Transmission Energy Consumption in MIMO Systems under Inter-Cell Interference

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***Abstract*—We investigate the base station (BS) downlink transmission energy for a multiple-input multiple-output (MIMO) communication system operating under an inter-cell interference environment with the receiver equipped with interference cancellation (IC) capability. It is demonstrated that, besides the number of antennas, receiver IC techniques can have an influence on the required BS transmission energy of a MIMO communication system. Specifically, the choice of receiver IC technique impacts the transmission energy more when the number of receive antennas is small. On the other hand, the transmission energy converges to a minimum value regardless of the type of receiver IC technique used when the number of receive antennas is large enough. We also show that inter-cell interference contributed by adjacent BSs have a detrimental effect on the performance of traditional IC techniques, causing the desired BS to use higher transmission energy to maintain the signal quality.**

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

I. Introduction

The carbon footprint of the mobile industry has increased by a staggering 170% just under a decade since 2002 [1]. Estimating a total of 8 billion subscribers by 2020, mobile operators and vendors must ensure sustainable growth by keeping CO_2 emissions at 2009 level. The base stations (BSs) are identified as one of the major contributor to the increase in the carbon footprint, consuming 60% of the total network infrastructure power [2]. Therefore, reducing the BS power consumption is key in reducing the overall carbon footprint of the mobile industry.

In [3], a transmission mode switching scheme to save energy was proposed. Depending on the dynamic load of the system, the authors demonstrated energy savings by switching between single-input multiple-output (SIMO) and MIMO transmission modes. In [4], the energy efficiency of the multiple-output single-input (MISO) orthogonal frequency division multiplexing (OFDM) transmission scheme with power and capacity constraints was investigated. In [5], random network coding was considered as a possible energy efficient strategy for the Long Term Evolution (LTE)-Advanced networks. Other strategies may require channel state information (CSI) to be available at the transmitter for efficient transmission. These transmitter side strategies include beamforming [6], antenna selection techniques [7], power allocation [8] and rate allocation [9]. A comprehensive overview of the recent advances in green communication can be found in [10].

One of the initiatives of low impact green BS is focused on multi-antenna systems to reduce power consumption during signal transmission. Particularly, MIMO is seen as a potential enabling technology for multi-antenna implementation in emerging wireless communication standards such as LTE-Advanced. Besides promising high data rates without increasing bandwidth utilization [11], MIMO is also considered as a potential strategy towards reducing BS transmission power. However, complex signal detection at the receiver makes practical implementation of MIMO systems a challenge. Since the introduction of the Vertical Bell Laboratories Space-Time (V-BLAST) receiver [12], further improvement to the receiver structure has been achieved to better balance between performance and complexity [13]– [15].

In this paper, we will analyse the impact of different types of receiver IC techniques on the transmission power of the BS in MIMO systems. We consider the zero forcing (ZF) and the minimum mean square error (MMSE) coefficient optimization approaches for both conventional and successive interference cancellation (SIC) receivers. We will demonstrate that depending on the number of transmit/receive antennas and the type of receiver IC technique, different transmission power is needed to maintain the same signal-to-interference-plus-noise ratio (SINR) at the output of the receiver. We will also show that treating inter-cell interference from adjacent BSs as background noise when detecting the desired signal is not an energy efficient approach.

II. System Model

A MIMO communication system for a BS with M transmit antennas transmitting to a receiver with N receive antennas is considered. The desired BS is labelled as BS^A to differentiate it from the other I adjacent BSs as shown in Fig. 1. The ith adjacent BS, BS^i, has L^i transmit antennas. The receiver has N receive antennas and is within transmission range of all BSs. Therefore, the received complex signal vector can be written as

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

where $\mathbf{h}_m^A = \left(h_{1,m}^A, \cdots, h_{N,m}^A\right)^{\mathrm{T}}$ 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 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 with zero mean and common 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

The estimated symbol from the mth transmit antenna of BS^A of the conventional (Conv.) linear receiver is denoted as $\hat{s}_m = \mathbf{w}_m^{\mathrm{H}}\mathbf{y}$ with $\mathbf{w}_m = (w_{1,m}, \cdots, w_{N,m})^{\mathrm{T}}$ being the complex weighting vector for the mth symbol and $(\cdot)^{\mathrm{H}}$ is the Hermitian transpose operator. Substituting (1) for $\mathbf{y}$, we obtain

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

Intra-cell interference refers to the interference from the transmit antennas of BS^A while inter-cell interference is caused by the I adjacent BSs. From (2), the mth symbol SINR at the output of the receiver is given as

$$\mathrm{SINR}_m = \frac{r_{m,m}^A p_m^A}{\sum\limits_{j\neq m}^{M} r_{m,j}^A p_j^A + \sum\limits_{i=1}^{I}\sum\limits_{l=1}^{L_i} r_{m,l}^i p_l^i + \sigma^2\mu_m} \quad (3)$$

where $r_{m,j}^A = \left|\mathbf{w}_m^{\mathrm{H}}\mathbf{h}_j\right|^2$, $r_{m,l} = \left|\mathbf{w}_m^{\mathrm{H}}\mathbf{h}_l\right|^2$ and $\mu_m = \|\mathbf{w}_m\|^2$ with $\|\cdot\|$ being the Euclidean norm operator. The symbol power transmitted from the jth and lth antennas of BS^A and BS^i is given as p_j^A $(j = 1, \cdots, M)$ and p_l^i $(l = 1, \cdots, L_i)$, respectively. For $m = 1, \cdots, M$, we can further rewrite (3) into a more compact matrix form given by

$$\left[\mathbf{D}^A - \mathbf{Q}\left(\mathbf{R}^A - \mathbf{D}^A\right)\right]\mathbf{p}^A = \left[\mathbf{Q}\sum_{i=1}^{I}\mathbf{R}^i\mathbf{p}^i + \sigma^2\mathbf{Q}\mathbf{u}\right]. \quad (4)$$

The matrix $\mathbf{R}^A = \left\{r_{m,j}^A : 1 \le m, j \le M\right\} = \left|\mathbf{W}^{\mathrm{H}}\mathbf{H}^A\right|^2$, where $\mathbf{W} = (\mathbf{w}_1, \cdots, \mathbf{w}_M)$ and $\mathbf{H}^A = \left(\mathbf{h}_1^A, \cdots, \mathbf{h}_M^A\right)$. Likewise, we define $\mathbf{R}^i = \left\{r_{m,l}^i : 1 \le m \le M,\ 1 \le l \le L_i\right\} = \left|\mathbf{W}^{\mathrm{H}}\mathbf{H}^i\right|^2$, where $\mathbf{H}^i = \left(\mathbf{h}_1^i, \cdots, \mathbf{h}_{L_i}^i\right)$. The matrix $\mathbf{D}^A$ represents a $M\times M$ diagonal matrix with its non-zero elements taken from the diagonal elements of $\mathbf{R}^A$. Furthermore, we define $\mathbf{Q} = \mathrm{Diag}\left(\mathrm{SINR}_1, \cdots, \mathrm{SINR}_M\right)$, $\mathbf{u} = (\mu_1, \cdots, \mu_M)^{\mathrm{T}}$, $\mathbf{p}^A = \left(p_1^A, \cdots, p_M^A\right)^{\mathrm{T}}$ and $\mathbf{p}^i = \left(p_1^i, \cdots, p_{L_i}^i\right)^{\mathrm{T}}$. Assuming an equal power allocation for all transmit antennas within the same BS, i.e., $p_1^A \cdots p_M^A = p^A$ and $p_1^i \cdots p_{L_i}^i = p^i$, we have $\mathbf{p}^A = \mathbf{c}^A p^A$ and $\mathbf{p^i} = \mathbf{c}^i p^i$, where $\mathbf{c}^A$ and $\mathbf{c}^i$ are $M \times 1$ and $L_i \times 1$ unit column vectors. Let us rename p^A as p_{Conv}^A to denote the transmitted symbol power per antenna from BS^A for the conventional linear receiver. Thus, (4) is rewritten as

$$p_{\mathrm{Conv}}^A = \left[\mathbf{D}^A\mathbf{c}^A - \mathbf{Q}\left(\mathbf{R}^A - \mathbf{D}^A\right)\mathbf{c}^A\right]^{-1} \times \left[\mathbf{Q}\sum_{i=1}^{I}\mathbf{R}^i\mathbf{c}^i p^i + \sigma^2\mathbf{Q}\mathbf{u}\right]. \quad (5)$$

We consider the ZF and MMSE coefficient optimization approaches [16] when designing $\mathbf{W}$, resulting in the ZF-Conv and MMSE-Conv receivers, respectively.

B. The SIC Receiver

Intra-cell interference in the SIC receiver is reconstructed from previous detected symbols and subtracted from the received signal vector to improve detection probability of the current symbol. For simplicity, we assume an SIC receiver without optimal sorting. Therefore, the mth symbol SINR is denoted as

$$\mathrm{SINR}_m = r_{m,m}^A p_m^A \Bigg/ \left(\sum_{j=1}^{m-1} r_{m,j}^A p_j^A e_j^A + \sum_{j=m+1}^{M} r_{m,j}^A p_j^A + \sum_{i=1}^{I}\sum_{l=1}^{L_i} r_{m,l}^i p_l^i + \sigma^2\mu_m\right) \quad (6)$$

where $e_j^A = \eta_j \mathrm{E}\left\{|s_j - \tilde{s}_j|^2\right\}$ with η_j being the detection error probability of the jth symbol. Similarly, assuming an equal power allocation scheme but this time renaming p^A to p_{SIC}^A as it is the transmitted symbol power per antenna from BS^A for the SIC receiver, we can rewrite (6), for $m = 1, \cdots, M$, as

$$p_{\mathrm{SIC}}^A = \left[\mathbf{D}^A\mathbf{c}^A - \mathbf{Q}\left(\mathbf{R}_{\mathrm{SLT}}^A\mathbf{G} + \mathbf{R}_{\mathrm{SUT}}^A\right)\mathbf{c}^A\right]^{-1} \times \left[\mathbf{Q}\sum_{i=1}^{I}\mathbf{R}^i\mathbf{c}^i p^i + \sigma^2\mathbf{Q}\mathbf{u}\right]. \quad (7)$$

In (7), $\mathbf{R}_{\mathrm{SLT}}^A$ and $\mathbf{R}_{\mathrm{SUT}}^A$ are $M \times M$ strictly lower triangular and strictly upper triangular matrices, respectively, with their non-zero elements taken from the corresponding elements in $\mathbf{R}^A$. Furthermore, $\mathbf{G} = \mathrm{Diag}\left(0, e_1^A, \cdots, e_{M-1}^A\right)$. We also consider both the ZF and MMSE coefficient optimization approaches when designing $\mathbf{W}$, resulting in the ZF-SIC and MMSE-SIC receivers, respectively.

C. Energy Consumption Ratio (ECR)

In this section, we describe the metric used to quantify the required transmission energy per bit at BS^A. By feeding back each SINR_m of s_m to BS^A so that the transmission rate of s_m is always at most $\log_2(1+\mathrm{SINR}_m)$, we assume all M symbols can be detected. Under this assumption, the sum rate of the transmitted symbols is given as

$$R_{\mathrm{sum}} = W \sum_{m=1}^{M} \log_2(1+\mathrm{SINR}_m) \tag{8}$$

where W is the bandwidth of the system. Therefore, the ECR is defined as

$$\mathrm{ECR} = \frac{\sum_{m=1}^{M} p_m^A}{R_{\mathrm{sum}}}. \tag{9}$$

Note that the ECR has a unit of Joules per bit (J/bit).

D. Energy Consumption in a Single-Input Multiple-Output (SIMO) System

In the SIMO case, there exists no intra-cell interference since only one transmit antenna is used at BS^A. Thus, the transmit power per antenna, shown in (5) and (7), now becomes

$$p^A_{\mathrm{Conv/SIC,SIMO}} = q\left(\sum_{i=1}^{I}\left|\left(\mathbf{h}_1^{\mathrm{H}}\mathbf{h}_1\right)^{-1}\mathbf{h}_1^{\mathrm{H}}\mathbf{H}^i\right|^2\mathbf{c}^i p^i + \sigma^2\left\|\left(\mathbf{h}_1^{\mathrm{H}}\mathbf{h}_1\right)^{-1}\mathbf{h}_1^{\mathrm{H}}\right\|^2\right). \tag{10}$$

where q is a scalar representing the receiver output SINR for the only one transmit symbol. From (10), it is observed that in a SIMO system the same amount of transmission power is consumed for both the conventional linear and SIC receivers, regardless of the type of weight optimization approach used. Equation (10) is confirmed through simulation and is shown in Fig. 2 in terms of ECR when $M = 1$.

E. Asymptotic Analysis for Large Number of Receive Antennas, N

For a given number of adjacent BSs at a particular receiver output SINR, the required transmission energy for all four types of receivers described here converges as the number of receive antennas becomes large. To derive this convergence limit, we utilize the Lemma given in [3] which states that given a channel matrix $\mathbf{H}$ with variance γ, we have $\mathbf{H}^{\mathrm{H}}\mathbf{H} = N\gamma\mathbf{I}$ as N becomes large. Here, $\mathbf{I}$ is the identity matrix. Since the simulation results in Fig. 3 suggest that both the conventional linear receiver and the SIC receiver converge to a similar transmission energy consumption when the number of receive antennas, N, becomes large, we will mathematically derive this limit using the conventional linear receiver. This is because the conventional linear receiver has a more tractable mathematical approach as opposed to the non-linear SIC receiver.

Applying the aforementioned Lemma to the following parameters for the ZF criterion, we have

$$\mathbf{W}^{\mathrm{H}} = \left(\mathbf{H}^{\mathrm{H}}\mathbf{H}\right)^{-1}\mathbf{H}^{\mathrm{H}} = (N\gamma\mathbf{I})^{-1}\mathbf{H}^{\mathrm{H}} = \frac{\mathbf{H}^{\mathrm{H}}}{N\gamma} \tag{11}$$

$$\mathbf{R}^A = \left|\mathbf{W}^{\mathrm{H}}\mathbf{H}\right|^2 = \left|\frac{\mathbf{H}^{\mathrm{H}}\mathbf{H}}{N\gamma}\right|^2 = \left|\frac{N\gamma\mathbf{I}}{N\gamma}\right|^2 = \mathbf{I} \tag{12}$$

$$\mathbf{u} = \frac{\mathbf{c}}{N\gamma}. \tag{13}$$

Substituting (11)–(13) into (5) and letting the receiver output SINR for all M symbols be q, we have

$$p^A_{\mathrm{ZF-Conv}}\big|_{N\to\infty} = \left(\mathbf{c}^A\right)^{-1}\left[q\sum_{i=1}^{I}\mathbf{R}^i\mathbf{c}^i p^i + \frac{\sigma^2 q}{N\gamma}\mathbf{c}^A\right]. \tag{14}$$

Similarly, for the MMSE criterion we have

$$\mathbf{W}^{\mathrm{H}} = \left(\mathbf{H}^{\mathrm{H}}\mathbf{H}+\sigma^2\mathbf{I}\right)^{-1}\mathbf{H}^{\mathrm{H}} = \frac{\mathbf{H}^{\mathrm{H}}}{N\gamma+\sigma^2} \tag{15}$$

$$\mathbf{R}^A = \left|\mathbf{W}^{\mathrm{H}}\mathbf{H}\right|^2 = \left|\frac{\mathbf{H}^{\mathrm{H}}\mathbf{H}}{N\gamma+\sigma^2}\right|^2 = \left(\frac{N\gamma}{N\gamma+\sigma^2}\right)^2\mathbf{I} \tag{16}$$

$$\mathbf{u} = \frac{N\gamma\mathbf{c}}{\left(N\gamma+\sigma^2\right)^2}. \tag{17}$$

Substituting (15)–(17) into (5) and letting the receiver output SINR for all M symbols be q, we have

$$p^A_{\mathrm{MMSE-Conv}}\big|_{N\to\infty} = \left(\mathbf{c}^A\right)^{-1}\left[q\sum_{i=1}^{I}\mathbf{R}^i\mathbf{c}^i p^i + \frac{\sigma^2 q}{N\gamma}\mathbf{c}^A\right]. \tag{18}$$

We find that for large N, (14) is identical to (18), i.e., the required transmit power per antenna is identical when both the ZF-Conv and MMSE-Conv are used as the receiver. Using (9) together with either (14) or (18), we can derive the minimum ECR that all the receivers described here converges to as

$$\mathrm{ECR}_{\min} = \frac{\left(\mathbf{c}^A\right)^{-1}\left[q\sum_{i=1}^{I}\mathbf{R}^i\mathbf{c}^i p^i + \frac{\sigma^2 q}{N\gamma}\mathbf{c}^A\right]}{W\log_2(1+q)}. \tag{19}$$

This convergence limit is confirmed through simulation in Fig. 3 when N becomes large.

III. Simulation Results and Analysis

A total of 50,000 Monte Carlo simulations were carried out to produce the average transmission energy shown in the figures. The Rayleigh flat fading channel model is assumed. We vary the number of receive/transmit antennas while keeping $N \geq M$. We assume the receiver knows only the CSI between BS^A and itself, thus, utilizing it to compute the ZF and MMSE weight vectors. For the SIC receiver, it is assumed that there is no detection error of previous symbols, i.e., $e_j^A = 0$. Practically, the probability of correct detection can be increased with the help of channel coding. The adjacent BSs (adj-BSs) transmit at 0.1W per antenna. The system bandwidth is 1 MHz while the noise variance $\sigma = 1$. The receiver output SINR is fixed at 6 dB per transmitted symbol.

The influence of different receiver IC techniques on the required amount of transmission energy with $N = 4$ and different number of transmit antennas $(1 \leq M \leq 4)$ is illustrated in Fig. 2. For a given number of adjacent BSs, it is observed that ZF based receivers require higher transmission energy than MMSE based receivers when $M \geq 2$. In the SIMO case ($M = 1$), it is observed that all receivers require the same ECR as shown by (10). Thus, compared to a MIMO system, a SIMO system requires less transmission energy consumption but it does not offer any multiplexing gain. As the number of transmit antennas increases (MIMO case), it is observed that the required transmission energy begin to increase when ZF based receivers are considered while it remains fairly constant when the MMSE based receivers are considered. This could be attributed to how the weights of the receivers are designed. In the ZF case, the weights are designed in such a way that it will completely null out all interfering intra-cell components, leaving only the desired signal to be detected. This, however, will greatly amplify the AWGN noise and the inter-cell interference. As the number of transmit antennas increases, so will the amplification of other undesired components in the receive signal vector by the very same ZF weights used to suppress the intra-cell interference. Therefore, the transmission energy from the desired BS has to be increased in order to maintain the same level of SINR at the receiver output. On the other hand, the MMSE receiver has its weights designed in such a way that it tries to minimise the effect of both intra-cell interference and noise, effectively contributing to a less severe amplification of the undesired components in the receive signal vector. Consequently, MMSE receivers require much less transmission energy to maintain the same receiver output SINR as the number of transmit antennas increases.

If the number of adjacent BS increases, we observe that all receivers require more transmission energy. This is due to the fact that adjacent BSs contribute by increasing interference additively by a given factor and thus, the transmission energy level has to be increased by a factor proportional to it in order to maintain the same receiver output SINR. On the whole, SIC receivers require less transmission energy than the conventional linear receiver and the MMSE-SIC receiver provides the best performance in terms of energy savings at the BS.

In Fig. 3, it is illustrated that the required transmission energy decreases as the number of receive antennas, N, is steadily increased for a given fixed number of transmit antennas, $M = 4$. When $N > M$, it is observed that the transmission energy requirement for all four types of receiver decreases. This could be due to the increase in receive diversity gain. As the number of available receive antennas increases, better signal quality can be derived as the desired transmitted symbol energy arriving at the receiver can be optimally summed and detected over a larger set of receive antennas. Therefore, less transmission energy is required to maintain the same receiver output SINR. As the number of receive antennas increases further, the required transmission energy converges to $\mathrm{ECR}_{\min}$ regardless of the type of receiver used. This minimum transmission energy is needed to overcome the remaining inter-cell interference plus noise which is present equally in all the receiver types. For the case without any adjacent base station, the minimum transmission energy is only used to overcome the background noise. The IC techniques described here treat inter-cell interference as background noise and consequently are not able to efficiently remove it, thus requiring higher transmission energy to maintain the receiver SINR. We also observe in Fig. 3 that there is always an energy gap between the case with no adjacent BS and with 3 adjacent BSs. This shows that increasing the number of receive antennas alone will not help in suppressing the inter-cell interference. Furthermore, only a limited number of receive antennas can be installed in a mobile station due to its processing power and size constraint. Due to this, the choice of receiver IC techniques does make a difference in the required BS transmission energy as can be seen from Fig. 3 when N is small. Therefore, this serves to emphasize the strong influence of receiver IC design on the BS transmission energy for a receiver with limited number of receive antennas. Note that we acknowledge the fact that the signal processing complexity, thus the energy consumption, of the receiver changes with the number of receive antennas and the type of IC being considered. However, in this work, we are only interested in the BS transmission energy consumption as it was shown in [2] that the energy consumption in current communication networks is largely attributed to the BSs.

IV. Conclusion

We have shown that ZF based receivers normally require higher BS energy consumption than MMSE based receivers. Besides the number of antennas, different weight design approaches have an impact on the required transmission energy of the BS. The MMSE-SIC receiver is the most efficient in transmission energy savings. Nevertheless, the interference effects of adjacent BSs are not jointly minimised by the IC techniques described here but treated as background noise. This necessitates higher transmission energy from the desired BS in order to maintain the same SINR at the receiver. In the future, efficient methods to acquire adjacent cell CSIs will be considered to facilitate the development of more robust IC techniques to simultaneously combat both intra-cell and inter-cell interference, resulting in further reduction of the required BS transmission energy.

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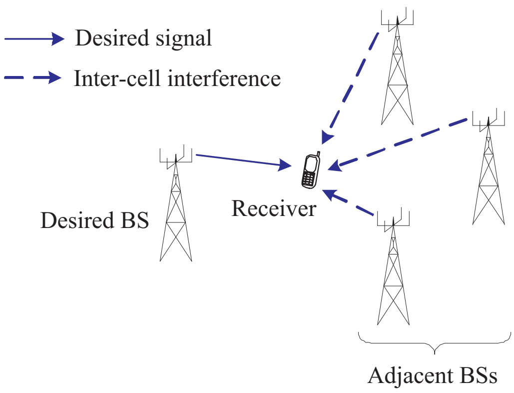

Fig. 1. The MIMO communication system model.

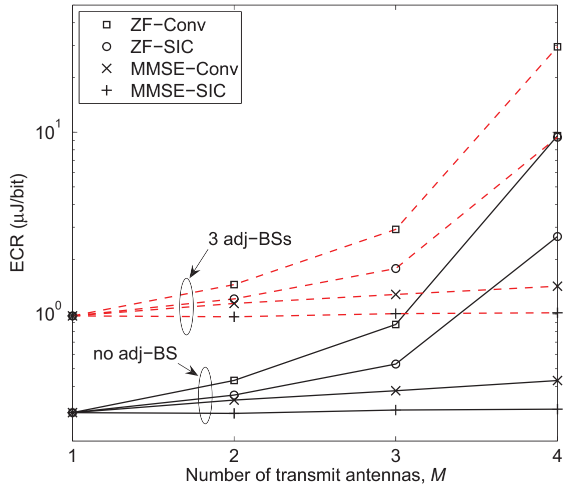

Fig. 2. The energy consumption ratios (ECRs) of the desired BS (BS^A) with different receiver IC techniques versus the number of transmit antennas ($N = 4$).

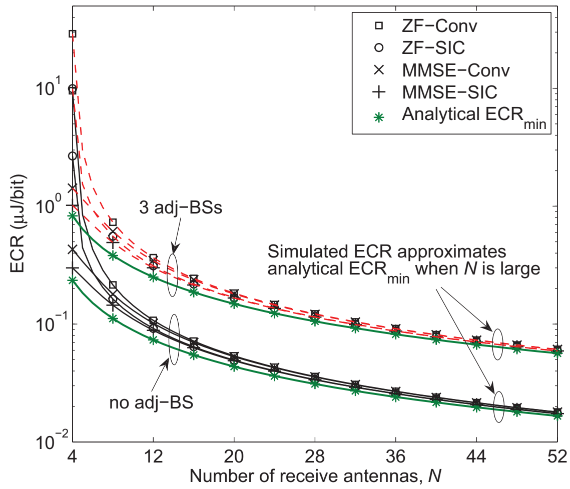

Fig. 3. The energy consumption ratios (ECRs) of the desired BS (BS^A) with different receiver IC techniques versus the number of receive antennas ($M = 4$).