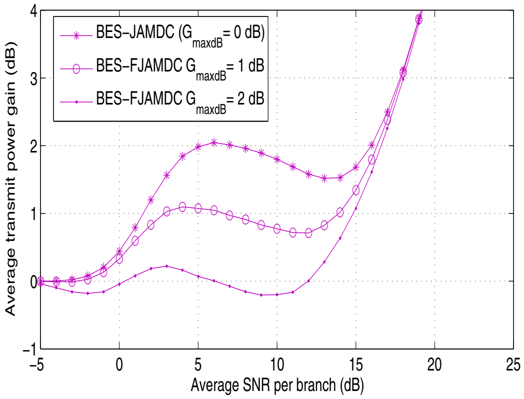

Fig. 5. Average transmit power for continuous adaptation versus the average SNR per branch, $\overline{\gamma}$, with BES-JAMDC and BES-FJAMDC for different $G_{\max\mathrm{dB}}$.

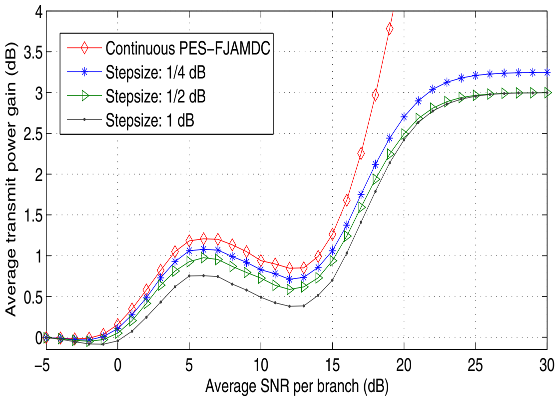

Fig. 6. Average transmit power for the PES-FJAMDC scheme versus the average SNR per branch.

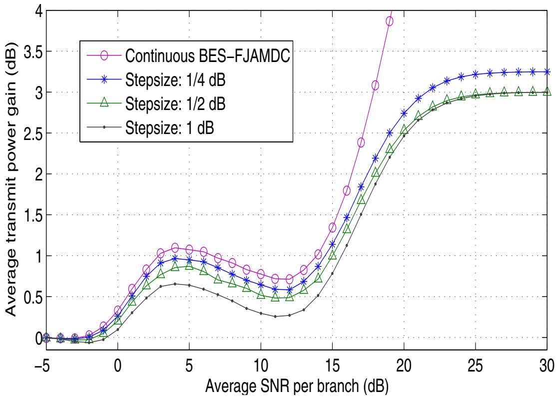

Fig. 7. Average transmit power for the BES-FJAMDC scheme versus the average SNR per branch, $\overline{\gamma}$.

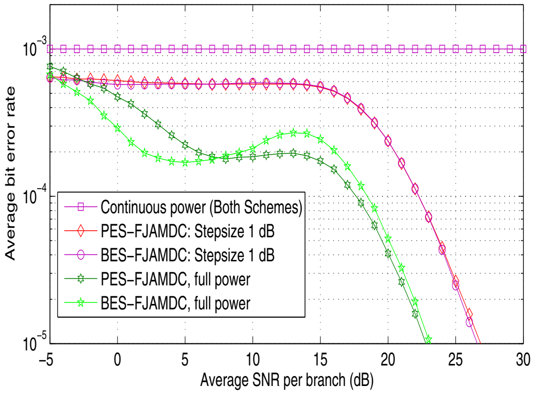

Fig. 8. Average bit error rate versus the average SNR per branch, $\overline{\gamma}$, with PES-FJAMDC and BES-FJAMDC when $L = 3$, $N = 4$, and a BER constraint $BER_0 = 10^{-3}$.