International Journal on Recent and Innovation Trends in Computing and Communication
ISSN: 2321-8169 Volume: 11 Issue: 9s
***Article Received:** 15 April 2023 **Revised:** 25 July 2023 **Accepted:** 18 August 2023*

Analysis of Power Consumption in Base Station in Massive MIMO Systems

Nikhil Rathore
Department of Electronics & Communication Engineering
Dr. A.P.J. Abdul Kalam University
Indore, India
nikhil.rathore6@gmail.com

Dr. Santosh Pawar
Department of Electronics & Communication Engineering
Dr. A.P.J. Abdul Kalam University
Indore, India
spawarrkdf@gmail.com

Abstract: The concept of massive MIMO enables high quality of service, Efficiency, and scalability. Therefore, a dense network has been established to enable services using the massive MIMO. But rapidly increasing deployment of cellular base stations increases the electricity energy consumption and increases the green house effect. Therefore, the balance between energy efficiency and high network performance is expected from the communication infrastructure. In this paper, the energy efficiency of the massive MIMO systems has been investigated in mainly two key scenarios i.e. single cell configuration and multi-cell configuration. In order to conduct experiments MATLAB based simulator has been used. Additionally, with the increasing number of User Equipments (UEs) the simulation has been done. Finally the configured network has been used to measure the optimal combination of antenna and UEs and the optimal energy consumption. Additionally the experiment also demonstrates how the different preprocessing technique will influence the massive MIMO energy efficiency. Finally the conclusion has been drawn and the future work has been proposed.

Keywords: *Massive MIMO systems, Energy Efficiency, Green Computing, Green Cellular Networks, Signal Pre-Processing, Base Station Energy Consumption*.

I. INTRODUCTION

The power consumption of the communication industry and corresponding energy-related pollution are becoming major concerns [1]. Thus, now in these days a number of efforts have been made where the goal is to design network architecture and technology to meet the growth in cellular data demand without increasing the power consumption. In this paper, the main aim is to jointly study the uplink and downlink of a multi-user MIMO system for optimal energy efficiency (EE). The study discusses the insights on how the M number of antennas at the base station (BS), the number K of active user equipments (UEs), and the transmit power must be chosen to 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 like network architecture, transmission protocol, spectral efficiency, radiated transmit power, and circuit power consumption. According to [2], it is of important to obtain reliable guidelines for EE optimization of M and K.

Assume that the total power consumption is computed as the sum of the radiated transmits power and a constant quantity for the circuit power [1]. This model might be 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 $M \to \infty$. Achieving infinite EE is impossible and holds true because the model does not take into account that the power consumed by digital signal processing and analog circuits grows with M and K. This means its contribution can be taken as a constant 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 systems in which $M, K \gg 1$ and all the BS antennas are processed coherently. The original massive MIMO assumed $\frac{M}{K} \gg 1$, while we consider the more general definition where $\frac{M}{K}$ can also be a small constant.

In [3] 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. In [4], the EE was shown to be a concave function of M and the UE rates. In [5] and [6] showed the EE is a concave function of M while a similar result was shown for K in [7]. The [8] derives the optimal M and K for a given uplink sum rate, but the necessary overhead signaling for channel acquisition is ignored leading to unrealistic results where it is beneficial to let K grow very large. In this paper the main purpose 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. 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. In this section, the overview of the proposed work has been discussed. The next section provides the understanding of the proposed work involved.

II. PROPOSED WORK

In this paper the total power consumption is measured to emphasize that the real power actually scales faster than linear with M and K. Then, the study has focused on ZF processing in single-cell systems and uses a model [9] for utilizing closed-form EE-optimal values of each of the three system parameters, when the other two are fixed. These expressions provide insights on the interplay between system parameters, propagation environment, and components of the power consumption model. Additionally, results are given for ZF with perfect channel state information (CSI), numerical results are provided for all the schemes with perfect CSI, for ZF with imperfect CSI, and in a multi-cell scenario. The results reveal that:

a. We should use antennas to serve a number of UEs of the same order of magnitude;
b. The transmit power should increase with the number of BS antennas since the circuit power increases;
c. ZF processing provides the highest EE due to active interference-suppression at affordable complexity.
d. These results prove that massive MIMO is the way to achieve high EE.

1. Simulation setup

This section uses simulations to validate the system design guidelines under ZF processing and to make comparisons with other processing schemes. Thus the different number of users is considered. Additionally, provide numerical results under both perfect and imperfect CSI. Additionally, considered both type of scenarios i.e. single-cell and multi-cell. Analytic results were used to simulate ZF, while Monte Carlo simulations with random user locations and small-scale fading were conducted to optimize Energy Efficiency (EE) with other schemes. The simulations were performed using Matlab and the code [10], which enables reproducibility as well as simple testing of other parameter values. Therefore different number of users is considered to perform experiments. Now the experiments have been configured with the following parameters as demonstrated in table 1.

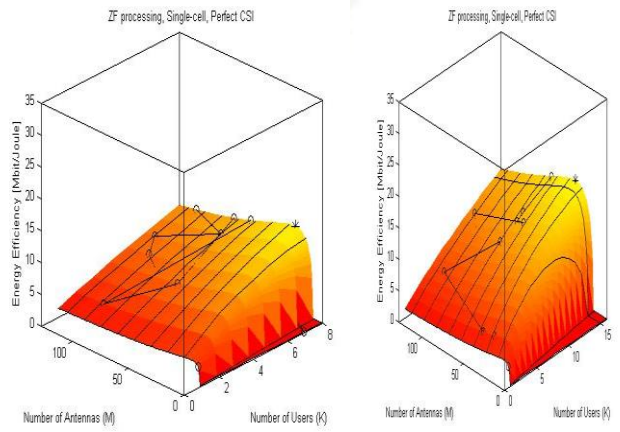
Table 1 Simulation setup

S. No.	Parameters	Values
1	Cell radius (single-cell): d_{max}	250 m
2	Fraction of downlink transmission: $\zeta^{(dl)}$	0.6
3	Minimum distance: d_{min}	35 m
4	Fraction of uplink transmission: $\zeta^{(ul)}$	0.4
5	Large-scale fading model: $l(x)$	$10^{-3.53}/\|\|x\|\|^{3.76}$
6	PA efficiency at the BSs: $\eta^{(dl)}$	0.39
7	Transmission bandwidth: B	20 MHz
8	PA efficiency at the UEs: $\eta^{(ul)}$	0.3
9	Channel coherence bandwidth: B_C	180 kHz
10	Fixed power consumption (control signals, backhaul, etc.): P_{FIX}	18 W
11	Channel coherence time: T_C	10 ms
12	Power consumed by local oscillator at BSs: P_{SYN}	2 W
13	Coherence block (symbols): U	1800
14	Power required to run the circuit components at a BS: P_{BS}	1 W
15	Total noise power: $B\sigma^2$	−96 dBm
16	Power required to run the circuit components at a UE: P_{UE}	0.1 W
17	Relative pilot lengths: $\tau^{(ul)}, \tau^{(dl)}$	1
18	Power required for coding of data signals: P_{COD}	0.1 W/(Gbit/s)
19	Computational efficiency at BSs: L_{BS}	12.8 Gflops/W
20	Power required for decoding of data signals: P_{DEC}	0.8 W/(Gbit/s)
21	Computational efficiency at UEs: L_{UE}	5 Gflops/W
22	Power required for backhaul traffic: P_{BT}	0.25 W/(Gbit/s)

2. Single-Cell Scenario

The aim of the proposed work is to analyze the energy efficiency and the performance influence of with the increasing number of users. In this context the experiments has been carried out with the 8, 16 and 32 number of users and energy efficiency has been measured. Figure 1 and 2 shows the set of achievable EE values with perfect CSI, ZF processing, and for different values of M and K. Here it is considered that M ≥ K + 1 in ZF. Each point uses the EE-maximizing value of ρ. For given values of M and K, the EE-optimal ρ ≥ 0 can be computed as:

$$\rho^* = \frac{e^{W\left(\frac{\eta}{B\sigma^2 S_x}\frac{(M-K)(C'+MD')}{e}-\frac{1}{e}\right)+1}-1}{M-K}$$



(A) (B)

Figure 1 Energy efficiency (in Mbit/Joule) with ZF processing (A) 8 users (B) 16 users

International Journal on Recent and Innovation Trends in Computing and Communication
ISSN: 2321-8169 Volume: 11 Issue: 9s
***Article Received:** 15 April 2023 **Revised:** 25 July 2023 **Accepted:** 18 August 2023*

Where C 0 > 0 and D0 > 0 are defined as:

$$C' = \frac{\sum_{i=0}^{3} C_i K^i}{K}$$

$$D' = \frac{\sum_{i=0}^{2} D_i K^i}{K}$$

It turns out that the optimal ρ^* increases with C' and D', and thus with the coefficients in the circuit power model. Since the EE maximizing total PA power with ZF processing is

$$P_{TX}^{(\mathrm{ZF})} = \frac{\mathrm{B}\sigma^2\mathrm{Sx}}{\eta}\mathrm{K}\rho^*$$

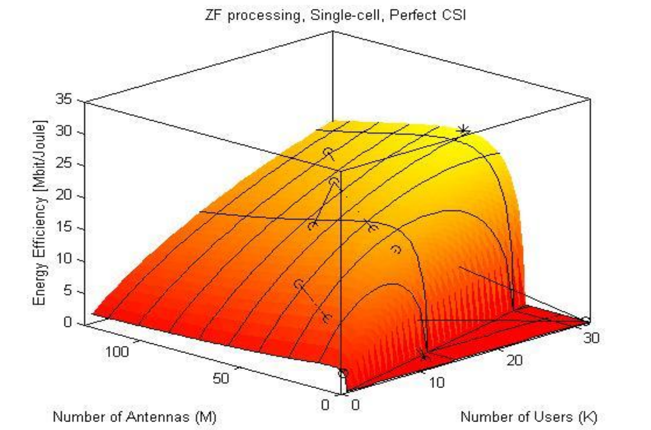
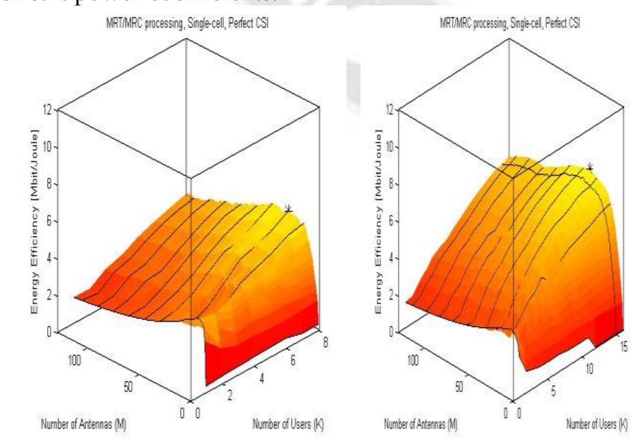


Figure 2 Energy efficiency (in Mbit/Joule) with ZF processing with 32 users

In this figure the global optimum is star-marked and the surroundings are white. The convergence of the alternating optimization algorithm is indicated with circles. Figures show that there is a global EE-optimum, which is achieved by ρ and practically reasonable spectral efficiency 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 surfaces in figures are concave and quite smooth; thus, there is a variety of parameters that provides close-to-optimal EE and the results appear to be robust to small changes in the circuit power coefficients.



(A) (B)

Figure 3 Energy efficiency (in Mbit/Joule) with MRT/MRC processing (A) 8 users and (B) 16 users

The alternating optimization algorithm initiated with a point in (M, K, ρ) = (3, 1, 1). According to a standard alternating optimization algorithm:

1) An initial set (K, M, ρ) is given
2) Update the number of UEs K (and implicitly M and ρ) as:
   Suppose $A, \{C_i\}$, and $\{D_i\}$ are non-negative and constant. For given values of $\bar{\rho}$ and $\bar{\beta}$, the number of UEs that maximize the EE metric is:

$$K^* = \max_l \left\lfloor K_l^{(o)} \right\rceil$$

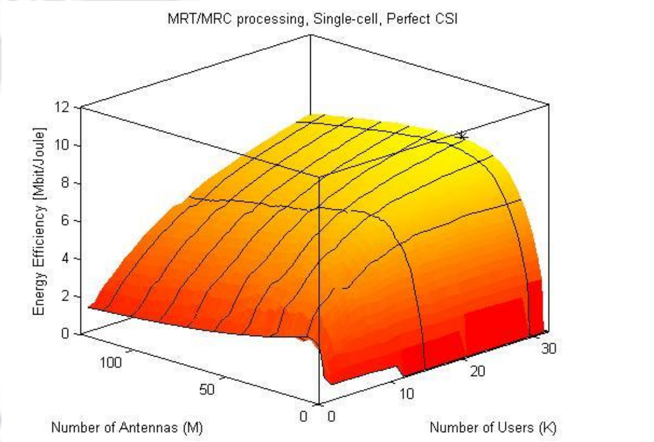


Figure 4 Energy efficiency (in Mbit/Joule) with MRT/MRC processing for 32 users

Where the quantities $\{K_l^{(o)}\}$ denote the real positive roots of the quartic equation

$$K^4 - \frac{2U}{T_{sum}}K^3 - \mu_1 K^2 - 2\mu_0 K + \frac{U\mu_0}{T_{sum}} = 0$$

Where,

$$\mu_1 = \frac{\frac{U}{T_{sum}}\left(C_2 + \bar{\beta}D_1\right) + C_1 + \bar{\beta}D_0}{C_3 + \bar{\beta}D_2}$$

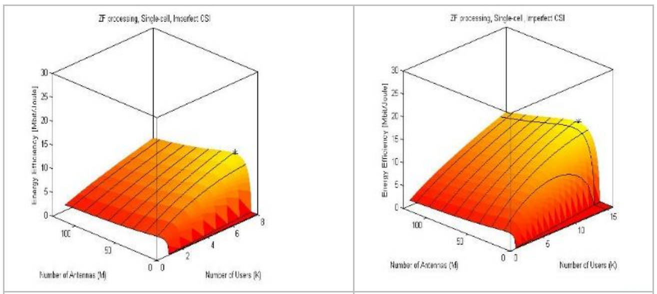
$$\mu_0 = \frac{C_0 + \frac{B\sigma^2 S_x}{\eta}\bar{\rho}}{C_3 + \bar{\beta}D_2}$$

3) Replace M with the optimal value such that: For given values of K and ρ, the number of BS antennas maximizing the EE metric can be computed as:

$$M^* = \left\lfloor M_l^{(o)} \right\rceil$$

$$M^* = \frac{e^{W\left(\frac{\rho\left(\frac{B\sigma^2 S_x}{\eta}\rho + C'\right)}{D'e} + \frac{\rho K - 1}{e}\right) + 1} + \rho K - 1}{\rho}$$

4) Optimize the PA power through ρ
5) Repeat 2) – 5) until convergence is achieved.



(A) (B)

Figure 5 Energy efficiency (in Mbit/Joule) with ZF processing with imperfect CSI (A) for 8 users (B) 16 users

Observe that the EE metric has a finite upper bound (for $C_i > 0$ and $D_i > 0$). Therefore, the alternating algorithm converges to a local optimum for any initial set (K, M, ρ), because the alternating updates of K, M, and ρ may either increase or maintain (but not decrease) the objective function. Convergence is declared when the M and K are left unchanged. Similarly the energy efficiency for MRT/MRC processing is given in Figure 3 and 4.

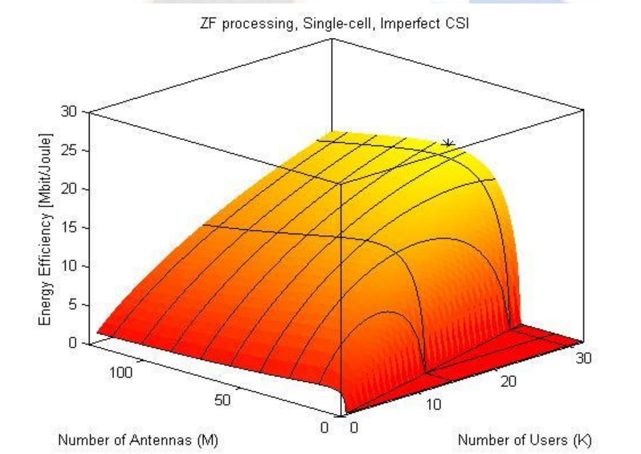
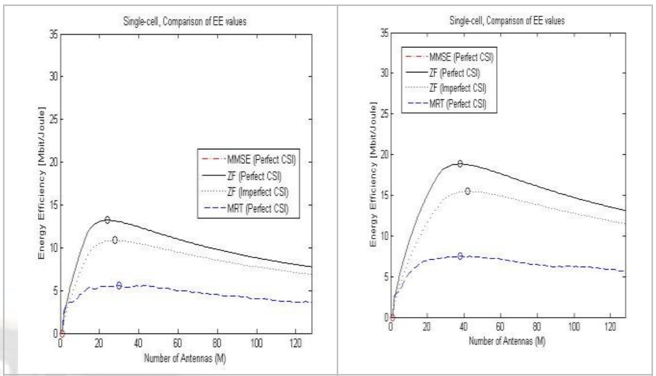


Figure 6 Energy efficiency (in Mbit/Joule) with ZF processing with imperfect CSI and 32 users

The figure 1(A) and (B), and figure 2 shows the energy efficiency of the massive MIMO system for ZF preprocessing and for the MRT/MRC processing results are given in figure 3(A) and (B) and figure 4. Based on the comparative results MRT/MRC processing is more energy efficient than the ZF process. Additionally, shows the lower energy consumption for working. But as the number of UEs is increasing the convergence is being delayed and also increases the energy requirements of the MIMO system. In addition, the number of antenna requirements is also increasing with increasing the UEs. Figure 5 and 6 considers ZF processing under imperfect CSI.



(A) (B)

Figure 7 Maximal EE for different number of BS antennas and different processing schemes (A) 8 users (B) 16 users

If approximate ZF precoding is applied under imperfect CSI (acquired from pilot signaling and MMSE channel estimation), the average gross rate

$$\bar{R} = B\log\left(1 + \frac{\rho(M-K)}{1 + \frac{1}{T^{(ul)}} + \frac{1}{\rho K T^{(ul)}}}\right)$$

is achievable using the same average PA power

$$\frac{B\sigma^2 \rho S_x}{\eta} K$$

As

$$P_{TX}^{(ZF)} = P_{TX}^{(ul-ZF)} + P_{TX}^{(dl-ZF)} = \frac{B\sigma^2 \rho S_x}{\eta} K$$

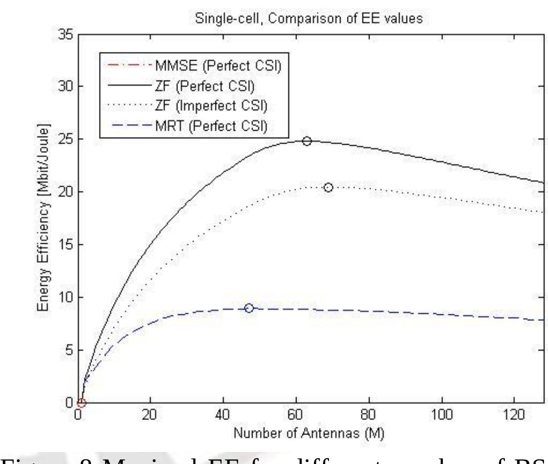
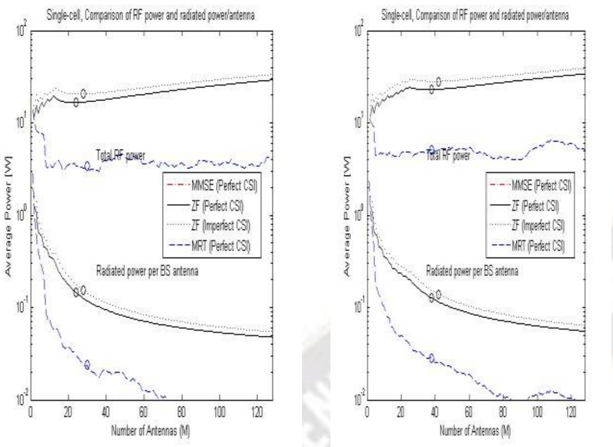


Figure 8 Maximal EE for different number of BS antennas and different processing schemes for 32 users

We observe that ZF processing achieves higher EE. The difference is otherwise quite small. ZF with imperfect CSI has a similar behavior as ZF and MMSE with perfect CSI, thus the analysis has a bearing also on realistic single-cell systems. Interestingly, MRT/MRC processing gives a very different behavior: the EE optimum is much smaller than with ZF/MMSE and is achieved. This can still be called a massive MIMO setup since there are a massive number of BS antennas. but it is a degenerative case where M and K are almost equal and thus the typical asymptotic massive MIMO properties will not hold. The reason for M ≈ K is that MRT/MRC operates under strong inter-user interference, thus the rate per UE is small and it makes sense to schedule as many UEs as possible.



(A) (B)

Figure 9 Total PA power at the EE-maximizing solution for different number of BS antennas for(A) 8 users (B) 16 users

The signal processing complexity is lower than with ZF for the same M and K, but the power savings are not big enough to compensate for the lower rates. To achieve the same rates as with ZF, MRT/MRC requires M K which would drastically increase the computational/circuit power and not improve the EE. Looking at the respective EE-optimal operating points, we can use the following formulas to compute:

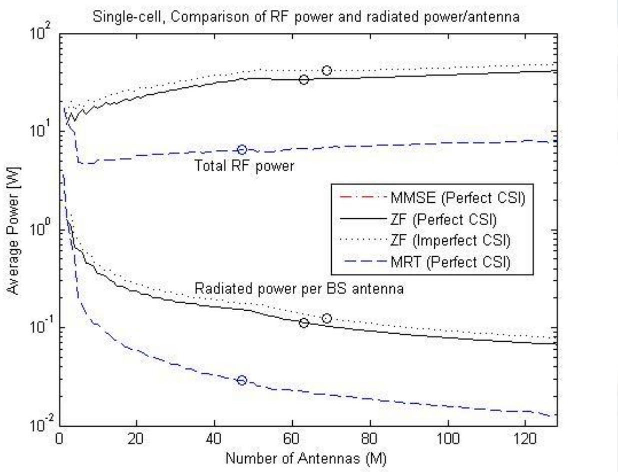


Figure 10 Total PA power at the EE-maximizing solution for different number of BS antennas and 32 users

The total complexity of channel estimation: The total power consumption:

$$P_{CE} = P_{CE}^{(ul)} + P_{CE}^{(dl)}$$

The channel estimation process becomes

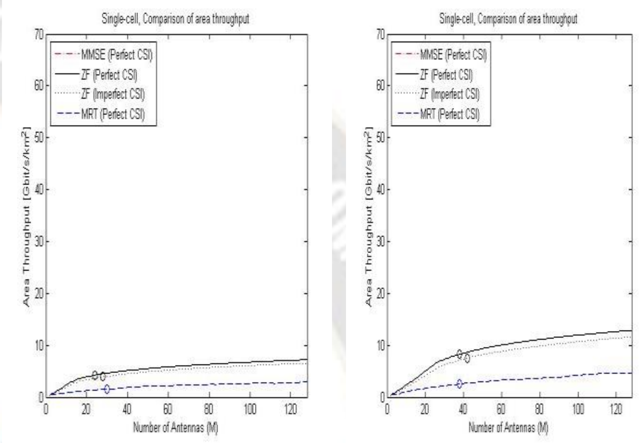
$$P_{CE} = \frac{B}{U}\,\frac{2T^{(ul)}MK^2}{L_{BS}} + \frac{B}{U}\,\frac{4T^{(ul)}K^2}{L_{UE}} \quad Watt$$

Computing the precoding/combining matrices: The power consumption $P_{C/D}$ accounting for these processes is proportional to the number of bits and can thus be quantified as:

$$P_{C/D} = \sum_{k=1}^{K}\left(E\left\{R_k^{(ul)} + R_k^{(dl)}\right\}\right)(P_{COD} + P_{DEC}) \quad Watt$$

Performing precoding and receive combining: The transmitted and received vectors of information symbols at the BS are generated by transmit precoding and processed by receive combining, respectively. This costs:

$$P_{LP} = B\left(1 - \frac{\left(T^{(ul)} + T^{(dl)}\right)K}{U}\right)\frac{2ML}{L_{BS}} + P_{LP-C} \quad Watt$$



(A) (B)

Figure 11 Area throughput at the EE-maximizing solution for different number of BS antennas (A) for 8 users (B) 16 users

Where the first term describes the power consumed by making one matrix-vector multiplication per data symbol. The second term, P_{LP-C}, accounts for the power required for the computation of $\boldsymbol{G}$ and $\boldsymbol{V}$. The precoding and combining matrices are computed once per coherence block and the complexity depends strongly on the choice of processing scheme. Since $\boldsymbol{G} = \boldsymbol{V}$ is a natural choice (except when the uplink and downlink are designed very differently), we only need to compute one of them and thereby reduce the computational complexity. If MRT/MRC is used, we only need to normalize each column of $\boldsymbol{H}$. This requires approximately:

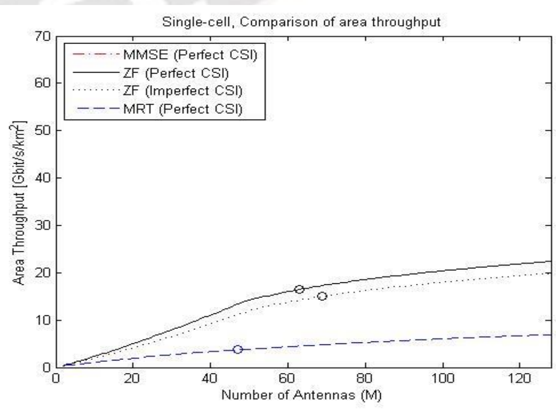


Figure 12 Area throughput at the EE-maximizing solution for different number of BS antennas for 32 users

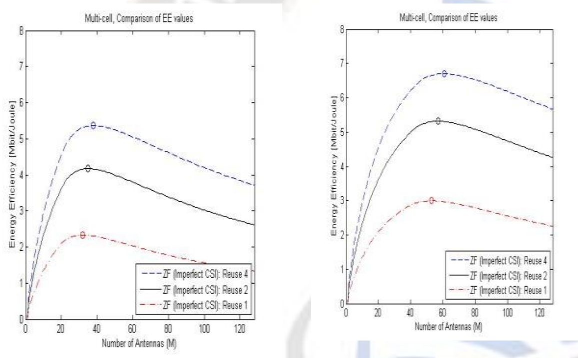
International Journal on Recent and Innovation Trends in Computing and Communication
ISSN: 2321-8169 Volume: 11 Issue: 9s
***Article Received:** 15 April 2023 **Revised:** 25 July 2023 **Accepted:** 18 August 2023*

$$P_{LP-C}^{(MRT/MRC)} = \frac{B}{U}\frac{3MK}{L_{BS}} \quad Watt$$

which was calculated using the arithmetic operations for standard linear algebra operations in [29]. On the other hand, if ZF processing is selected, then approximately

$$P_{LP-C}^{(ZF)} = \frac{B}{U}\left(\frac{K^3}{3L_{BS}} + \frac{3MK^2 + MK}{L_{BS}}\right) \quad Watt$$

These numbers are all within a realistic range and a majority of the computations can be parallelized for each antenna. Despite its larger number of BS antennas and UEs, ZF processing only requires $3x$ more operations than MRT/MRC. This is because the total complexity is dominated by performing precoding and receives combining on every vector of data symbols, while the computation of the precoding matrix (which scales as $O(K^3 + MK^2)$ for ZF) only occurs once per coherence block.



(A) (B)

Figure 13 Maximal EE in the multi-cell scenario for different number of BS antennas and different pilot reuse factors (A) for 8 users (B) 16 users

To further compare the different processing schemes, Figure 7 and 8 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. Next, Fig. 9 and 10 shows the total PA power that maximizes the EE for different M using the corresponding optimal K. For all the considered processing schemes, the most energy-efficient strategy is to increase the transmit power with M.

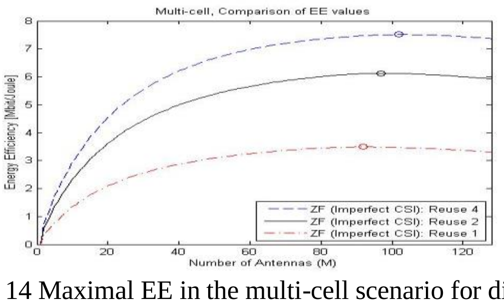
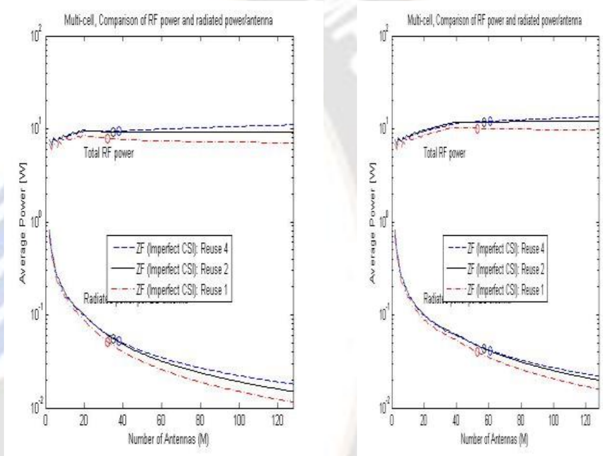


Figure 14 Maximal EE in the multi-cell scenario for different number of BS antennas and different pilot reuse factors for 32 users

That indicated that the transmit power should be decreased with M. However, figure also shows that the transmit power per BS antenna decreases with M. The EE-optimal solution can be deployed with low-power UE-like RF amplifiers. Similar transmit power levels are observed for the UEs in the uplink, but are not included. Finally, Figure 11 and 12 shows the area throughput (in Gbit/s/km^2) that maximizes the Energy Efficiency for different M. We consider the same processing schemes as previously discussed experiments. According to the measured throughput there is an 8-fold improvement. The majority of this gain is achieved also under imperfect CSI, which shows that massive MIMO with proper interference-suppressing precoding can achieve both great energy efficiency and unprecedented area throughput. In contrast, it is wasteful to deploy a large number of BS antennas and then co-process them using a MRT/MRC processing scheme that is severely limiting both the energy efficiency and area throughput.



(A) (B)

Figure 15 Total PA power at the EE-maximizing solution in the multi-cell scenario, for different number of BS antennas. The radiated power per BS antenna is also shown (A) for 8 users and (B) for 16 users

3. Multi-Cell Scenario

In this experimental scenarios the similar amount of users are considered and the symmetric multi-cell scenario has been used. Additionally, each cell is considered as a 500 × 500 square with uniformly distributed UEs, with the same minimum distance. The similar cell configuration has been used in the single-cell scenario. We consider only interference that arrives from the two closest cells, thus the cell is representative for any cell in the system. Motivated by the single-cell results, we consider only ZF processing and focus on comparing different pilot reuse patterns. The cells are divided into four clusters. Three different pilot reuse patterns are considered:

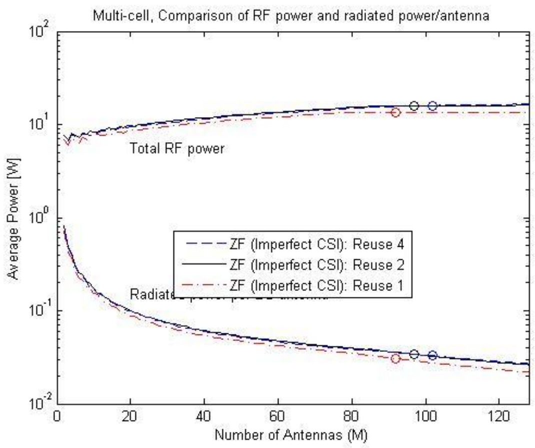
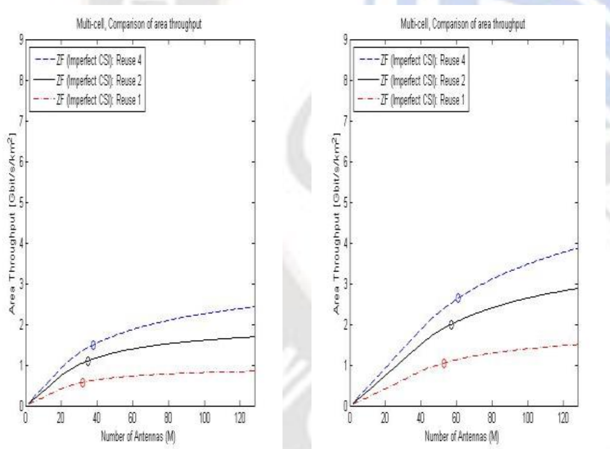


Figure 16 Total PA power at the EE-maximizing solution, for different number of BS antennas for 32 users

- The same pilots in all cells (τ (ul) = 1),
- Two orthogonal sets of pilots with Cluster 1 and Cluster 4 having the same (τ (ul) = 2), and
- All clusters have different orthogonal pilots (τ (ul) = 4).

Numerical computations of the relative inter-cell interference give $I_{PC} \in \{0.5288, 0.1163, 0.0214\}$ and $I_{PC^2} \in \{0.0405, 0.0023, 7.82 * 10^{-5}\}$, where the values reduce with increasing reuse factor $\tau^{(ul)}$.



(A) (B)

Figure 17 Area throughput at the EE-maximizing solution for different number of BS antennas (A) when the number of users 8 and (B) when the number of user 16

Moreover, $I = 1.5288$ and $\frac{B\sigma 2\rho Sx}{\eta} = 1.6022$ is considered in this multi-cell scenario. The maximal EE for different number of antennas is shown in Figure 13 and 14. Additionally, Figure 15 and 14(D) show the corresponding PA power (and power per BS antenna). Similarly, Figure 16 and 17 shows the area throughput. These figures are very similar to the single-cell counterparts, but with the main difference that all the numbers are smaller.

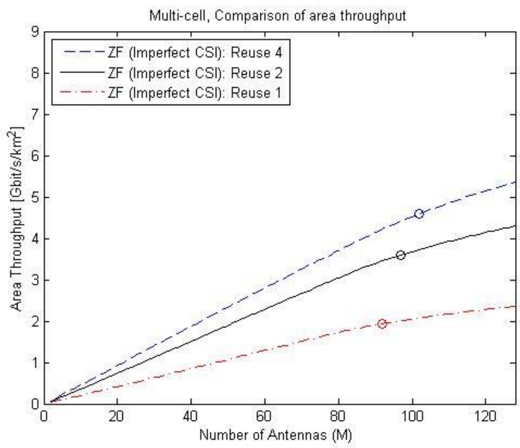
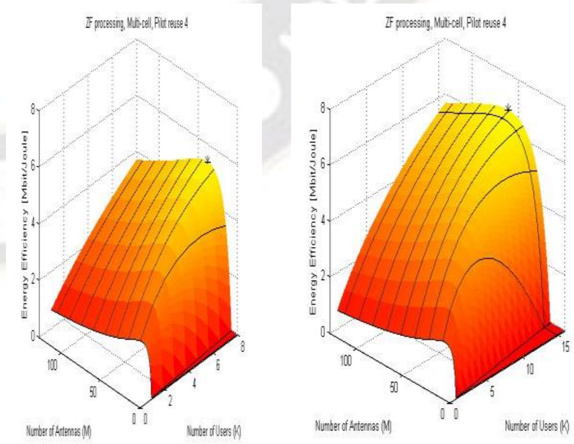


Figure 18 Area throughput at the EE-maximizing solution for different number of BS antennas when the number of users 32

Hence, the inter-cell interference affects the system by reducing the throughput, reducing the transmit power consumption, and thereby also the EE. Interestingly, the largest pilot reuse factor ($\tau^{(ul)} = 4$) gives the highest EE and area throughput. This shows the necessity of actively mitigating pilot contamination in multi-cell systems. We stress that it is still EE-optimal to increase the transmit power with M, but at a pace where the power per antenna reduces with M. Finally, the set of achievable EE values is shown in Figure 18 and 19 for different values of M and K. This figure considers a pilot reuse of $\tau^{(ul)} = 4$, since it gives the highest EE. We note that the shape of the set is similar to the single-cell, but the optimal EE value is smaller since it occurs at the smaller system dimensions. This is due to inter-cell interference, which forces each cell to sacrifice some degrees-of-freedom. We note that the pilot overhead is almost the same as in the single-cell scenario, but the pilot reuse factor gives room for fewer UEs. Nevertheless, we conclude that massive MIMO is the EE-optimal architecture.



(A) (B)

Figure 19 Energy efficiency (in Mbit/Joule) with ZF processing in the multi-cell scenario with pilot reuse 4 for (A) 8 users and 128 Antennas (B) 16 users and 128 Antenna

4. Conclusion and future work

The massive MIMO system is a base architecture of 5G communication. It enables the high quality of service delivery and provides the better user experience. Thus, a rapid increase in cellular infrastructure has done in recent year. The increasing density of cellular base stations will also increase the electric energy consumption and also responsible of green house effect. In this context, the proposed work is aimed to analyze and study the energy requirements of the base station antenna. Therefore, a massive MIMO simulator has been used for conducting the experiments. The aim of the experiments is to demonstrate the influence of number of UEs over the energy efficiency of the base station. In this context, the maximal energy efficiency and optimal energy efficiency has been measured with the optimal throughput. Additionally the different preprocessing techniques have also compared and the relevant energy consumption has been measured. Based on the final consequences the ZF processing technique provides optimal results.

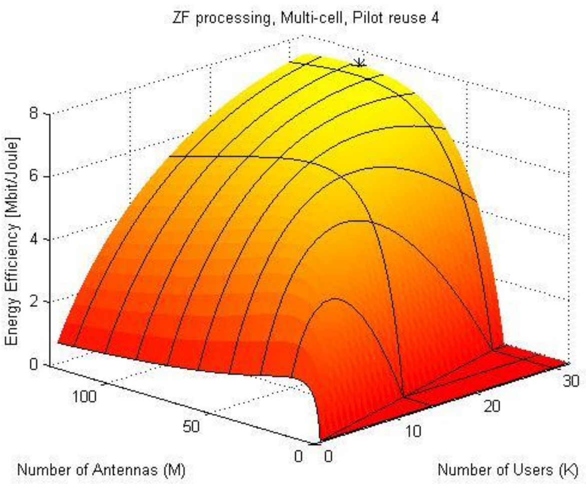


Figure 20 Energy efficiency (in Mbit/Joule) with ZF processing in the multi-cell scenario with pilot reuse 4 for 32 users and 128 Antenna

References

[1] G. Auer and et al., "D2.3: Energy efficiency analysis of the reference systems, areas of improvements and target breakdown", INFSO-ICT-247733 EARTH, ver. 2.0, 2012. Available: http://www.ict-earth
[2] S. Tombaz, A. Vastberg, and J. Zander, "Energy- and cost-efficient ultra-high-capacity wireless access," IEEE Wireless Commun. Mag., vol. 18, no. 5, pp. 18–24, 2
[3] G. Miao, "Energy-efficient uplink multi-user MIMO," IEEE Trans. Wireless Commun., vol. 12, no. 5, pp. 2302–2313, 2013
[4] Y. Hu, B. Ji, Y. Huang, F. Yu, and L. Yang, "Energy-efficiency resource allocation of very large multi-user MIMO systems," Wireless Netw., 2014.
[5] E. Bjornson, M. Kountouris, and M. Debbah, "Massive MIMO and small ¨ cells: Improving energy efficiency by optimal soft-cell coordination," in Proc. Int. Conf. Telecommun. (ICT), 2013.
[6] D. Ha, K. Lee, and J. Kang, "Energy efficiency analysis with circuit power consumption in massive MIMO systems," in Proc. IEEE Int. Symp. Personal, Indoor and Mobile Radio Commun. (PIMRC), 2013.
[7] H. Yang and T. Marzetta, "Total energy efficiency of cellular large scale antenna system multiple access mobile networks," in Proc. IEEE Online Conference on Green Communications (OnlineGreenComm), 2013.
[8] S. Mohammed, "Impact of transceiver power consumption on the energy efficiency spectral efficiency tradeoff of zero-forcing detector in massive MIMO systems," 2014, submitted. [Online]. Available: http://arxiv.org/abs/1401.4907v1
[9] Emil Bjornson, Luca Sanguinetti, Jakob Hoydis, Merouane Debbah, "Optimal Design of Energy-Efficient Multi-User MIMO Systems: Is Massive MIMO the Answer?", arXiv:1403.6150v2 [cs.IT] 5 Mar 2015
[10] https://github.com/emilbjornson/is-massive-MIMO-the-answer