Impact of Receiver Interference Cancellation Techniques on the Base Station Power Consumption in MIMO Systems with Inter-Cell Interference

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***Abstract*—In this paper, we investigate the impact of receiver interference cancellation (IC) techniques on the base station (BS) downlink transmission power for a multiple-input multiple-output (MIMO) communication system with inter-cell interference. Besides the power amplifier module whose power consumption is determined by the required transmission power, we also consider the signal processing module when characterizing the total power consumption of the BS. Rather than specifying absolute values, we define the power consumption of the signal processing module as a proportion of the power consumption of the power amplifier module. We investigate the influence of both the signal processing module and receiver IC techniques on the total power consumption of the BS. Results show that besides receiver IC techniques, the power consumed at the signal processing module should not be overlooked when evaluating the BS total power consumption. Particularly, when the power consumption of the signal processing module becomes too dominant, it may contribute more to the increase of the BS total power consumption as compared to the additional power needed by the power amplifier module to combat inter-cell interference. Furthermore, any transmission power savings that are potentially obtained from receive diversity gain and receiver IC techniques may not be justified if the signal processing consumes too much power relative to that of the power amplifier.**

***Index Terms* – energy efficiency, inter-cell interference, interference cancellation, MIMO.**

I. Introduction

The reduction of BS power consumption is very important for the next generation communication networks in an effort to reduce the global carbon footprint which stands at 245 megatonnes of carbon dioxide equivalent (Mt CO_2e) in 2009, a rise of 155 Mt CO_2e since 2002 [1]. It was reported in [1] that BSs consume the most operational power, typically around 60% of the total network infrastructure power.

MIMO communication system is being considered in emerging wireless communication standards such as the Long Term Evolution Advanced (LTE-A) to reduce BS power consumption during signal transmission. However, MIMO suffers from complex signal processing, making practical implementation a challenge. The development of the Vertical Bell Laboratories Space-Time (V-BLAST) receiver structure [2] provides a good tradeoff between performance and complexity. Since then, with the move to LTE-A, research has been predominantly focused on further improving the receiver interference cancellation and signal detection capabilities to better balance data rate and complexity [3]–[5].

Efforts in reducing BS transmission energy are usually focused on transmission side techniques. Examples here include power allocation [7], beamforming [8], rate allocation [9] and antenna selection techniques [10]. In [11], the authors proposed a transmission mode switching scheme that switches between single-input multiple-output (SIMO) and MIMO modes to save energy. In [12], a channel estimation scheme was proposed to minimize both the transmitter and receiver energy consumption. In [13], the energy efficiency of random network coding for LTE-A networks was examined while several green radio techniques to reduce BS power consumption were proposed in [14]. However, little work has been presented to address the impact of receiver IC techniques on the BS power consumption under inter-cell interference. Examples for the BS power consumption model can be found in [15] and [16].

The following are our contributions. We will analyse the contribution of different types of receiver IC techniques on the transmission power of the BS in MIMO systems with inter-cell interference. The zero forcing (ZF) and the minimum mean square error (MMSE) weight optimization approaches for the conventional and successive interference cancellation (SIC) receivers are considered. The power consumption of the signal processing module will also be taken into account when evaluating the BS total power consumption as it is well known that MIMO circuits require a substantial amount of power to operate and may exceed the transmission power savings obtained from implementing the receiver IC techniques.

II. System Model

Let us consider a MIMO communication system consisting of a BS with M transmit antennas communicating to a receiver with N receive antennas. We label this BS as BS^A to differentiate it from other BSs. All the M transmit antennas are assumed to transmit at an equal rate. Furthermore, let us assume there are I adjacent BSs and the receiver is within their transmission range. The ith adjacent BS, BS^i, has L_i transmit antennas. Therefore, assuming a full spatial multiplexing system, the complex signal vector received by the N receive antennas at a particular time under the uncorrelated

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Rayleigh flat fading channel condition can be written as

$$\mathbf{y} = \sum_{m=1}^{M} \mathbf{h}_m^A s_m + \sum_{i=1}^{I} \sum_{l=1}^{L_i} \mathbf{h}_l^i x_l^i + \mathbf{z}. \quad (1)$$

Here, $\mathbf{h}_m^A = \left(h_{1,m}^A, \cdots, h_{N,m}^A\right)^{\mathrm{T}}$ is the channel vector from the mth $(m = 1, \cdots, M)$ transmit antenna of BS^A to the receiver with $(\cdot)^{\mathrm{T}}$ denoting the transpose operator. The complex coefficient $h_{n,m}^A$ in $\mathbf{h}_m^A$ is a complex random variable, the absolute value of which follows a Rayleigh distribution, and represents the complex channel coefficient from the mth transmit antenna of BS^A to the nth $(n = 1, \cdots, N)$ receive antenna. The complex symbols to be transmitted at time t from BS^A and BS^i are denoted by s_m and x_l, respectively. The second term in (1) is the additive interference contributed by the I adjacent BSs with $\mathbf{h}_l^i = \left(h_{1,l}^i, \cdots, h_{N,l}^i\right)^{\mathrm{T}}$ being the channel vector from the lth transmit antenna of BS^i to the receiver. Furthermore, the vector $\mathbf{z} = (z_1, \cdots, z_N)^{\mathrm{T}}$ represents the noise present at the receiver with its elements being independent and identically distributed (i.i.d.) complex additive white Gaussian noise (AWGN) random variables having zero mean and variance σ^2. The average power of the mth transmitted symbol of BS^A is given by $\mathrm{E}\{s_m s_m^*\} = p_m^A$. Here, $\mathrm{E}\{\cdot\}$ and $(\cdot)^*$ represent the statistical average and conjugate operators, respectively.

A. The Conventional Linear Receiver

In a conventional (Conv.) linear receiver structure, the estimated symbol from the mth transmit antenna of BS^A is given by $\hat{s}_m = \mathbf{w}_m^{\mathrm{H}} \mathbf{y}$, whereby $\mathbf{w}_m = (w_{1,m}, \cdots, w_{N,m})^{\mathrm{T}}$ is the complex weight vector for the mth symbol and $(\cdot)^{\mathrm{H}}$ is the Hermitian transpose operator. Substituting (1) for $\mathbf{y}$, we have the following expression

$$\hat{s}_m = \underbrace{\mathbf{w}_m^{\mathrm{H}} \mathbf{h}_m^A s_m}_{\text{desired signal}} + \underbrace{\sum_{j \neq m}^{M} \mathbf{w}_m^{\mathrm{H}} \mathbf{h}_j^A s_j}_{\substack{\text{intra}-\text{cell} \\ \text{interference}}} + \underbrace{\sum_{i=1}^{I} \sum_{l=1}^{L_i} \mathbf{w}_m^{\mathrm{H}} \mathbf{h}_l^i x_l^i}_{\text{inter}-\text{cell interference}} + \underbrace{\mathbf{w}_m^{\mathrm{H}} \mathbf{z}}_{\text{noise}}. \quad (2)$$

The intra-cell interference refers only to the interference from different antennas of the desired BS, BS^A, while the inter-cell interference is the interference from the I adjacent BSs. The signal-to-interference-plus-noise ratio (SINR) at the output of the receiver for the mth symbol can be expressed as

$$\mathrm{SINR}_m = \left|\mathbf{w}_m^{\mathrm{H}} \mathbf{h}_m^A\right|^2 p_m^A \Bigg/ \left(\sum_{j \neq m}^{M} \left|\mathbf{w}_m^{\mathrm{H}} \mathbf{h}_j^A\right|^2 p_j^A + \sum_{i=1}^{I} \sum_{l=1}^{L_i} \left|\mathbf{w}_m^{\mathrm{H}} \mathbf{h}_l^i\right|^2 p_l^i + \sigma^2 \|\mathbf{w}_m\|^2 \right) \quad (3)$$

where $\|\cdot\|$ is the Euclidean norm operator while p_j^A $(j = 1, \cdots, M)$ and p_l^i $(l = 1, \cdots, L_i)$ are the symbol power transmitted from the jth and lth antennas of BS^A and BS^i, respectively. Since there is no channel state information (CSI) available at the transmit side, equal power allocation is assumed at all transmit antennas of the BSs, i.e., $p_1^A \cdots p_M^A = p_{\mathrm{Conv}}^A$ and $p_1^i \cdots p_{L_i}^i = p^i$. Thus, p_{Conv}^A represents the radio frequency (RF) power per antenna allocated to each symbol transmitted from BS^A for a conventional linear receiver. Furthermore, we consider two weight optimization approaches [6] to calculate $\mathbf{w}_m$ at the receiver. Let $\mathbf{H} = \left(\mathbf{h}_1^A, \cdots, \mathbf{h}_M^A\right)$. In the ZF weight optimization approach, the weights are

$$\mathbf{W}_{\mathrm{ZF}} = (\mathbf{w}_1, \cdots, \mathbf{w}_M) = \left(\mathbf{H}\mathbf{H}^{\mathrm{H}}\right)^{-1} \mathbf{H} \quad (4)$$

while in the MMSE weight optimization approach, the weights are given as

$$\mathbf{W}_{\mathrm{MMSE}} = (\mathbf{w}_1, \cdots, \mathbf{w}_M) = \left(\mathbf{H}\mathbf{H}^{\mathrm{H}} + \sigma^2 \mathbf{I}_N\right)^{-1} \mathbf{H} \quad (5)$$

where $(\cdot)^{-1}$ is the inverse operator and $\mathbf{I}_M$ is an identity matrix of size $M \times M$. Depending on the weight optimization approach, we have the ZF-Conv and the MMSE-Conv receivers being considered here. Correspondingly, p_{Conv}^A can be further classified to $p_{\mathrm{ZF-Conv}}^A$ and $p_{\mathrm{MMSE-Conv}}^A$ depending on whether the ZF-Conv or MMSE-Conv receiver is being considered. The $p_{\mathrm{ZF-Conv}}^A$ and $p_{\mathrm{MMSE-Conv}}^A$ values are calculated by averaging them over a large number of channel realizations for a specified SINR and interference power, p^i. Their values will then be used to calculate the power consumption of the power amplifier in the later section of this paper. From (2), we observe that N multiplications and N additions followed by one decision operation are required to estimate each symbol in the conventional linear receiver. Therefore, the processing complexity and hardware requirements at the receiver scale with N.

B. The SIC Receiver

In a SIC receiver, which is utilized in V-BLAST, the intra-cell interference is reconstructed from previous detected symbols transmitted from BS^A and subtracted from the received signal vector to improve detection of the current symbol. We assume a SIC receiver without optimal sorting for simplicity, i.e., the symbols are detected in the same order as they were transmitted. Therefore, the SINR for the mth symbol can be written as

$$\mathrm{SINR}_m = \left|\mathbf{w}_m^{\mathrm{H}} \mathbf{h}_m^A\right|^2 p_m^A \Bigg/ \left(\sum_{j=1}^{m-1} \left|\mathbf{w}_m^{\mathrm{H}} \mathbf{h}_j^A\right|^2 p_j^A e_j^A + \sum_{j=m+1}^{M} \left|\mathbf{w}_m^{\mathrm{H}} \mathbf{h}_j^A\right|^2 p_j^A + \sum_{i=1}^{I} \sum_{l=1}^{L_i} \left|\mathbf{w}_m^{\mathrm{H}} \mathbf{h}_l^i\right|^2 p_l^i + \sigma^2 \|\mathbf{w}_m\|^2 \right) \quad (6)$$

where $e_j^A = \beta_j \mathrm{E}\left\{|s_j - \tilde{s}_j|^2\right\}$ and β_j is the detection error probability of the jth symbol. Likewise, equal power allocation is assumed at all transmit antennas of the BSs, i.e., $p_1^A \cdots p_M^A = p_{\mathrm{SIC}}^A$ and $p_1^i \cdots p_{L_i}^i = p^i$. The ZF and MMSE weight optimization approaches are also considered here.

Therefore, depending on the weight optimization approach, we have the ZF-SIC and MMSE-SIC receivers. Correspondingly, p^A_{SIC} can be further classified to $p^A_{\mathrm{ZF-SIC}}$ and $p^A_{\mathrm{MMSE-SIC}}$ depending on whether the ZF-SIC or MMSE-SIC receiver is being considered. Similarly, the $p^A_{\mathrm{ZF-SIC}}$ and $p^A_{\mathrm{MMSE-SIC}}$ values are calculated by averaging them over a large number of channel realizations for a specified SINR and interference power, p^i and will be used to calculate the power consumption of the power amplifier in the later section of this paper. Similar to the linear conventional receiver, N multiplications and N additions followed by one decision operation are required to estimate each symbol. However, the SIC receiver further requires the reconstruction of the received signal due to the estimated symbol and subtracting it from the original composite received signal in (1). This additional step requires another N multiplication and N additions followed by N subtractions. Therefore, the processing complexity of the SIC receiver is more than twice that of the linear conventional receiver. Both the processing complexity and hardware requirements of the SIC receiver also scale with N.

III. BS Power Consumption Model

In this work, we focus only on the BS power consumption as it was shown in [14] that the CO_2 emission due to operational energy consumption of the BS components is at 68% of its total CO_2 emission while the mobile handset stood at 24%. Furthermore, the typical size of the mobile handset will put an upper limit on the number of receive antennas, N, that can be practically installed. Since the receiver processing complexity and hardware requirements scale with N, the power consumption of the mobile handset will also be limited by the number of receive antennas that can be practically installed.

We are interested in the impact of different receiver IC techniques on the BS total power consumption at different power consumption ratios between the signal processing and power amplifier modules. The signal processing module consists of circuits for the digital to analogue converter, mixer, baseband digital signal processor, and so on. Each transmit antenna is assumed to be attached to a signal processing module and a power amplifier module. Let the power consumption per antenna of the power amplifier module be given as

$$P_{\mathrm{amp}} = \frac{P_{\mathrm{RF}}}{\eta} \tag{7}$$

where P_{RF} is the required transmitted symbol power per antenna corresponding to a particular receiver IC technique to obtain the same receiver output SINR. For example, $P_{\mathrm{RF}} = p^A_{\mathrm{MMSE-SIC}}$ if a SIC receiver with MMSE weight optimization approach is considered. The efficiency of the power amplifier is η. Thus, the total power consumption of the power amplifier module for M transmit antennas is

$$P^{\mathrm{Total}}_{\mathrm{amp}} = P_{\mathrm{amp}} \cdot M. \tag{8}$$

Furthermore, we are interested in the power consumption of the signal processing module as a proportion of the power amplifier module. This is to evaluate the impact of the MIMO circuit power consumption on the transmit power savings potentially obtained from implementing the receiver IC techniques described here. We choose the 4×4 MIMO configuration as the reference system. The power consumption per antenna for the signal processing module is calculated as a proportion, α, of the power consumption per antenna for the power amplifier module of the reference system, i.e.,

$$P_{\mathrm{sp}} = \alpha P^{4\times4}_{\mathrm{amp}} = \alpha \frac{P^{4\times4}_{\mathrm{RF}}}{\eta}. \tag{9}$$

Therefore, the total power consumption of the signal processing module for M transmit antennas is

$$P^{\mathrm{Total}}_{\mathrm{sp}} = P_{\mathrm{sp}} \cdot M. \tag{10}$$

Thus, by combining (7)–(10), the BS total power consumption is written as

$$P_{\mathrm{Total}} = P^{\mathrm{Total}}_{\mathrm{amp}} + P^{\mathrm{Total}}_{\mathrm{sp}} = \frac{M}{\eta}\left(P_{\mathrm{RF}} + \alpha P^{4\times4}_{\mathrm{RF}}\right). \tag{11}$$

The BS total power consumption model derived in (11) is similar to the existing models, e.g. [15] and [16]. In these models, the total power consumption is usually represented by the summation of two terms. The first term is related to the RF power being transmitted and it scales with a certain quantity of interest. In our case, it scales with the number of transmit antennas and is represented by $P^{\mathrm{Total}}_{\mathrm{amp}}$ in (11). The second term of these existing models is related to the constant power being consumed by the BS. This is represented by $P^{\mathrm{Total}}_{\mathrm{sp}}$ in (11). In [15], the authors defined $P^{\mathrm{Total}}_{\mathrm{sp}} = 412\mathrm{W}$ for a macro site with $P^{\mathrm{Total}}_{\mathrm{amp}}$ taking values of 226W, 452W and 904W. In [16], examples were given for a Global System for Mobile Communications (GSM) macro site with $P^{\mathrm{Total}}_{\mathrm{sp}} = 54.8\mathrm{W}$ and $P^{\mathrm{Total}}_{\mathrm{amp}} = 114\mathrm{W}$ and for a Universal Mobile Telecommunications System (UMTS) macro site with $P^{\mathrm{Total}}_{\mathrm{sp}} = 73.5\mathrm{W}$ and $P^{\mathrm{Total}}_{\mathrm{amp}} = 267\mathrm{W}$.

IV. Simulation Results and Analysis

Monte Carlo simulations were carried out and the average results of 50,000 runs were used to calculate the required transmission power in BS^A. We assume the Rayleigh flat fading channel model and the receiver knows only the CSI between BS^A and itself, utilizing it to compute the ZF and MMSE weight vectors. Furthermore, perfect detection of previous symbols is assumed in the SIC based receivers, i.e., $e^A_j = 0$. Practically, the probability of correct detection can be increased with the help of channel coding. In the following figures, adj-BS denotes an adjacent BS transmitting at RF power of 0.1W per antenna, thus, acting as an intercell interferer to the receiver. We assume the noise variance, $\sigma^2 = 1$ and the receiver output SINR is fixed at 6 dB for each symbol.

The total power consumption of BS^A with different receiver IC techniques is shown in Fig. 1 for different number of receive antennas. Here, we consider the ideal case where there is no power consumption at the signal processing module and the total power consumption at the BS is solely due to the power amplifier module ($\alpha = 0$). It is observed that the required transmission power decreases as the number of receive antennas at all the four types of receivers increases. More receive antennas improves receive diversity as the received signal power can be optimally summed over a larger set of receive antennas, thus requiring less transmission power to achieve the targeted SINR. For a smaller number of receive antennas, the MMSE based receivers require less transmission power than the ZF based receivers for the targeted SINR. While completely removing the intra-cell interference, the weights of the ZF based receivers will greatly amplify the inter-cell interference and noise of the received signal. On the other hand, the MMSE based receivers have their weights designed to jointly minimise the effect of both the intra-cell interference and noise, effectively achieving the targeted SINR at a lower transmission power by reducing the severe amplification of the undesired components in the received signal. For a large number of receive antennas, the choice of receiver IC technique has no impact on the transmission power. We note that the total number of receive antennas differs from one device to another. Here, we simulated a large number of receive antennas solely to demonstrate the power consumption trend. Without considering the signal processing module, we also observe that for a given receiver IC technique, more transmission power is needed if the number of adjacent BS increases. This is because adjacent BSs increase interference additively by a given factor and thus the transmission power has to be increased by an equal factor in order to maintain the same SINR.

In Fig. 2, the total power consumption of BS^A with different receiver IC techniques is again illustrated for different number of receive antennas. This time, the signal processing module operating at low power consumption relative to that of the power amplifier ($\alpha = 0.1$) is considered. It is observed that while receive diversity gain still contributes to the BS total power reduction as the number of receive antennas in the MMSE based receivers increases, the same advantage is not seen for the ZF based receivers. Specifically, there is no further reduction in the BS total power consumption at $N > 8$ as the power consumption of the signal processing module cancels out the transmission power savings achieved through the ZF based receivers.

In order to further understand the impact of the signal processing module on the BS total power consumption, we take the MMSE-SIC receiver as a case study since it delivers the most power savings among the receivers. Thus, Fig. 3 depicts the power consumption of the signal processing module and the power amplifier module of BS^A at various α values when considering the MMSE-SIC receiver in the presence of inter-cell interference. It is observed that the power consumption of the signal processing module at $\alpha > 1$ is always higher than that of the power amplifier. Therefore, any power savings obtained through the combined use of MMSE-SIC technique and MIMO is very limited due to the high power consumption of the signal processing module. On the other hand, if $\alpha < 1$, there will be a certain number of receive antennas where the power consumption of both modules are equal, after which the power consumption of the signal processing module will once again dominate that of the power amplifier module. For example, in Fig. 3 when $\alpha = 0.25$, that number of receive antennas is $N = 14$.

In Fig. 4, the total power consumption of BS^A at various α values is illustrated for different number of receive antennas of the MMSE-SIC receiver. The ideal case where there is no power consumption for the signal processing module is shown when $\alpha = 0$. When α increases, it is observed that increasing the number of receive antennas no longer reduces the BS total power consumption. It is also observed that the BS total power consumption without inter-cell interference but with dominant P_{sp} (e.g., $\alpha = 4$) may even exceed that of the case with inter-cell interference but with lower P_{sp} (e.g., $\alpha = 0.25$). This shows that the power consumed at the signal processing module may have a significant impact on the BS total power consumption as compared to the additional transmission power needed to overcome the detrimental effects of inter-cell interference to maintain the same SINR level.

V. Conclusion

We have shown that ZF based receivers normally require higher BS total power consumption than the MMSE based receivers to maintain the same SINR at the receiver. The power consumption of the signal processing module is also an important factor to be considered in determining the overall BS total power consumption. In some cases, the power consumption of the signal processing module may exceed the transmission power savings obtained from receive diversity gains (multiple receive antennas) and receiver IC techniques. It may also contribute to the increase in the BS total power consumption more significantly than the additional transmission power needed to maintain the receiver SINR in the presence of inter-cell interference. In general, the MMSE-SIC receiver is the most efficient, providing the lowest BS total power consumption.

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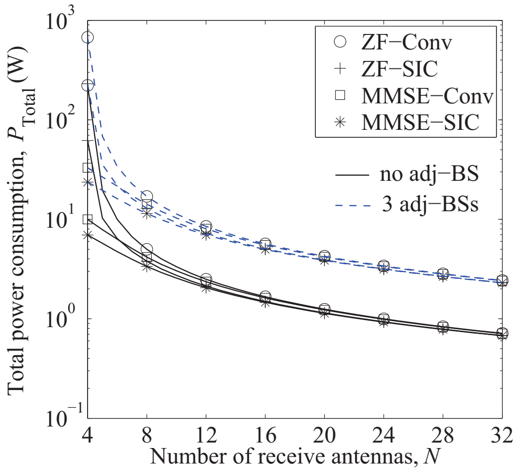

Fig. 1. Total power consumption of BS^A with different receiver IC techniques versus the number of receive antennas for $\alpha = 0$ $(M = 4, \eta = 0.4)$.

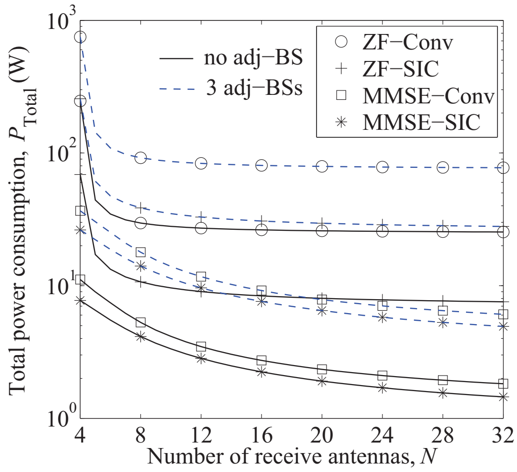

Fig. 2. Total power consumption of BS^A with different receiver IC techniques versus the number of receive antennas for $\alpha = 0.1$ $(M = 4, \eta = 0.4)$.

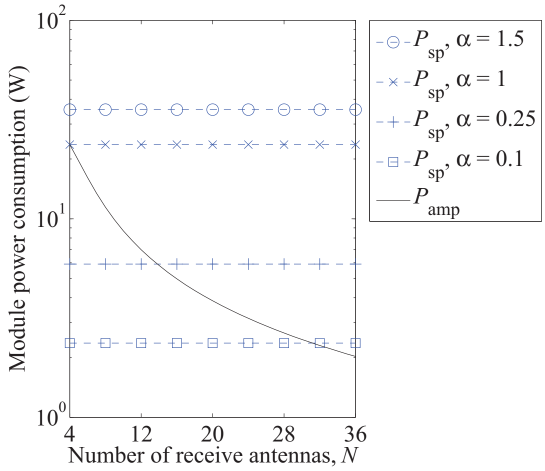

Fig. 3. Power consumption of the signal processing and power amplifier modules of BS^A at various α values versus the number of receive antennas while considering the MMSE-SIC receiver with 3 adj-BS $(M = 4, \eta = 0.4)$.

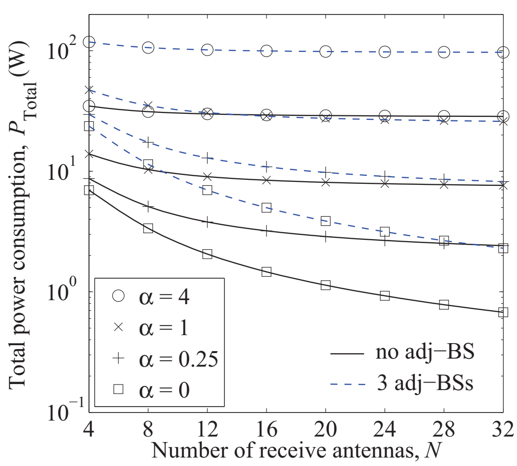

Fig. 4. Total power consumption of BS^A at various α values versus the number of receive antennas while considering the MMSE-SIC receiver $(M = 4, \eta = 0.4)$.