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Impact of Circuit Power on the Energy Efficiency of Massive Multiple-Input Multiple-Output (MIMO) Cellular Systems

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ABSTRACT

Massive multiple-input multiple-output (MIMO) systems are designed to increase data capacity systems. However, there are growing social and economic concerns in developing these communication technologies. Energy efficient systems are desirable for these systems considering the costs and minimizing resources. Thus, the optimization of these approaches is significant in the advancement of green communication. This paper converges on the circuit power in modelling massive MIMO systems. Specifically, to apply various power consumption of the transceiver chains, to determine the desired power of the base station value for maximum energy efficiency, and to define the effects of a realistic circuit power consumption model in Massive MIMO systems. Mathematical models were developed, and the corresponding codes were simulated using MATLAB. Different processing schemes were also studied, namely, maximum ratio transmission/maximum ratio combining, and zero forcing for the perfect and imperfect single-cells scenario. In contrast, multiple cells consider different re-use factors. As observed, a low power wattage consumption of transceiver chains and base stations is desired to produce a more remarkable relative change in energy efficiency. Local oscillators' power usage is also recommended to be low wattage. Low-power systems utilize low energy consumption but not disregarding higher energy efficiency. Other factors in data throughput – bandwidth, transmit power, noise power spectral density, and path loss, can be studied to optimize energy-efficient massive MIMO systems.

1. Introduction

Communications has become a crucial part of the contemporary world, with wireless transmission dominating the field. Since the advent of mobile telephony, phones, tablets, laptops, and other electronic communication devices have been indispensable for humans, and life without wireless communication has become unimaginable. Antennas have gained impetus as the pillar of wireless communication systems, functioning as an electronic eye and ear [1,2]. Antennas have

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existed for many years but have recently gone through a significant revolution, particularly the link between the radio system and the outside world [2]. Massive multiple-input multiple-output (MIMO) plays a significant role in 5G, even though conventional MIMO concepts are currently used in several Wi-Fi and 4G standards. Fifth-generation (5G) networks are the latest mobile technology. Their application is rapidly crucial because of the advantages this brings to cellular telecommunications [3]. 5G cellular networks that enable high-speed traffic have emerged as a crucial technology. The utilization of the available spectrum to accomplish the quality of service (QoS) and improve network quality generally is made possible by 5G [4-6]. Massive MIMO is an innovative technology with many antenna elements to increase capacity systems [7]. However, energy-related pollution and the power consumption of the communication technology sector are growing social and economic issues [8]. Also, issues related to the environment have emerged as efforts to develop different techniques to increase data capacity [7,9]. There are a few strategies to use when maximizing energy: enhancing the base station hardware's energy efficiency; selectively turning off components; enhancing the radio transmission process' energy efficiency; organizing and deploying various cells [10,11]. For addressing this concern of green communications [12], this paper considers the circuit power consumption (P_{CP}) used by massive MIMO systems. P_{CP} is the overall power used by various analog elements, and digital signal processing [13].

This paper focused on the effects of P_{CP} and its relative change in massive MIMO systems' energy efficiency (EE). Notably,

i. to apply various power usage levels of the transceiver chains (P_{TC}) based on their actual data sheets
ii. to determine the desired power of the base station (P_{BS}) value for maximum EE
iii. define the effects of a realistic circuit power consumption model in massive MIMO systems.

1.1 Massive MIMO Systems

Massive MIMO systems are multi-antenna or multi-input multi-output wireless communication devices with many antenna components for their arrays. It can provide needed data rates which became an essential technology in wireless Internet [14-16]. User terminals, tablets, and base stations are a few examples of the devices used in massive MIMO networks. These devices may be built with numbers of antenna elements that are times greater than those used by existing devices.

Antennas, electrical parts, network structures, protocols, and signal processing are essential components [17-19]. The mobile station typically uses only a few antennas for most MIMO implementations. While this gain in spectral efficiency is significant, it is still moderate [20]. Massive MIMO enhances the wireless communication network's capacity, complements beamforming, and enables next-generation technologies. However, the expense involved in implementing and deploying Massive MIMO is one of its main drawbacks [21-23]. The EE of a communication system is expressed in bits/Joule [12], sometimes referred to as the ratio of the total average power consumption to the average possible cumulative information rate. The assumption that radiated power of transmitter base stations is proportional to the power consumption is not always so in massive MIMO systems [8]. This observation occurs when infinite EE is reached as the number of antennas of these systems also approaches infinity [24]. Thus, a more accurate and comprehensive model is needed.

1.2 Optimization of Circuit Power for Energy Efficiency

According to [25], each antenna's broadcast power usage in massive MIMO systems is low. Another similar research about EE uses an existing power model that considers transmitting power usage, increasing the number of antennas, which results in higher data rates and EE performance. As the system's hardware grows, the number of antennas continually impact the circuit power consumption. Therefore, the transmit power and radio frequency circuit power utilization should be significant factors in the real power consumption model [7]. A new power consumption model is made using the model for the massive MIMO systems' EE. When considering the circuit power consumption for transmit antennas, it is not recommended to expect the energy efficiency to increase much with the increase in the number of transmit antennas [26].

In the benefit-cost analysis, EE is the data throughput divided by energy consumption. Data throughput is the area of spectral efficiency. In contrast, energy consumption is the sum of the transmit and circuit power per area [27]. This description clarifies that while a cellular network's EE is being optimized, three key variables may be changed - area spectral efficiency, transmit power, and circuit power per area. Spectral efficiency considers the bandwidth, path loss, and noise power spectral density.

2. Methodology

2.1 Realistic Circuit Power Utilization of Massive MIMO Systems

The multiuser MIMO systems circuit power consumption model is based on the paper developed by Björnson *et al.,* Eq. (1) shows a way to obtain massive MIMO systems' circuit power. P_{CP} is the sum of the fixed power (P_{FIX}), power of the load-dependent backhaul (P_{BH}), power of the channel estimation process performed once per coherence block (P_{CE}), power of the channel coding and decoding units ($P_{\mathrm{C/D}}$), power of the linear processing at the base station (P_{BS}), and the power of the transceiver chains (P_{TC}) [13].

$$P_{\mathrm{CP}} = P_{\mathrm{FIX}} + P_{\mathrm{BH}} + P_{\mathrm{CE}} + P_{\mathrm{C/D}} + P_{\mathrm{BS}} + P_{\mathrm{TC}} \quad (1)$$

P_{FIX} accounts for the power consumption needed for baseband processors, backhaul infrastructure, control signals, and site cooling [8]. Commonly, the backhaul's power utilization is calculated as the sum of one load-independent and one load-dependent [28]. Power consumption is constant for load-independent components like the cooling system, microwave connection, and rectifier. However, it fluctuates for load-dependent components like the power amplifier, digital signal processing, and transceiver [29].

The power in base stations (P_{BS}) for circuit components formula is based on the paper of [13] and is reflected below:

$$P_{\mathrm{BS}} = \frac{P_{\mathrm{TC}} - P_{\mathrm{SYN}} - KP_{\mathrm{UE}}}{M} \quad (2)$$

where P_{SYN} is the electrical power utilized by local oscillators, K is the number of active user equipment, P_{UE} is the power required by amplifiers, mixers, oscillators, and filters of every single-antenna user equipment, and M is the number of antennas.

The relative change or absolute change is the quotient that describes the size of the absolute change in comparison to the reference value Eq. (3). This formula is utilized to see the EE percentage difference of the different circuit power values.

$$\text{Relative Change} = \frac{\text{New Value} - \text{Reference Value}}{\text{Reference Value}} \tag{3}$$

2.2 Transceiver Chains Data Sheets

A small cell's antenna transmission power ranges from 250 mW to 120 W for the 5G MIMO arrays. A typical antenna lower than this generation has a transmission power of 20W [30]. For this paper, the assumption of the transceiver power is based on the datasheets from manufacturers. The typical power usage for outdoor 5G systems are 20W, 30W, and 40W [30,31]. Datasheets from manufacturers use 950W and 975W power consumption of active antenna units (AAU) [32,33]. For this reason, these values are used in the simulation to determine the relative change in the efficiency of massive MIMO systems.

Table 1 summarizes the simulation power values that were manipulated from the values used by the paper of Björnson [13]. P_{SYN} equal to 0 is also considered for systems using multiple oscillators. Other values in the paper were calculated based on the data sheets and using the formula of Eq. (2).

Table 1
Values used in the simulation

P_{BS} (W)	P_{SYN} (W)	P_{TC} (W)
0.06	2	30
0.07	0	30
0.10	2	40
0.11	0	40
4.24	2	950
4.25	0	950
4.35	2	975
4.36	0	975

The complete values used are shown in Table 2. The manipulation of output power is based on the assumption of their paper. The corresponding simulation parameters were executed using MATLAB, on which the figures and values represented in the next section are based. The code has been made available for download on this link (https://github.com/emilbjornson/is-massive-MIMO-the-answer). The present study changed the P_{BS}, and P_{SYN} values in line 83 and line 82 of the code.

Table 2
Simulation Values [13]

Parameter	Value	Parameter	Value
$d_{\max}$	250m	$\zeta^{(dl)}$	0.6
$d_{\min}$	35m	$\zeta^{(ul)}$	0.4
$l(\text{x})$	$10^{-3}/\|\|\text{x}\|\|^{3.76}$	$\eta^{(dl)}$	0.39
B	20MHz	$\eta^{(ul)}$	0.3
B_{C}	180kHz	P_{FIX}	2
T_{C}	10ms	P_{SYN}	As computed
U	1800	P_{BS}	As computed
$B\sigma^2$	−96dBm	P_{UE}	0.1W
$\tau^{(ul)}, \tau^{(dl)}$	1	P_{COD}	0.1W/(Gbit/s)
L_{BS}	12.8Gflops/W	P_{DEC}	0.8W/(Gbit/s)
L_{UE}	5Gflops/W	P_{BT}	0.25W/(Gbit/s)

2.3 Precoding Techniques of Massive MIMO Systems

The antenna diversity technique is one of the often-employed strategies by wireless communications engineers to counter multipath fading. This paper used the common precoding and received combining schemes as a method also used by Björnson. These are the maximum ratio transmission/combining (MRT/MRC), the minimum mean squared error (MMSE) processing, and zero-forcing (ZF) [13].

In a MIMO wireless communications system, a multiple antenna transmitter can eliminate multiuser interference by using the zero-forcing (also known as null-steering) precoding technique. [34]. MRC is a traditional combining method that maximizes the signal-to-noise ratio (SNR) of the summed signals from the received antenna components [35]. This paper utilized the model developed by [13], which is reflected in Eq. (4). This equation determines the maximum optimal EE of different cell architectures. Please note that values used in processing are based on Table 2, and other values/variables are from the assumptions of [13]. Table 3 depicts the different formulas used in the computation of ZF circuit power coefficients.

$$\rho^{\star} = \frac{e^{W\left(\frac{\eta}{\beta\sigma S_x}\frac{(M-K)(C'+MD')}{e}-\frac{1}{e}\right)+1}-1}{M-K} \quad (4)$$

Table 3
ZF Circuit Power Coefficients [13]

Coefficients $\{C_i\}$	Coefficients A and $\{D_i\}$
$C_0 = P_{FIX} + P_{SYN}$	$A = P_{COD} + P_{DEC} + P_{BT}$
$C_1 = P_{UE}$	$D_0 = P_{BS}$
$C_2 = \frac{4B\tau^{(dl)}}{UL_{UE}}$	$D_1 = \frac{B}{LBS}\left(2+\frac{1}{U}\right)$
$C_3 = \frac{B}{3UL_{BS}}$	$D_2 = \frac{B}{UL_{BS}}(3-2\tau^{(dl)}$

where $C' > 0$ and $D' > 0$ are characterized as

$$C' = \frac{\sum_{i=0}^{3} C_i K^i}{K} \text{ and } D' = \frac{\sum_{i=0}^{2} D_i K^i}{K} \quad (5)$$

3. Results

The results produced by the paper of Björnson [13] were the baseline data of this paper in the computation of relative change in energy efficiency. The mathematical equations and assumptions of the paper [13] were modified to produce results. Particularly on the circuit power values of the massive MIMO systems. Results on the effects of the circuit power are presented by the EEs produced after running the simulation parameters in MATLAB.

For calculating the relative EE, a standard single-cell scenario is used. A basic model optimizes the base stations and intelligent reflecting surface phase changes. Then, the same model is expanded to a multi-cell setting where each base station performs the precoding function separately [36]. The cells of the multi-cell are separated into four clusters. Three distinct pilot re-use forms are considered: identical pilots in all cells, the two sets of orthogonal pilots with the same lengths, and the different orthogonal pilots in each cluster [13].

The maximal EE for the various base station antennas and processing schemes in a single-cell scenario is shown in Figure 1. These figures were produced in MATLAB after running the codes.

Depicted here are the baseline data (Figure 1, upper left) results used to find the relative change in energy efficiency, where it is noticeable that a lower P_{BS} value, 0.06W, produced a higher EE (Figure 1, top center) and, inversely, a higher P_{BS} value, 4.36W, resulted in a lower EE (Figure 1, bottom right). This result validates all processing schemes, ZF perfect and imperfect channel state information (CSI), and MRT. Perfect CSI produced the highest EE, as shown (circles are EE optimal points). It can also be observed that the number of antennas varies per processing scheme. Due to close-to-zero energy efficiency, the MMSE processing scheme is omitted in representing the EE of massive MIMO antennas.

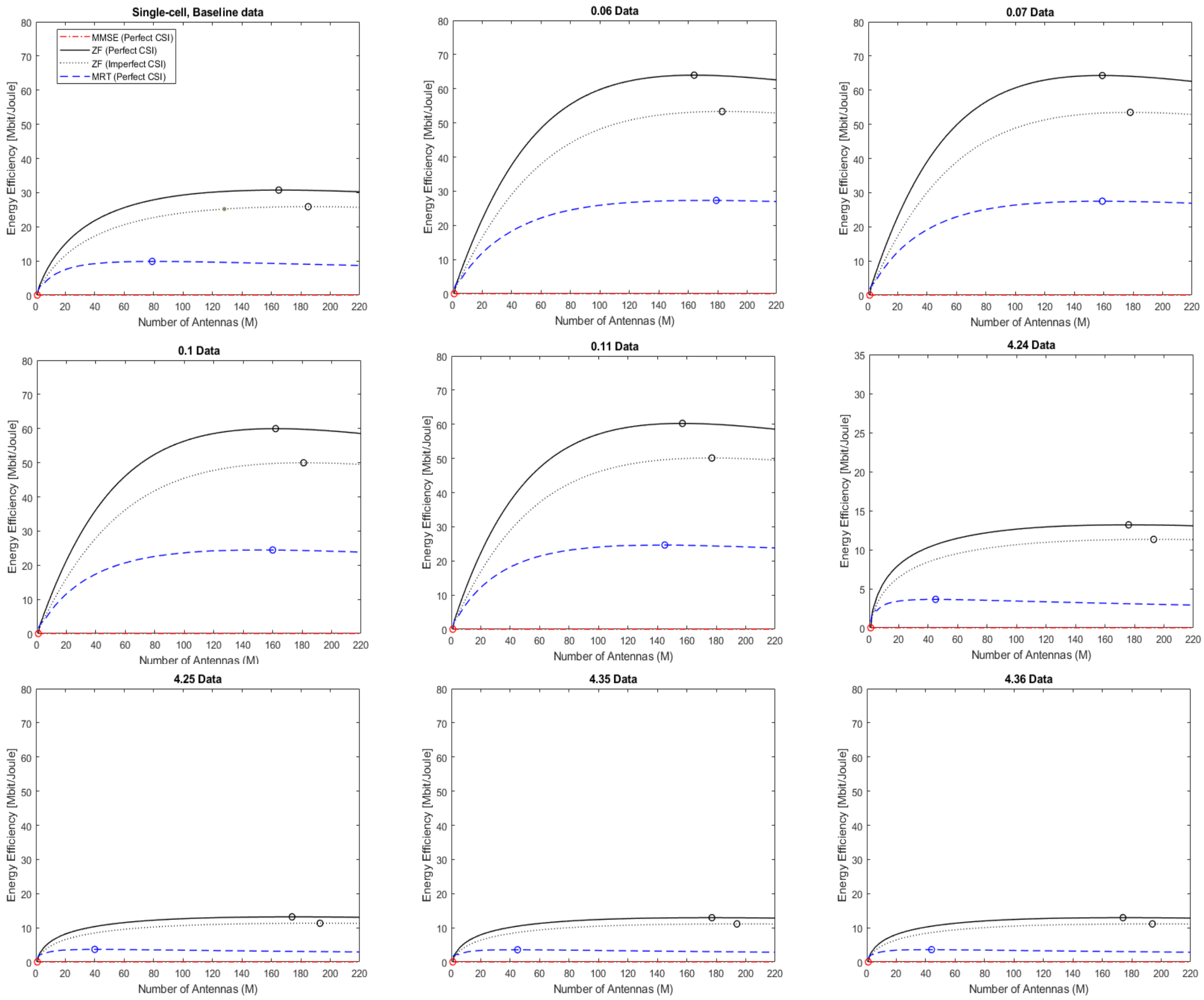

Fig. 1. Single-cell maximal EE using ZF, MRT, and MMSE schemes

Multi-cell EE is depicted in Figure 2. Baseline data used results from the assumption of Björnson *et al.,* [13]. Blue broken lines represent the ZF imperfect CSI re-use 4, black line for re-use 2, and red line for re-use 1. Circles are the maximum EE point per re-use. The pilot re-use factor aims to provide the neighboring cells with distinct orthogonal signals. The only issue is intra-pilot contamination because these distinctive orthogonal signals are only utilized once and within the cell [37]. The concept of re-use factors uses the same frequency upon a specific geographical location. Thus a higher re-use factor produces higher EE because there is less limit in the use of frequency in limited locations [38].

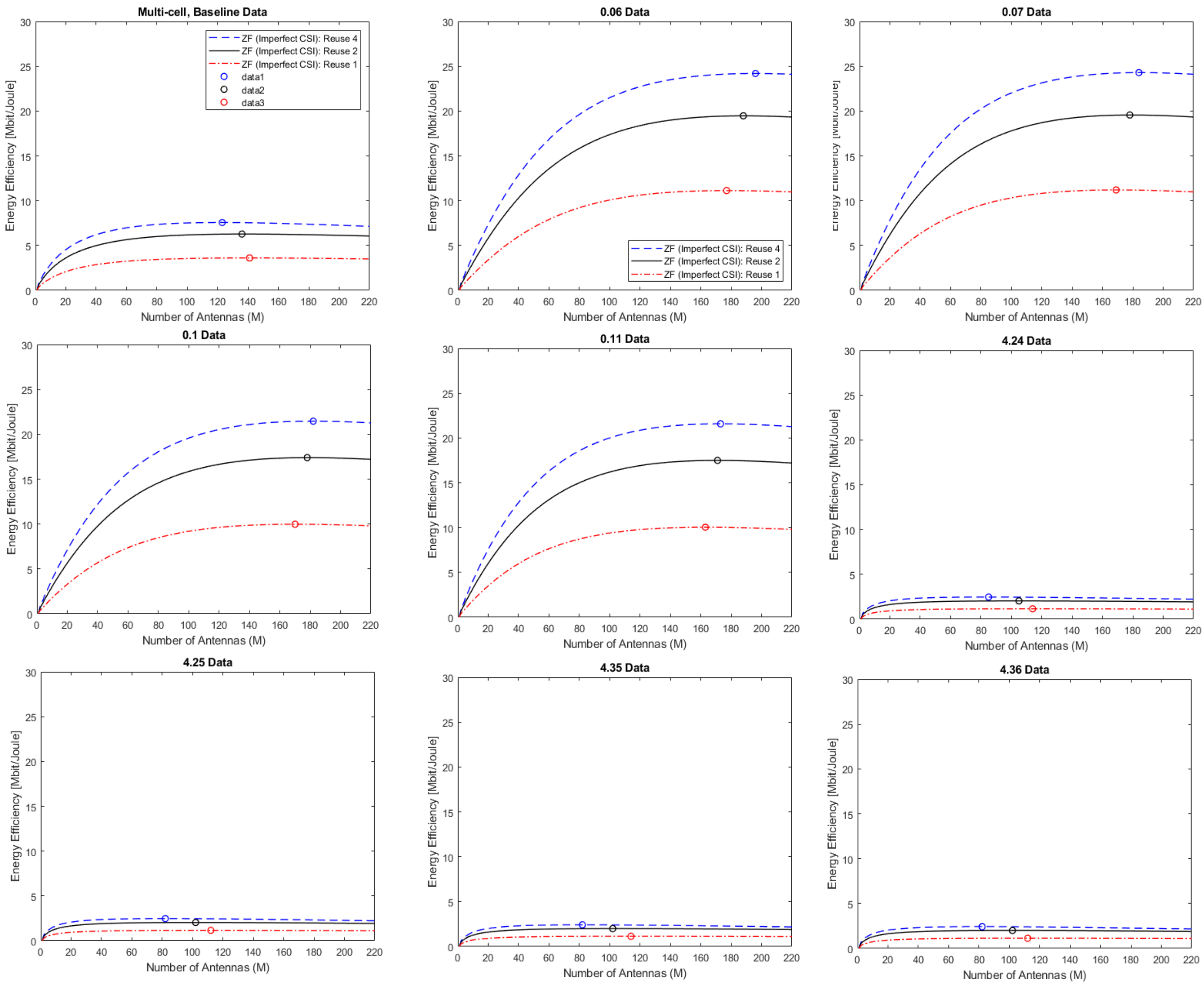

Fig. 2. Multi-cell maximal EE using different re-use factors

The energy efficiency simulation results using 0.06W and 4.36W P_{BS} values are depicted in Figure 3 and 4, respectively. These figures include results of the three linear processing schemes for the single-cell, while the ZF processing result for the multi-cell pilot re-use 4. After running the codes, these graphs were generated in MATLAB to determine the optimal efficiency of the corresponding circuit power. The x-axis corresponds to the optimum number of users, the y-axis is the optimum number of antennas, and the z-axis is the energy efficiency.

These variables differ in the results upon entering the varying P_{BS} values. The ZF produced the highest efficiency from the different processing schemes. This result applies to both single- and multi-cell systems. It is seen in these figures that a low P_{BS} value (0.06W) produced a higher energy efficiency, while a high P_{BS} value (4.36W) generated a lower energy efficiency, which answers our assumption of the paper of [27], where circuit power contributes to the total EE of massive MIMO systems.

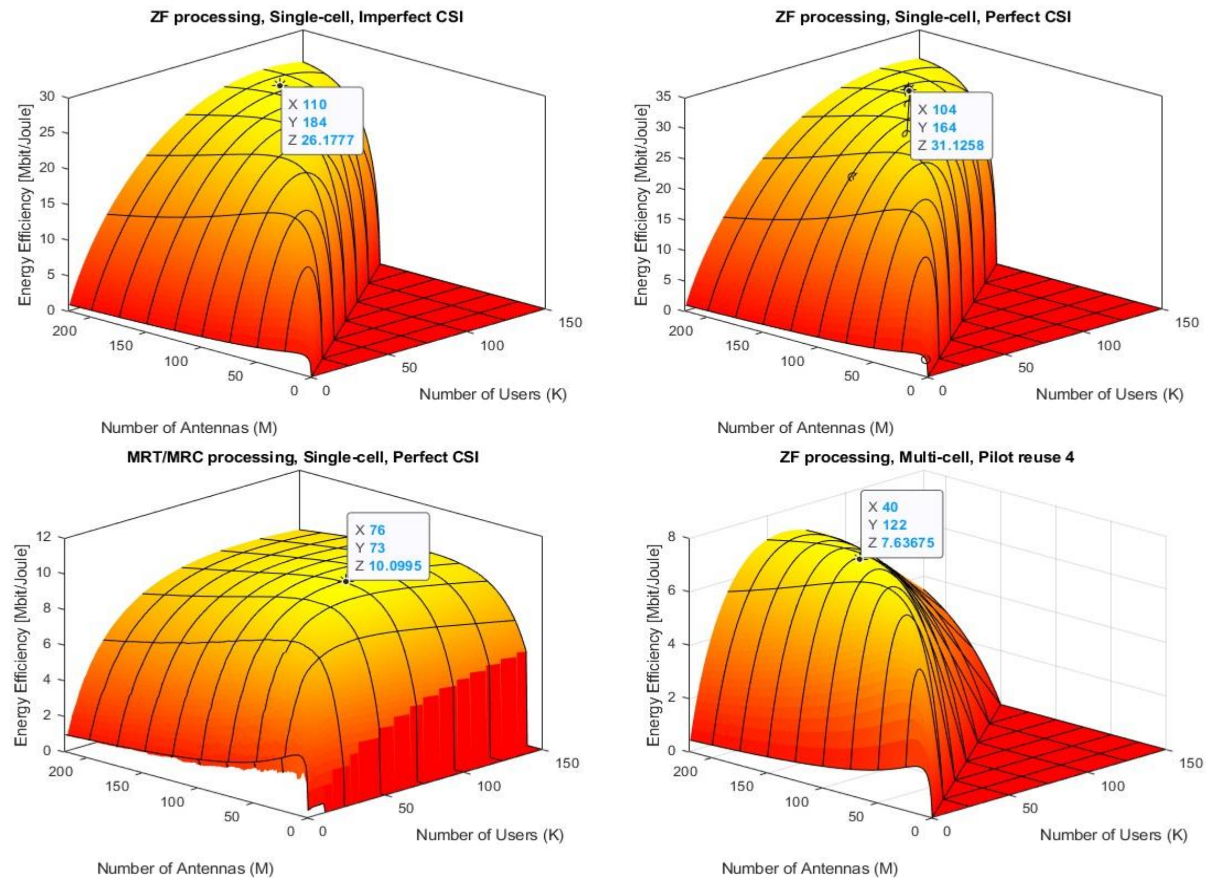

Fig. 3. Energy efficiency of the 0.06W P_{BS} Value

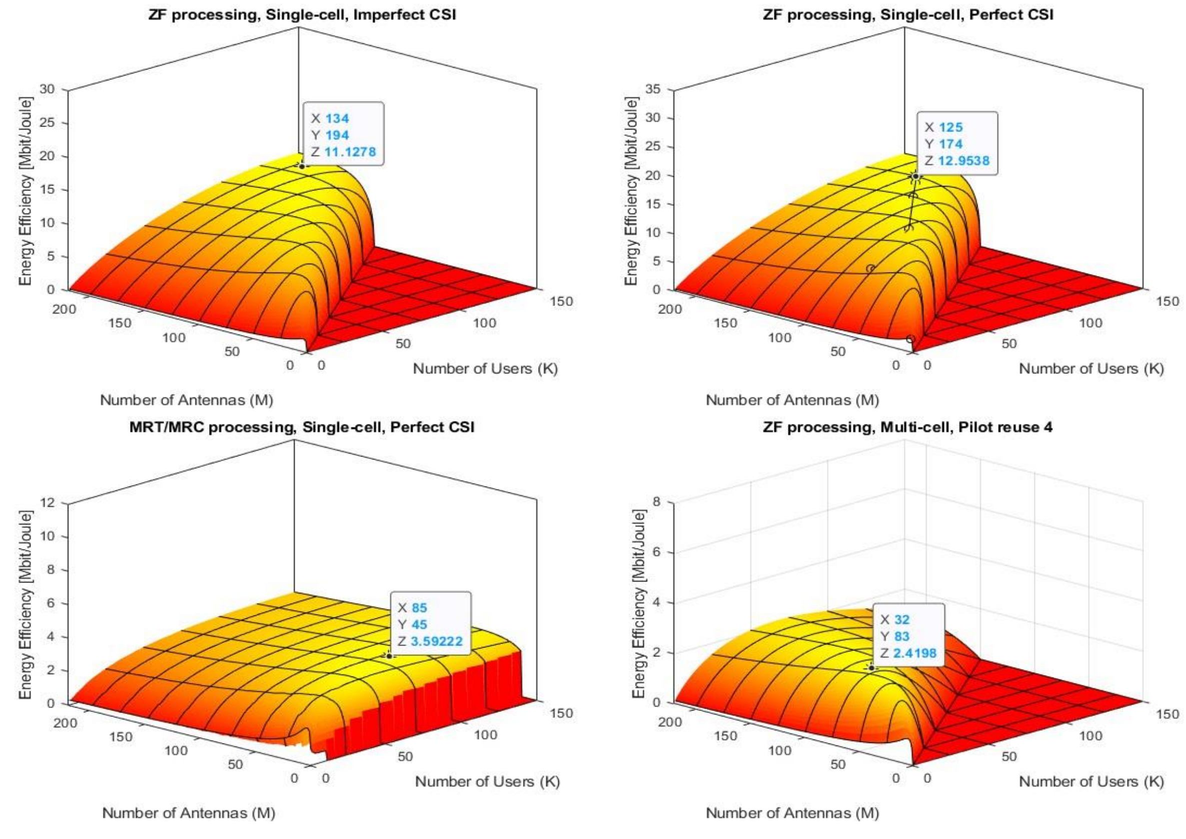

Fig. 4. Energy efficiency of the 4.36W P_{BS} Value

3.1 Relative Change in Energy Efficiency

The relative change in EE is applied in this paper to determine the effects of circuit power in massive MIMO systems. It is the change in energy efficiency from the baseline data. It is prominent in Table 4 that in single-cell, low P_{BS} value has a very high percentage difference in energy efficiency in reference to a 1W P_{BS}. While higher than 1W P_{BS} produced a negative relative change percentage in EE, which means that these values produced a much lower EE than the baseline data. A similar interpretation for a multi-cell scenario can be observed. As denoted in the P_{BS} values used were based on the transceiver powers used in massive MIMO systems. It does not necessarily mean that all low P_{BS} have higher efficiency, it is still dependent on the P_{SYN} values. It was observed that the P_{SYN} values have effects on the result, a low P_{BS} with P_{SYN} equal to zero (0) produced a higher relative change in EE (2nd line of Table 4) compared to the P_{SYN} equal to two (2) (1st line of Table 4). This outcome can also be observed in other results in the table. A lower P_{SYN} value produced a higher EE compared to a higher P_{SYN} value. Different processing schemes produced a related interpretation of results except for MMSE, where results produced no change or no difference. MRT scheme has the highest relative change percentage in EE produced at 178.64% for single cell and ZF Perfect CSI with 220.94% for multi-cell. This result was obtained with 0.07W P_{BS} and 0W P_{SYN} values.

Table 4
Relative change in energy efficiency

P_{BS} (W)	Single-cell			Multi-cell		
	ZF Imperfect CSI	ZF Perfect CSI	MRT Perfect	ZF Imperfect CSI (Reuse2)	ZF Perfect CSI	ZF Imperfect (Reuse4)
0.06	1.06	1.08	1.77	2.10	2.20	2.08
0.07	1.07	1.09	1.79	2.11	2.21	2.10
0.1	0.93	0.63	1.48	1.77	1.84	1.76
0.11	0.94	0.96	1.50	1.79	1.85	1.78
4.24	-0.56	-0.57	-0.63	-0.68	-0.67	-0.68
4.25	-0.56	-0.57	-0.63	-0.67	-0.67	-0.68
4.35	-0.57	-0.58	-0.64	-0.68	-0.68	-0.69
4.36	-0.57	-0.58	-0.64	-0.68	-0.68	-0.69

4. Conclusions

Considering power control in designing energy-efficient massive MIMO systems can be realized by regulating the transmit power by accurately modeling to find the optimum. The power consumption of transceiver chains – like amplifiers, filters, mixers, attenuators, and detectors should be designed to utilize low wattage. The desired power of base stations should be consuming relatively low wattage. From the simulated power of base stations, 0.07 W emerged with the highest EE using MRT perfect processing scheme for a single cell, while ZF perfect CSI for a multi-cell. Also, circuit power has effects in modeling massive MIMO systems to be energy efficient in considering the cost and for green communication to be realized. Low-power systems utilize low energy consumption but not disregarding higher energy efficiency. This paper suggests AAU equipment that the usage of power parameters can be improved. Considering if there is an increase in the power of AAUs, it results in a decrease in EE. Researchers can also explore the variable effects of the number of users in massive MIMO systems. Also, other factors in data throughput – bandwidth, transmit power, noise power spectral density, and path loss can be studied to optimize energy-efficient massive MIMO systems.

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