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A Naive Method to Calculate the Maximum Number of Active Users, Number of Antennas Required and Calculating the Optimum Transmit Power in a Multi-User Multiple-Input Multiple Output (MIMO) System

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ABSTRACT

Assume we will make a multi-client Multiple-Input Multiple Output (MIMO) framework. This framework will cover a given area with maximal vitality proficiency known as energy efficiency (EE) consistently. Presently the propose technique will ascertain the ideal (least) number of users utilized around there to cover, all out number of dynamic clients that can utilize the system, and the ideal transmit control. Furthermore, we will contrast our outcome and the other available methods. The numerical and systematic outcomes demonstrate that the maximal EE is accomplished by an enormous MIMO setup wherein many receiving wires are conveyed to serve a generally huge number of clients utilizing ZF handling. The numerical outcomes demonstrate a similar conduct under flawed direct state data and in symmetric multi-cell situations.

Keywords : Multi-user multiple-input multiple output (MIMO) system, Energy efficiency, uplink, system design, imperfect CSI, downlink, single and multi-cell.

I. INTRODUCTION

The power consumption of the communication technology industry and the corresponding energy-related pollution are becoming major societal and economical concerns [1]. This has stimulated academia and industry to an intense activity in the new research area of green cellular networks [2], recently spurred by the SMART 2020 report [3] and the Green Touch consortium [4]. The ultimate goal is to design new innovative network architectures and technologies needed to meet the explosive growth in cellular data demand without increasing the power consumption.

Along this line, in this paper we aim at jointly designing the uplink and downlink of a multi-user MIMO system for optimal energy efficiency (EE). In particular, we aim at bringing new insights on how the number M of antennas at the base station (BS), the number K of active user equipment (UEs), and the transmit power must be chosen in order to uniformly cover a given area with maximal EE. The EE is defined as the number of bits transferred per Joule of energy and it is affected by many factors such as network architecture, transmission protocol, spectral efficiency, radiated transmit power, and circuit power consumption [1]–[5].

As discussed in [5], an accurate modeling of the total power consumption is of primary importance to obtain reliable guidelines for EE optimization of M and K. To see how this comes about, assume (as usually done in the related literature) that the total power consumption is computed as the sum of the radiated transmit power and a constant quantity accounting for the circuit power consumption [1]. Although widely used, this model might be very misleading. In fact, it can lead to an unbounded EE if used to design systems wherein M can be very large because the user rates grow unboundedly as M → ∞ [6]. Achieving infinite EE is obviously impossible and holds true simply because the model does not take into account that the power consumed by digital signal processing and analog circuits (for radio-frequency (RF) and baseband processing) grows with M and K. This means that its contri- bution can be taken as a constant only in multi-user MIMO systems where M and K take relatively small values, while its variability plays a key role in the so-called massive MIMO (or large-scale MIMO) systems in which $M,K \gg 1$ and all the BS antennas are processed coherently [6]–[10]. We stress that the original massive MIMO definition in [7] also assumed $\frac{M}{K} \gg 1$ while we consider the more general definition from [8] and [9] $\frac{M}{K}$ can also be a small constant.

The way that the number of antennas M impacts definition the from EE has been recently investigated in [11]–[16]. In particular, in [11] the author focused on the power allocation problem in the uplink of multi-user MIMO systems and showed that the EE is maximized when specific UEs are switched off. The uplink was studied also in [12], where the EE was shown to be a concave function of M and the UE rates. The downlink was studied in [13]–[15], whereof [13] and [14] showed that the EE is a concave function of M while a similar result was shown for K in [15]. Unfortunately, the system parameters were optimized by means of simulations that (although useful) do not provide a complete picture of how the EE is affected by the different system parameters. The concurrent work [16] derives the optimal M and K for a given uplink sum rate, but the necessary overhead signaling for channel acquisition is ignored thereby leading to unrealistic results where it is beneficial to let K grow very large, or even go to infinity.

The main purpose of this paper is to provide insights on how M, K, and the transmit power affect the total EE of a multi-user MIMO system for different linear processing schemes at the BS. The most common precoding and receive combining are considered: zero-forcing (ZF), maximum ratio transmission/combining (MRT/MRC), and minimum mean squared error (MMSE) processing [17]. A new refined model of the total power consumption is proposed to emphasize that the real power actually scales faster than linear with M and K (in sharp contrast with most existing models). Then, we concentrate on ZF processing in single-cell systems and make use of the new model for deriving closed-form EE- optimal values of each of the three system parameters, when the other two are fixed. These expressions provide valuable design insights on the interplay between system parameters, propagation environment, and different components of the power consumption model. While analytic results are given only for ZF with perfect channel state information (CSI), numerical results are provided for all the investigated schemes with perfect CSI, for ZF with imperfect CSI, and in a multi- cell scenario. Our results reveal that (a) a system with 100-200 BS antennas is the right way to go if we want to be energy efficient, (b) we should use these antennas to serve a number of UEs of the same order of magnitude, (c) the transmit power should increase with the number of BS antennas since the circuit power increases, (d) ZF processing provides the highest EE due to active interference-suppression at affordable complexity. These are highly relevant results that prove that massive MIMO is the way to achieve high EE (tens of Mbit/Joule) in future cellular networks.

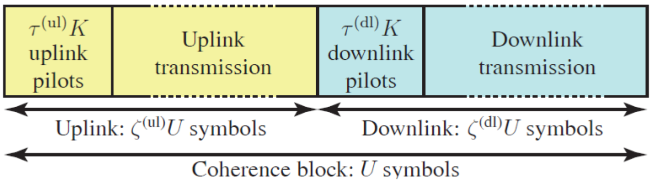


Fig. 1. Illustration of the TDD protocol, where ζ(ul) and ζ (dl) are the fractions of UL and DL transmission, respectively.

SYSTEM AND SIGNAL MODEL

We consider the uplink and downlink of a single-cell multi- user MIMO system operating over a bandwidth of B Hz. The BS uses a co-located array with M antennas to communicate with K single-antenna UEs that are selected in round-robin fashion from a large set of UEs within the coverage area. We consider block flat-fading channels where B_C (in Hz) is the coherence bandwidth and T_C (in seconds) is the coherence time. Hence, the channels are static within time-frequency coherence blocks of $U = B_C T_C$ symbols. We assume that the BS and UEs are perfectly synchronized and operate according to the time-division duplex (TDD) protocol shown in Fig. 1. The fixed ratios of uplink and downlink transmission are denoted by $\zeta^{(ul)}$ and $\zeta^{(dl)}$, respectively, with $\zeta^{(ul)}+\zeta^{(dl)} = 1$. As seen from Fig. 1, uplink transmission takes place first and consists of Uζ(ul) symbols. The subsequent downlink transmission consists of $U\zeta^{(dl)}$ symbols. The pilot signaling occupies $\tau^{(ul)}K$ symbols in the uplink and τ (dl)K in the downlink, where $\tau^{(ul)}$, $\tau^{(dl)} \geq 1$ to enable orthogonal pilot sequences among the UEs [6], [9], [10]. The uplink pilots enable the BS to estimate the UE channels. Since the TDD protocol is matched to the coherence blocks, the uplink and downlink channels are considered reciprocal2 and the BS can make use of uplink estimates for both reception and downlink transmission. TDD protocols basically require M and K to be the same in the uplink and downlink. The downlink pilots let each UE estimate its effective channel and interference variance with the current precoding.

The physical location of UE *k* is denoted by $x_k \in \mathbb{R}^2$ (in meters) and is computed with respect to the BS (as- sumed to be located in the origin). For analytic tractability, we consider only non-line-of-sight propagation. The function $l(\cdot) : \mathbb{R}^2 \rightarrow \mathbb{R}$ describes the large-scale channel fading at different user locations, that is, $l(x_k)$ is the average channel attenuation3 due to path-loss, scattering, and shadowing at location x_k. Since the UEs are selected in a round-robin fashion, the user locations can be treated as random variables from a user distribution f(x) implicitly defining the shape and user density of the coverage area (see Fig. 2). The large-scale fading between a UE and the BS is assumed to be the same for all BS antennas. This is reasonable since the distances between UEs and the BS are much larger than the distance between the antennas. Since the forthcoming analysis does not depend on a particular choice of l(.) and user distribution, we keep it generic. The following symmetric example is used for simulations.

The physical channels are reciprocal within a coherence block, but efficient calibration schemes are needed to compensate for any possible amplitude and phase difference between the transmit and receive RF chains, we refer the reader to [18] and [19] for state-of-the-art calibration schemes.

It is also known as channel gain, but since we deal with EE we stress that channels attenuate rather than amplify signals.

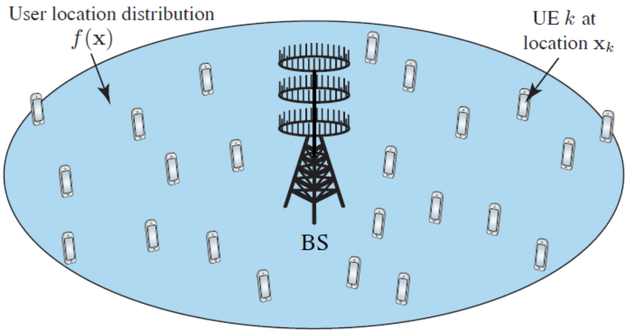


Fig. 2. Illustration of a generic multi-user MIMO scenario: A BS with M omnidirectional antennas communicates with K single-antenna UEs in the uplink and downlink. The user locations are selected from an arbitrary random user distribution f(x).

II. CHANNEL MODEL AND LINEAR PROCESSING

The M antennas at the BS are adequately spaced apart such that the channel components between the BS antennas and the single-antenna UEs are uncorrelated. The channel vector hk = $[h_{k,1}\ h_{k,2}, \ldots, h_{k,M}]^T \in C^{M\times 1}$ has entries $\{h_{k,n}\}$ that describe the instantaneous propagation channel between the nth antenna at the BS and the kth UE. We assume a Rayleigh small-scale fading distribution such that $\mathbf{h}_k \sim \mathcal{CN}(\mathbf{0}_M, l(\mathbf{x}_k)\mathbf{I}_M)$, which is a valid model for both small and large arrays [21]. Linear processing is used for uplink data detection and downlink data precoding. For analytic tractability, we assume that the BS is able to acquire perfect CSI from the uplink pilots, the imperfect CSI case is considered in Section VI. We denote the uplink linear receive combining matrix by G = [g1, g2, … , gK] ϵ $C^{M\times K}$ with the column g_k being assigned to the kth UE. We consider MRC, ZF, and MMSE for uplink detection, which gives

$$\mathbf{G} = \begin{cases} \mathbf{H} & \text{for MRC,} \\ \mathbf{H}\left(\mathbf{H}^H\mathbf{H}\right)^{-1} & \text{for ZF,} \\ \left(\mathbf{H}\mathbf{P}^{(\mathrm{ul})}\mathbf{H}^H + \sigma^2\mathbf{I}_M\right)^{-1}\mathbf{H} & \text{for MMSE,} \end{cases} \tag{4}$$

where H = $[h_1, h_2, \ldots ,, h_K]$ contains all the user channels, σ^2 denotes the noise variance (in Joule/symbol), $P^{(ul)}$ = diag($p_1^{(ul)}$, $p_2^{(ul)}$, …, $p_k^{(ul)}$), and the design parameter $P_i^{(ul)} \geq 0$ is the transmitted uplink power of UE i (in Joule/symbol) for i = 1, 2, … ,K. Similarly, we consider MRT, ZF, and transmit-MMSE as precoding schemes for downlink transmissions [17]. Denoting by V = $[v_1, v_2, \ldots v_K] \in C^{M\times K}$ the precoding matrix, we have that

$$\mathbf{V} = \begin{cases} \mathbf{H} & \text{for MRT,} \\ \mathbf{H}\left(\mathbf{H}^H\mathbf{H}\right)^{-1} & \text{for ZF,} \\ \left(\mathbf{H}\mathbf{P}^{(\mathrm{ul})}\mathbf{H}^H + \sigma^2\mathbf{I}_M\right)^{-1}\mathbf{H} & \text{for MMSE.} \end{cases} \tag{5}$$

It is natural to set V = G, since it reduces the computational complexity, but it is not necessary.

While conventional systems have large disparity between peak and average rates, we aim at designing the system so as to guarantee a uniform gross rate $\overline{R}$ (in bit/second) for any active UE, where of ζ(ul) $\overline{R}$ is the uplink rate and ζ(ul) $\overline{R}$ is the downlink rate. As detailed below, this is achieved by combining the linear processing with proper power allocation.

Uplink

Under the assumptions of Gaussian codebooks, linear processing,

and perfect CSI [9], the achievable uplink rate (inbbit/second) of the kth UE is

$$R_k^{(\mathrm{ul})} = \zeta^{(\mathrm{ul})}\left(1 - \frac{\tau^{(\mathrm{ul})}K}{U\zeta^{(\mathrm{ul})}}\right)\bar{R}_k^{(\mathrm{ul})} \tag{6}$$

where the pre-log factor $\left(1 - \frac{\tau^{(ul)}K}{U\zeta^{(ul)}}\right)$ accounts for pilot overhead and $\zeta^{(\mathrm{ul})}$ is the fraction of uplink transmission. In addition,

$$\bar{R}_k^{(\mathrm{ul})} = B\log\left(1 + \frac{p_k^{(\mathrm{ul})}|\mathbf{g}_k^H\mathbf{h}_k|^2}{\sum\limits_{\ell=1,\ell\neq k}^{K} p_\ell^{(\mathrm{ul})}|\mathbf{g}_k^H\mathbf{h}_\ell|^2 + \sigma^2\,\|\mathbf{g}_k\|^2}\right) \tag{7}$$

is the uplink gross rate (in bit/second) from the kth UE, where "gross" refers to that overhead factors are not included. As mentioned above, we aim at providing the same gross rate $\overline{R}_k^{(ul)} = \overline{R}$ for k = 1,2, … , K. By utilizing a technique from [22], this equal-rate condition is met if and only if the uplink power allocation vector $\mathbf{p}^{(\mathrm{ul})} = [p_1^{(\mathrm{ul})}, p_2^{(\mathrm{ul})}, \ldots, p_K^{(\mathrm{ul})}]^T$ is such that

$$\mathbf{p}^{(\mathrm{ul})} = \sigma^2(\mathbf{D}^{(\mathrm{ul})})^{-1}\mathbf{1}_K \tag{8}$$

where the (k,ℓ)th element of $\mathbf{D}^{(\mathrm{ul})} \in \mathbb{C}^{K\times K}$ is

$$\left[\mathbf{D}^{(\mathrm{ul})}\right]_{k,\ell} = \begin{cases} \frac{|\mathbf{g}_k^H\mathbf{h}_k|^2}{(2^{\bar{R}/B}-1)\|\mathbf{g}_k\|^2} & \text{for } k = \ell, \\ -\frac{|\mathbf{g}_k^H\mathbf{h}_\ell|^2}{\|\mathbf{g}_k\|^2} & \text{for } k \neq \ell. \end{cases} \tag{9}$$

The power allocation in (8) is computed directly for MRC and ZF detection, while it is a fixed-point equation for MMSE

detection since also G depends on the power allocation [23].

The average uplink PA power (in Watt) is defined as

the power consumed by the power amplifiers (PAs), which includes radiated transmit power and PA dissipation. By using

(8) it is found to be

$$P_{\mathrm{TX}}^{(\mathrm{ul})} = \frac{B\zeta^{(\mathrm{ul})}}{\eta^{(\mathrm{ul})}}\mathbb{E}\{\mathbf{1}_K^T\mathbf{p}^{(\mathrm{ul})}\} = \sigma^2\frac{B\zeta^{(\mathrm{ul})}}{\eta^{(\mathrm{ul})}}\mathbb{E}\left\{\mathbf{1}_K^T(\mathbf{D}^{(\mathrm{ul})})^{-1}\mathbf{1}_K\right\} \tag{10}$$

where $0 < \eta^{(\mathrm{ul})} \leq 1$ is the PA efficiency at the UEs.

Observe that it might happen that $\overline{R}$ cannot be supported for any transmit powers. In such a case, computing $P^{(ul)}$ in (8) would lead to some negative powers. However, this can easily be detected and avoided by computing the spectral radius of

$D^{(ul)}$ [22]. Moreover, it only happens in interference-limited cases; thus, it is not an issue when ZF is employed (under perfect CSI). In these circumstances, $P_{TX}^{(ul)}$

in (10) can be computed in closed form as stated in the following.

Downlink

The downlink signal to the kth UE is assigned a transmit power of $p_k^{(dl)}$ (in Joule/symbol) and a normalized precoding vector $v_k/||v_k||$. Assuming Gaussian codebooks and perfect CSI [17], the achievable downlink rate (in bit/second) of the kth UE with linear processing is

$$R_k^{(\mathrm{dl})} = \zeta^{(\mathrm{dl})}\left(1 - \frac{\tau^{(\mathrm{dl})}K}{U\zeta^{(\mathrm{dl})}}\right)\bar{R}_k^{(\mathrm{dl})} \tag{13}$$

III. PROBLEM STATEMENT

As mentioned in Section I, the EE of a communication system is measured in bit/Joule [2] and is computed as the ratio between the average sum rate (in bit/second) and the average total power consumption PT (in Watt = Joule/second).

In a multi-user setting, the total EE metric accounting for both uplink and downlink takes the following form.

Definition 1. The total EE of the uplink and downlink is

$$\mathrm{EE} = \frac{\sum\limits_{k=1}^{K}\left(\mathbb{E}\left\{R_k^{(\mathrm{ul})}\right\} + \mathbb{E}\left\{R_k^{(\mathrm{dl})}\right\}\right)}{P_{\mathrm{TX}}^{(\mathrm{ul})} + P_{\mathrm{TX}}^{(\mathrm{dl})} + P_{\mathrm{CP}}} \tag{20}$$

where P_{CP} accounts for the circuit power consumption.

The proposed model is inspired by [1], [5], [15], [26]– [29], but goes beyond these prior works by modeling all the terms with realistic, and sometimes non-linear, expressions.

IV. REVIEW OF LITERATURE AND METHODOLOGY

Whatever discusses in Introduction section, the big question is how it will come, assume that the total power consumption is computed as the sum of the radiated transmit power and a constant quantity accounting for the circuit power consumption [1]. Although widely used, this model might be very misleading. In fact, it can lead to an unbounded EE if used to design systems wherein M can be very large because the user rates grow unboundedly as M → ∞ [6]. Achieving infinite EE is obviously impossible and holds true simply because the model does not take into account that the power consumed by digital signal processing and analog circuits (for radio-frequency (RF) and baseband processing) grows with M and K. This means that its contribution can be taken as a constant only in multi-user MIMO systems where M and K take relatively small values, while its variability plays a key role in the so-called massive MIMO (or large-scale MIMO) systems in which M, K >> 1 and all the BS antennas are processed coherently [6]–[10]. We stress that the original massive MIMO definition in [7] also assumed $\frac{M}{K} >> 1$, while we consider the more general definition from [8] and [9] where $\frac{M}{K}$ can also be a small constant. The way that the number of antennas M impacts the EE has been recently investigated in [11]–[16]. In particular, in [11] the author focused on the power allocation problem in the uplink of multi-user MIMO systems and showed that the EE is maximized when specific UEs are switched off.

The uplink was studied also in [12], where the EE was shown to be a concave function of M and the UE rates. The downlink was studied in [13]–[15], whereof [13] and [14] showed that the EE is a concave function of M while a similar result was shown for K in [15]. Unfortunately, the system parameters were optimized by means of simulations that (although useful) do not provide a complete picture of how the EE is affected by the different system parameters. The concurrent work [16] derives the optimal M and K for a given uplink sum rate, but the necessary overhead signaling for channel acquisition is ignored thereby leading to unrealistic results where it is beneficial to let K grow very large, or even go to infinity.

The main purpose of this paper is to provide insights on how M, K, and the transmit power affect the total EE of a multi-user MIMO system for different linear processing schemes at the BS. The most common precoding and receive combining are considered: zero-forcing (ZF), maximum ratio transmission/combining (MRT/MRC), and minimum mean squared error (MMSE) processing [17].

Our new refined model of the total power consumption is proposed to emphasize that the real power actually scales faster than linear with M and K (in sharp contrast with most existing models). Then, we concentrate on ZF processing in single-cell systems and make use of the new model for deriving closed-form EE optimal values of each of the three system parameters, when the other two are fixed. These expressions provide valuable design insights on the interplay between system parameters, propagation environment, and different components of the power consumption model. While analytic results are given only for ZF with perfect channel state information (CSI), numerical results are provided for all the investigated schemes with perfect CSI, for ZF with imperfect CSI, and in a multicell scenario.

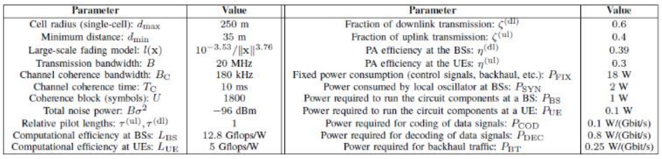
Our results will reveal that

a. A system with 100-200 BS antennas is the right way to go if we want to be energy efficient;
b. We should use these antennas to serve a number of UEs of the same order of magnitude
c. The transmit power should increase with the number of BS antennas since the circuit power increases
d. ZF processing provides the highest EE due to active interference-suppression at affordable complexity.

Our complete analysis will show that our result is highly relevant results that proved that massive MIMO is the way to achieve high EE (tens of Mbit/Joule) in future cellular networks.

V. SIMULATION AND RESULT

This section uses simulations to validate the system design guidelines. To compute the total power consumption in a realistic way, we use the hardware characterization. We first consider the single-cell simulation scenario in example (i.e., a circular cell with radius 250 m) and assume operation in the 2 GHz band. The corresponding simulation parameters are given in Table and are inspired by a variety of prior works:



Parameter	Value	Parameter	Value
Cell radius (single-cell): $d_{\max}$	250 m	Fraction of downlink transmission: $\zeta^{(\mathrm{dl})}$	0.6
Minimum distance: $d_{\min}$	35 m	Fraction of uplink transmission: $\zeta^{(\mathrm{ul})}$	0.4
Large-scale fading model: $l(\mathbf{x})$	$10^{-3.53}/\|\mathbf{x}\|^{3.76}$	PA efficiency at the BSs: $\eta^{(\mathrm{dl})}$	0.39
Transmission bandwidth: B	20 MHz	PA efficiency at the UEs: $\eta^{(\mathrm{ul})}$	0.3
Channel coherence bandwidth: B_{C}	180 kHz	Fixed power consumption (control signals, backhaul, etc.): P_{FIX}	18 W
Channel coherence time: T_{C}	10 ms	Power consumed by local oscillator at BSs: P_{SYN}	2 W
Coherence block (symbols): U	1800	Power required to run the circuit components at a BS: P_{BS}	1 W
Total noise power: $B\sigma^2$	−96 dBm	Power required to run the circuit components at a UE: P_{UE}	0.1 W
Relative pilot lengths: $\tau^{(\mathrm{ul})}, \tau^{(\mathrm{dl})}$	1	Power required for coding of data signals: P_{COD}	0.1 W/(Gbit/s)
Computational efficiency at BSs: L_{BS}	12.8 Gflops/W	Power required for decoding of data signals: P_{DEC}	0.8 W/(Gbit/s)
Computational efficiency at UEs: L_{UE}	5 Gflops/W	Power required for backhaul traffic: P_{BT}	0.25 W/(Gbit/s)

Fig. 3 shows the set of achievable EE values with perfect CSI, ZF processing, and for different values of M and K (note that $M \geq K+1$ in ZF). Each point uses the EE-maximizing value of ρ from Theorem (refer my complete thesis). The figure shows that there is

a global EE-optimum at M = 165 and K = 104, which is achieved by = 0:8747 and the practically reasonable spectral efficiency 5:7644 bit/symbol (per UE). The optimum is clearly a massive MIMO setup, which is noteworthy since it is the output of an optimization problem where we did not restrict the system dimensions whatsoever. The surface in Fig. is concave and quite smooth; thus, there is a variety of system parameters that provides close-to-optimal EE and the results appear to be robust to small changes in the circuit power coefficients. In Fig. 2 and the algorithm converged after 7 iterations to the global optimum.

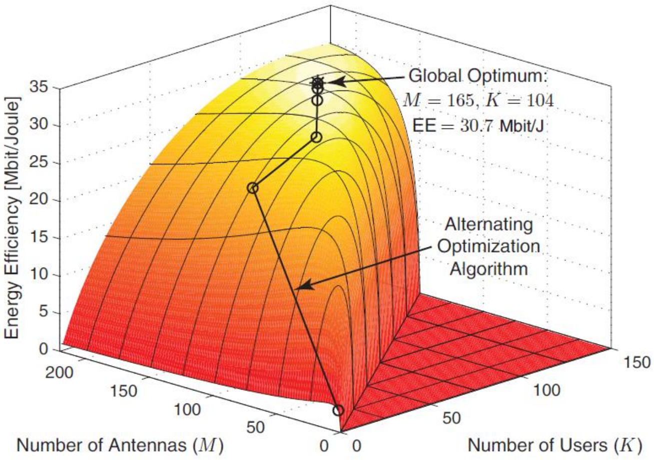


Fig. 2. Energy efficiency (in Mbit/Joule) with ZF processing in the single cell scenario. The global optimum is star-marked and the surroundings are white. The convergence of the proposed alternating optimization algorithm is indicated with circles.

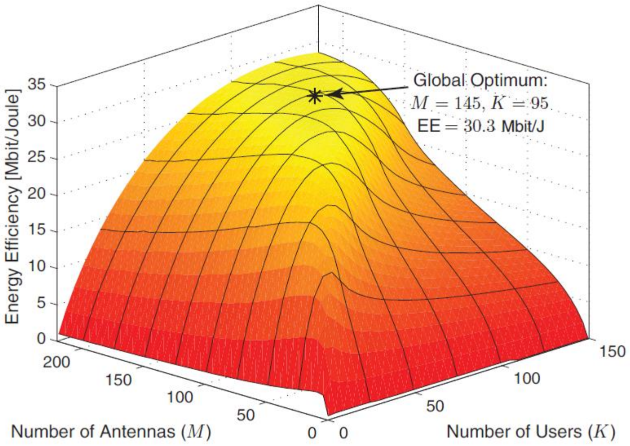


Fig. 3. Energy efficiency (in Mbit/Joule) with MMSE processing in the single-cell scenario.

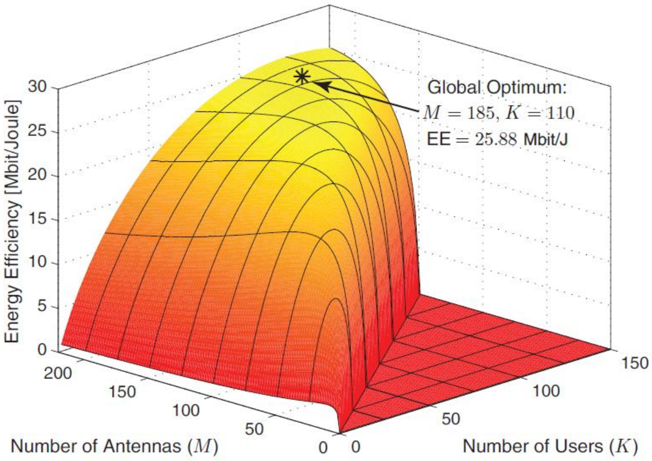


Fig. 5. Energy efficiency (in Mbit/Joule) with ZF processing in the single-cell scenario with imperfect CSI.

For comparisons, Fig. 3 shows the corresponding set of achievable EE values under MMSE processing (with Q = 3), Fig. 4 illustrates the results for MRT/MRC processing, and Fig. 5 considers ZF processing under imperfect CSI. The MMSE and MRT/MRC results were generated by Monte Carlo simulations, while the ZF results were computed using the expression in Lemma 5.

To further compare the different processing schemes, Fig. 7 shows the maximum EE as a function of the number of BS antennas. Clearly, the similarity between MMSE and ZF shows an optimality of operating at high SNRs (where these schemes are almost equal).

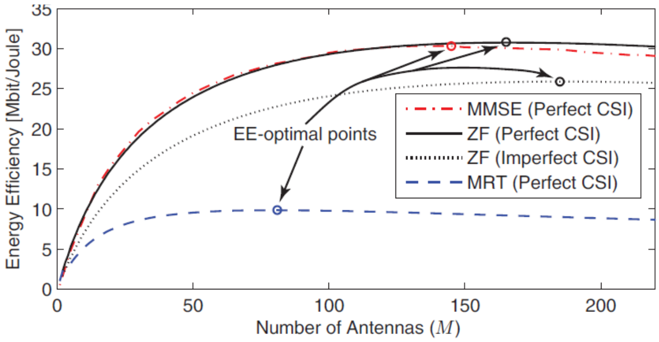


Fig. 7. Maximal EE for different number of BS antennas and different processing schemes in the single-cell scenario.

VI. CONCLUSIONS AND OUTLOOK

This paper analyzed how to select the number of BS antennas M, number of active UEs K, and gross rate R (per UE) to maximize the EE in multi-user MIMO systems. Contrary to most prior works, we used a realistic power consumption model that explicitly describes how the total power consumption depends non-linearly on M, K, and $\overline{R}$. Simple closedform expressions for the EE-maximizing parameter values and their scaling behaviors were derived under ZF processing with perfect CSI and verified by simulations for other processing schemes, under imperfect CSI, and in symmetric multi-cell scenarios. The applicability in general multi-cell scenarios is

an important open problem that we leave for future work.

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