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5G Massive MIMO and its Impact on Energy Efficiency

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Abstract: 5G has a lot of potential opportunities for bringing new capabilities and network efficiencies. Moreover, with these opportunities, energy efficiency plays a vital role in delivering cost-efficient networks in operations. This paper discusses the impact of 5G massive multiple-input multiple-output (MIMO) technology on network energy efficiency by utilizing the 5G spectrum band and a 5G massive MIMO antenna. A multi-cell, multi-user, 5G massive MIMO system integrated into an existing network is assumed to obtain the impact on energy efficiency given an optimal number of users and at an operational power consumption of an actual 5G antenna system. Using 5G massive MIMO works well on both zero-forcing (ZF) in the single-cell, perfect channel state information (CSI), and imperfect CSI scenarios, which all yielded high energy efficiency values. Based on the simulation, minimum mean square error (MMSE) processing did not contribute much to the energy efficiency improvement, unlike maximum ratio transmission/combining (MRT/MRC). Because of the wider bandwidth, the network was opened up to more user equipments (UEs) but statistically selected those with less interference to camp to the network at a higher throughput to limit the possibility of creating interference. The incremental power induced to the network due to more radio frequency (RF) chains has affected the power consumption and impacted the overall energy efficiency. New models must be created for future research considering end-to-end network parameters to derive optimal energy efficiency.

Keywords: 5G network, Massive MIMO, Energy efficiency, Multi-user, Multi-cell, Single-cell, Coherence block, Downlink, Uplink, Total noise power

Introduction

With the increasing demand from customers for higher internet speed and more capacity to cater to the numerous devices latching to the network, there is a pressing need to accelerate the implementation of the 5G network. 5th generation mobile network is based on 3GPP Release 15 standard (3GPP Global Initiative, 2019). It is a global standard after 1G, 2G, 3G, and 4G networks, where 5G enables a unique kind of network that is intended to connect virtually everyone and everything together, including machines, objects, and devices (Qualcomm, 2022). With the 5G wireless technology, customers can experience higher peak data rates, ultra-low latency for machines, more reliable and massive network capacity, increased availability and improved efficiency, better performance, and enhanced user experience to connect more devices to the network (3GPP Global Initiative, 2021). There is a pressing need to assess network capabilities from access and transport to the core network for such network improvements. This paper aims to explain the use of a 5G MIMO antenna and its impact on energy efficiency, given the change in power consumption.

Moreover, the impact of activating more radio resources affects energy efficiency due to increasing power consumption brought about by the deployment of multi-technology radio units and upgrading the antenna systems, which require more power to drive the network (Huawei Technologies Co., Ltd, 2017), (Osseiran et al., 2016). Also, we need to consider the impact of improving user throughput by increasing transmission bandwidth and lowering the total noise power, which affects the signal-to-noise ratio (SNR), thus improving the number of users who latch in the network. Several parameters would need further study to understand the end-to-end impact on network efficiencies.

Spectrum

Spectrum availability is vital in the 5G network deployment. According to the 3GPP Standard Release 17 (3GPP Global Initiative, 2021), there are two Frequency range designations. These are FR1: 410 MHz – 7125 MHz and FR2: 24250 MHz – 52600 MHz. Also, this can be sub-categorized into (a) Coverage Layers utilizing low frequencies covering below 2GHz with 20MHz paired/unpaired systems bandwidth to provide wide area and deep indoor coverage, (b) Coverage and Capacity Layers utilizing medium frequencies covering between 2GHz – 6GHz with contiguous 100MHz assignments to provide wide area but no in-depth coverage, and (c) Super Data Layer utilizing high frequencies above 6GHz with contiguous 100MHz assignments to address specific use cases that require extremely high data rates (Huawei Technologies Co., Ltd, 2017).

Bandwidth

A much wider bandwidth would be vital in adopting the deployment strategy based on spectrum availability. Likewise, it shall be considered to provide the needed capacity demand. At the Base Station (BS) side, the BS channel bandwidth supports each single New Radio RF carrier both in the uplink or downlink (European Telecommunications Standards Institute (ETSI)., 2019). For transmission and reception of RF signals from the UE's connected to the Base Stations, different User Equipment (UE) channel bandwidths can support it within the same spectrum. The subcarrier spacing in kHz with the corresponding transmission bandwidth configuration expressed in resource blocks N_{RB} for the respective Base Station channel bandwidth is specified below:

Table 1. Transmission bandwidth configuration expressed in resource blocks N_{RB} for FR1 (European Telecommunications Standards Institute (ETSI)., 2019)

SCS (KHz)	5 MHz	10 MHz	15 MHz	20 MHz	25 MHz	30 MHz	40 MHz	50 MHz	60 MHz	70 MHz	80 MHz	90 MHz	100 MHz
	$\mathbf{N}_{RB}$	$\mathbf{N}_{RB}$	$\mathbf{N}_{RB}$	$\mathbf{N}_{RB}$	$\mathbf{N}_{RB}$	$\mathbf{N}_{RB}$	$\mathbf{N}_{RB}$	$\mathbf{N}_{RB}$	$\mathbf{N}_{RB}$	$\mathbf{N}_{RB}$	$\mathbf{N}_{RB}$	$\mathbf{N}_{RB}$	$\mathbf{N}_{RB}$
15	25	52	79	106	133	160	216	270	NA	NA	NA	NA	NA
30	11	24	38	51	65	78	106	133	162	189	217	245	273
60	NA	11	18	24	31	38	51	65	79	93	107	121	135

Applications of 5G and its Usage Scenarios

According to the ITU-R IMT-2020 (5G) Vision 1, the following are the three usage scenarios:

Enhanced Mobile Broadband (eMBB)

This scenario addresses improvement in systems performance, seamless user experience, and access to multi-media content; it focuses on human-centric use cases as the demand for mobile broadband is expected to continue to increase.

Massive Machine Type Communications (mMTC)

This scenario addresses the connection of non-delay sensitive and a vast number of devices like sensors that are typically transmitting low-power at a relatively low volume that extends long battery life.

Ultra-Reliable and Low Latency Communications (URLLC)

This scenario addresses the need for more latency-sensitive use cases. Throughput, latency, and availability are stringent capability requirements for enterprise deployments.

Figure 1 below shows the key capabilities of IMT-2020 that contain improvements compared to the previous generations of International Mobile Telecommunications (IMT) systems.

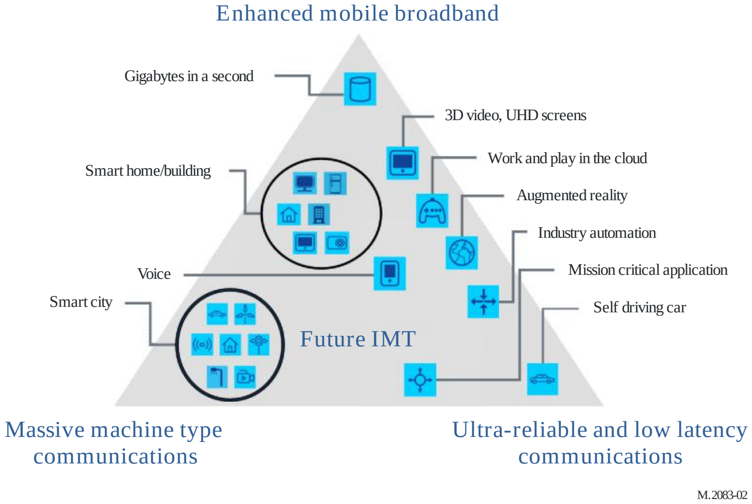

Figure 1. The three usage scenarios of IMT-2020 and beyond (Huawei Technologies Co., Ltd, 2017), (International Telecommunication Union, Radio Communication Sector (ITU-R), 2015)

Energy Efficiency

When less energy is used to perform the same task, thus, eliminating energy wastage, that is energy efficiency (Environmental and Energy Study Institute, n.d.). In telecoms, it is defined as the amount of reliable information that is transmitted per unit of energy, which is expressed mathematically as (Björnson et al., 2015):

$$\text{Energy Efficiency} = \frac{\text{Area throughput [bits/s/km}^2]}{\text{Area power consumption }[\frac{\text{W}}{\text{km}^2}]} \tag{1}$$

$$\text{Energy Efficiency} = \frac{\text{BW [Hz] . ASE [bits/s/Hz/km}^2]}{\text{APC }[\frac{\text{W}}{\text{km}^2}]} \tag{2}$$

which is measured in [bit/Joule]. This equation is analyzed through a benefit-cost ratio, where the area throughput (the service quality) is compared with the area power consumption (the associated cost). In equation 2, ASE is the area spectral efficiency, while APC is the area power consumption.

Method

Systems Model

In a single-cell multi-user 5G massive MIMO system, we consider both the uplink and downlink operating over a transmission bandwidth of B Hz. The BS upgraded to 5G New Radio shall then be collocated with M array antennas to communicate with K users with UEs having a single antenna. UEs are then selected in a round-robin scheme considering large sets of UEs within the target coverage area. The channels shall be static within a time-frequency coherence block in $U = B_c T_c$ symbols. The coherence bandwidth B_C in Hz shall operate in a flat-fading channel within the coherence time T_C in seconds.

The 5G system shall operate in the time-division duplex (TDD) mode and be synchronized with Base Station and UEs. The relative pilot lengths of both downlink and uplink shall be 1. Thus, the fixed ratios of uplink $\zeta^{(UL)}$ and downlink $\zeta^{(DL)}$ transmission are denoted as $\zeta^{(UL)} + \zeta^{(DL)} = 1$. In the context of TDD, uplink transmits first through the $U\,\zeta^{(UL)}$ symbols, followed by the downlink transmission of $U\,\zeta^{(DL)}$ symbols. For facilitating channel estimation, the pilot signaling occupies $\tau^{(UL)}\,K$ symbols and $\tau^{(DL)}\,K$ symbols, where $\tau^{(UL)}$,

$\tau^{(UL)} \geq 1$ so that at the UE side, it enables orthogonal pilot sequencing. The UE channel estimation shall be enabled at the BS side through the uplink pilots. Both the M antennas and K users are the same on the uplink and downlink side as required in a TDD protocol

The UE (denoted as k) physical location is computed in reference to the location of the Base Station and is calculated by $X_k \in R^2$ (in meters). The large-scale channel fading experience by different users of different locations is denoted by the function $l(.): R^2 \rightarrow R$, whereby, at a particular location of X_k, the function $l(X_k)$ is the average channel attenuation due to path loss, scattering, and shadowing in the communication channel. Figure 2 shows the UE location that is treated as a random variable and is selected through round robin from a user distribution *f*(x) that implicitly provides the shape and user density in a given coverage area. The large-scale fading is assumed to be the same across all the BS antennas, especially during transmission between a UE and the BS. The following parameters shall be used for simulations.

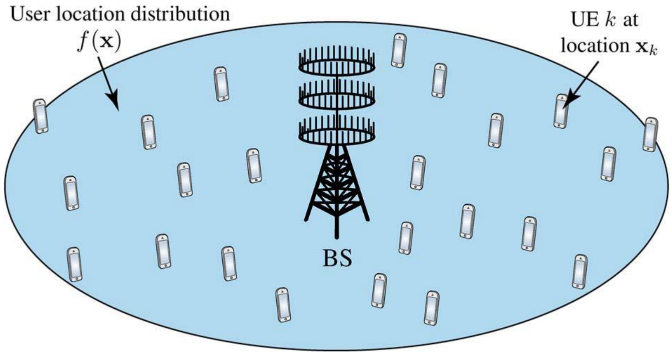

Figure 2. Typical multi-user MIMO scenario: A Base Station with M omnidirectional antennas communicates with K single-antenna UEs in the uplink and downlink.
Arbitrary random user distribution *f(x)* is used to select user locations (Björnson et al., 2015).

The simulation parameter in Table 2 shall be used as the basis for running the Matlab program to identify the direct impact on energy efficiency by upgrading the 4G LTE network into a 5G network, thus utilizing the new parameters identified in the study. (Link: https://github.com/emilbjornson/is-massive-MIMO-the-answer)

Table 2. Simulation parameters for 5G massive MIMO

Parameters	Reference Values
Cell Radius (single cell): d_{max}	250 m
Minimum Distance: d_{min}	35 m
Large Scale Fading model: $l(x)$	10-3.53 / |x|^3.76
Transmission Bandwidth: B	60 MHz
Channel Coherence Bandwidth: B_C	360 kHz
Channel Coherence Time: T_C	0.5 ms
Coherence Block (symbols): U	180
Total Noise Power: $B\sigma^2$	- 99dBm
Relative Pilot Lengths: $\tau^{(UL)}$, $\tau^{(DL)}$	1
Computational Efficiency at BSs: L_{BS}	12.8 Gflops/W
Computational Efficiency at UEs: L_{UE}	5 Gflops/W
Fraction of downlink transmission: $\zeta^{(DL)}$	0.8
Fraction of uplink transmission: $\zeta^{(UL)}$	0.2
PA Efficiency at the BSs: $\eta^{(DL)}$	0.39
PA Efficiency at the UEs: $\eta^{(UL)}$	0.3
Fixed Power consumption (control signals, backhaul, etc.): P_{FIX}	25.2 W
Power Consumed by the local oscillator at BSs: P_{SYN}	2W
Power Required to run the circuit components at a BS: P_{BS}	1W
Power Required to run the circuit components at a UE: P_{UE}	0.1W
Power Required for coding of data signals: P_{COD}	0.1 W/(Gbit/s)
Power Required for decoding of data signals: P_{DEC}	0.8 W/(Gbit/s)
Power Required for backhaul traffic: P_{BT}	0.25 W/(Gbit/s)

Results and Discussion

Matlab simulations were used in this paper to assess the system design based on the simulation parameters described in Table 2. Also, a validation was made to analyze the impact of utilizing a 5G MIMO antenna based on its power consumption and the baseband units. Part of the assessment was the analysis of ZF processing compared to other signal processing schemes. Simulated results were provided on both perfect and imperfect CSI and single-cell and multi-cell scenarios. Optimization of energy efficiency of the different schemes was conducted using Monte Carlo simulations.

In reference to early works done by (Björnson et al., 2015), several parameters were changed in Table 2 for this study. Using a 5G massive MIMO antenna of Huawei using an AAU5613 unit (Huawei Technologies Co., Ltd, 2022), the frequency band used was 3.5GHz (3GPP Global Initiative, 2021) with a transmission bandwidth B of 60 MHz (European Telecommunications Standards Institute (ETSI)., 2019) following the 5G FR1 spectrum band. The Fraction of downlink transmission $\zeta^{(DL)}$ is set to 80%, while the fraction of uplink transmission $\zeta^{(UL)}$ is set to 20% based on FORMAT 31. The values considered are $M = 192$ antennas and $K = 150$ users.

The propagation environment is based on 3GPP Standards Release 9 (3GPP Global Initiative, 2017), Fixed Power consumption from (Huawei Technologies Co., Ltd, 2022), and computational efficiencies (Parker, 2013), (Yang & Marzetta, 2013). The simulations were performed using Matlab, and the code used is from (Björnson et al., 2015), downloaded at https://github.com/emilbjornson/is-massive-MIMO-the-answer. Values were changed based on Huawei's 5G massive MIMO antenna array unit, AAU5613 (Huawei Technologies Co., Ltd, 2022).

Single Cell Scenario

The figure below shows that the global optimal energy efficiency is 51.3167 Mbit/J at $M = 46$ antennas and $K = 24\,users$. The 3D surface in Figure 3 is steep and slightly concave; thus, various system parameters need optimization to achieve close-to-optimal energy efficiency. The results appear to have an abrupt change in energy efficiency brought about by the circuit power coefficients.

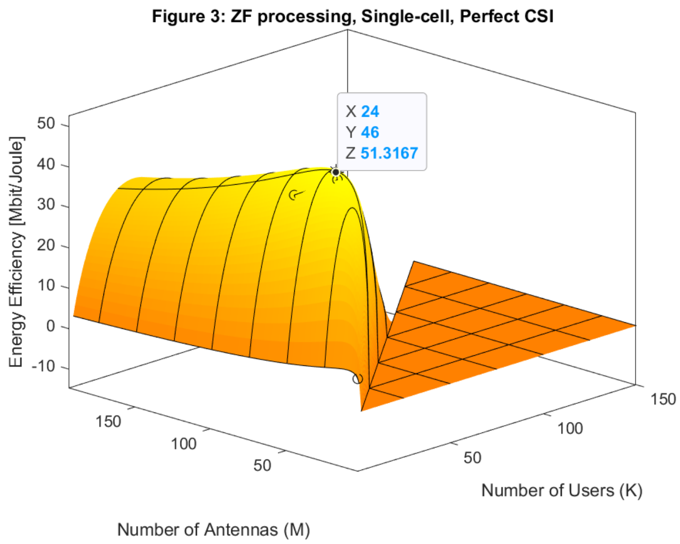

Figure 3. Energy efficiency (Mbit/J) with ZF processing in the single-cell scenario with perfect CSI

Figure 4 shows an optimal energy efficiency of 16.74 Mbit/J at $M = 46$ antennas and $K = 21$ users using MRT/MRC processing. While in figure 5, the results show an energy efficiency of 43.49 Mbit/J at $M = 50$ antennas and $K = 24$ users using ZF processing in the single-cell scenario with imperfect CSI. It is observed that using MMSE processing is optimal from a throughput perspective, while it is evident that ZF processing achieves much higher energy efficiency. MMSE has a much higher computational complexity compared to ZF processing.

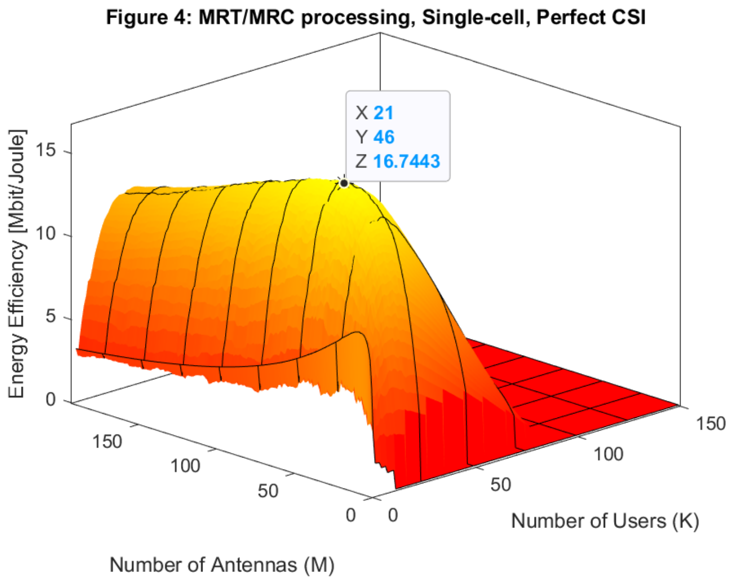

Figure 4. In the single-cell scenario, energy efficiency (Mbit/J) with MRT/MRC processing.

It is also noticed that using MRT/MRC processing, different results were generated: the energy efficiency optimum value is much smaller compared to ZF processing and is achieved at $M = 46$ and $K = 21$. MRT/MRC signal processing complexity is lower than ZF for the same M and K values. However, considering the power, its savings are insufficient to compensate for the lower data rates. It is an example of a degenerative case where M and K are almost equal at a particular instant; therefore, it is the typical asymptotic massive MIMO properties similar to LTE.

The reason for M ≈ K is that MRT/MRC operates under substantial inter-user interference due to a multi-user environment, and as a result, the rate per user is low; therefore, it is necessary to do traffic balancing and UE scheduling as part of the optimization. Increasing the computational/circuit power reduces the energy efficiency but addresses the challenges of having M >> K for MRT/MRC and having the same rates as ZF.

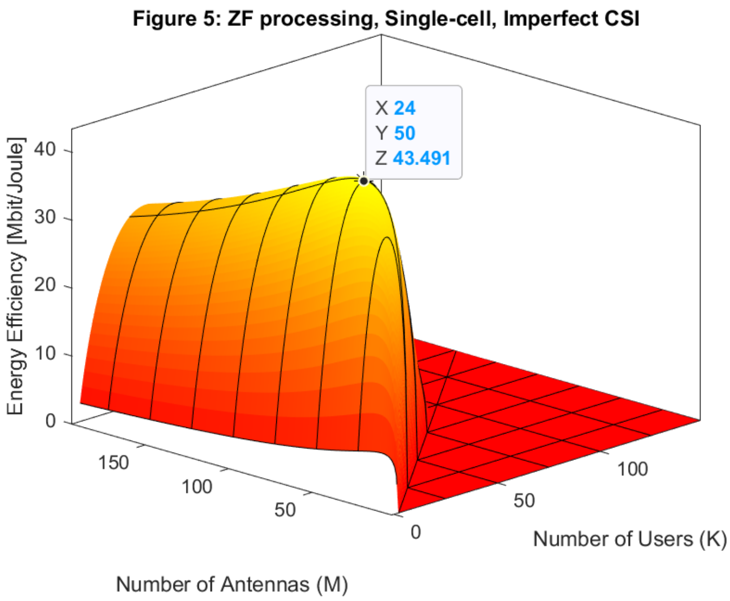

Figure 5. Energy efficiency (Mbit/J) with ZF processing in the single-cell scenario with imperfect CSI.

Figure 6 shows the comparison of the different processing schemes. This figure shows the maximum energy efficiency as a function of the number of Base Station antennas. The energy efficiency of MRT/MMSE in a perfect CSI is way below the other processing schemes. It is also noticed that it reached its optimal energy efficiency between $M = 40$ antennas and $M = 60$ antennas. Thus, as the number of antennas increased, there was a seemingly exponential drop.

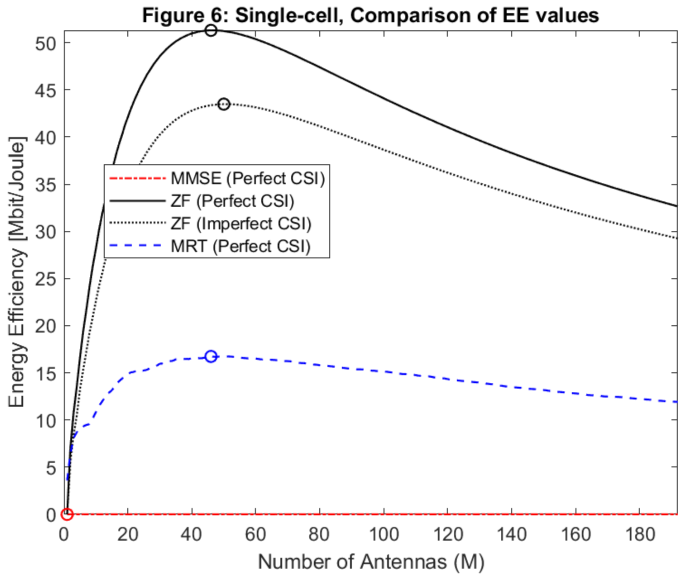

Figure 6. Maximal energy efficiency for different numbers of BS antennas and different processing schemes in the single-cell scenario.

Figure 7 shows the average power (W) with respect to the number of antennas (M). The total Power Amplifier power affects the maximization of the energy efficiency for different numbers of antennas (M) using the corresponding optimal values of K. Across the different processing schemes, increasing the transmit power with respect to the number of antennas (M) will a good energy efficiency strategy. Nevertheless, in contrast, the transmit power should be decreased with respect to the number of antennas (M) to achieve better Energy efficiency. Figure 7 also shows that the transmit power per Base Station antenna decreases with the number of antennas (M).

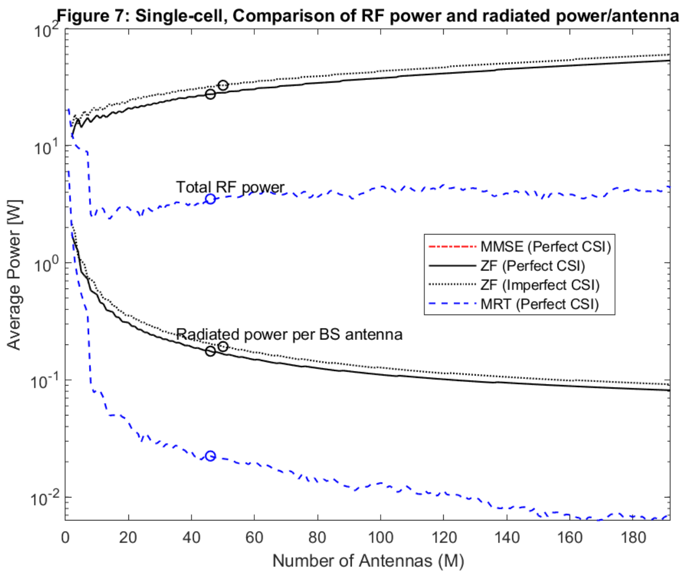

Figure 7. Total PA power at the EE-maximizing solution for different numbers of BS antennas in the single-cell scenario. The radiated power per BS antenna is also shown.

Figure 8 shows the area throughput (Gbit/s/km2) with respect to the number of antennas (M), which maximizes the energy efficiency for different numbers of antennas (M). Considering the same processing schemes in Figures 6 and 7, we applied them in Figure 8. In Figure 6, there were noticeable improvements in optimal energy efficiency ZF perfect CSI and ZF imperfect CSI compared to MRT/MRC and MMSE. Figure 8 shows the simultaneous improvement in area throughput across different schemes but not that huge; ZF perfect CSI and ZF imperfect CSI contribute to the improvements. Deploying a large number of Base Station antennas and being processed by MRT/MRC and MMSE processing schemes is wasteful, given that it limits achieving energy efficiency and higher area throughput. Proper optimization of the site and interference-suppressing precoding schemes on the massive MIMO antenna can achieve better energy efficiency and area throughput.

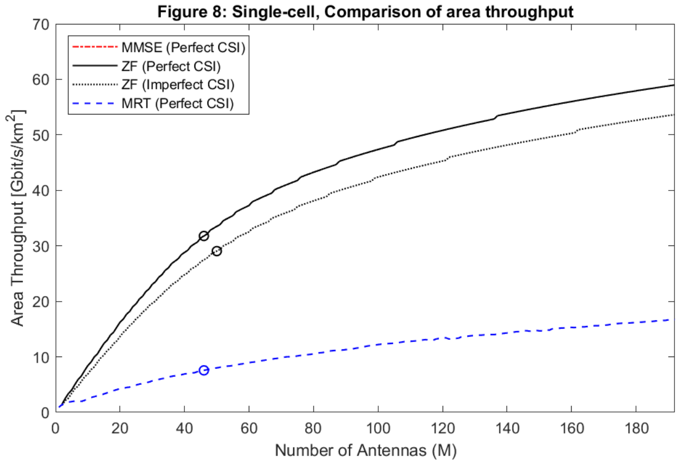

Figure 8. Area throughput at the energy efficiency maximizing solution for different numbers of BS antennas in the single-cell scenario.

Multi-Cell Scenario

Figure 9 represents a symmetrical multi-cell scenario that concentrates on the cell under study in the middle. Each cell corresponds to a 500 × 500 square. UEs are uniformly distributed with the same minimum distance, similar to a single-cell scenario. Interference from the two closest cells is considered relative to the cell under study, as shown below. The cells are divided into four clusters. There are three pilot re-use patterns: a. at $\tau^{(UL)} = 1$, we consider the same pilots in all cells, b. $\tau^{(UL)} = 2$, we consider two orthogonal sets of pilots (Cluster 1 & Cluster 4 with the same pilot), c. $\tau^{(UL)} = 4$, we consider all clusters having different orthogonal pilots.

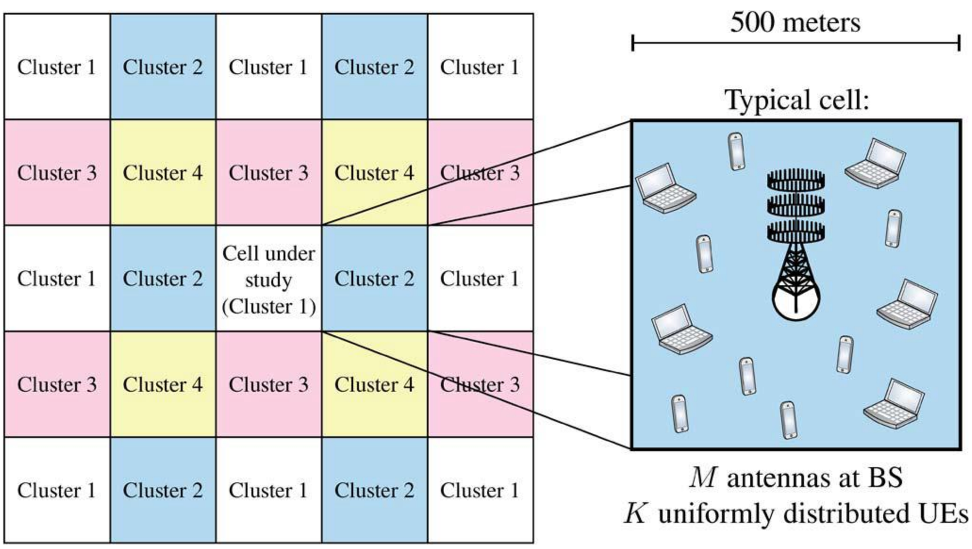

Figure 9. The multi-cell simulation scenario where the cell under study is surrounded by 24 identical cells. The cells are clustered to enable different pilot re-use factors (Björnson et al., 2015)

Figure 10 shows the maximal Energy efficiency for different numbers of antennas in a multi-cell scenario of different re-use factors showing interesting results where all the Energy Efficiencies are much smaller. Figure 11 shows that the corresponding total PA power and radiated power per Base Station are closely patterned with each processing scheme. Inter-cell interference is prevalent in a multi-user environment, affecting the whole system, including throughput and Energy efficiency. The higher the pilot re-use factor $\tau^{(UL)} = 4$, the better the energy efficiency and much higher area throughput. However, because incremental power was consumed in 5G, the optimal Energy efficiency is not that high.

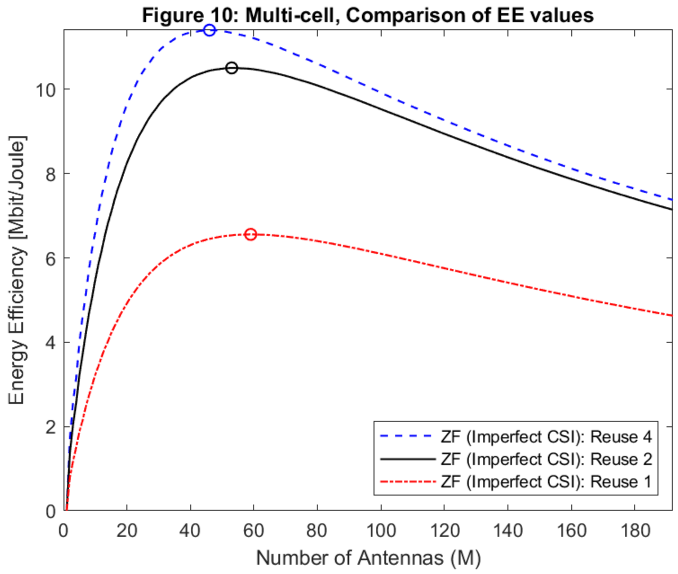

Figure 10. Maximal energy efficiency in the multi-cell scenario for different numbers of BS antennas and different pilot re-use factors.

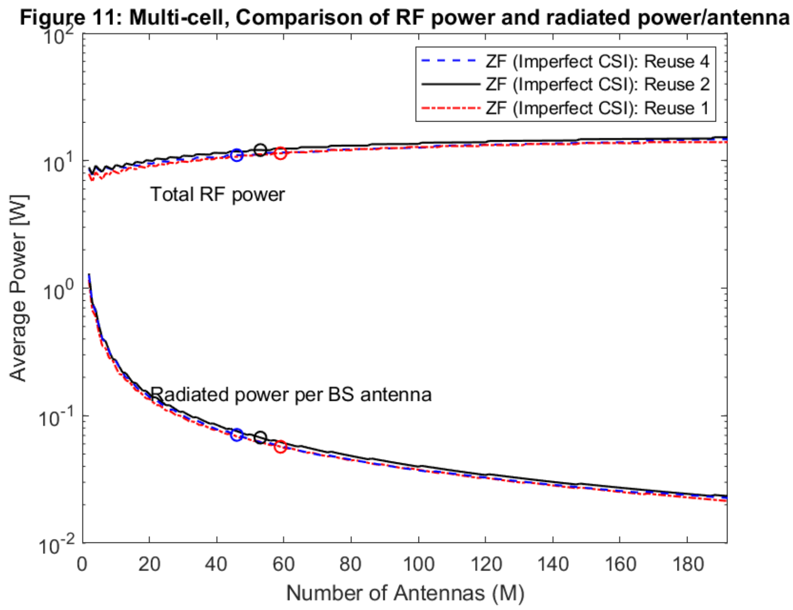

Figure 11. Total PA power at the energy efficiency maximizing solution in the multi-cell scenario for different numbers of BS antennas. The radiated power per BS antenna is also shown.

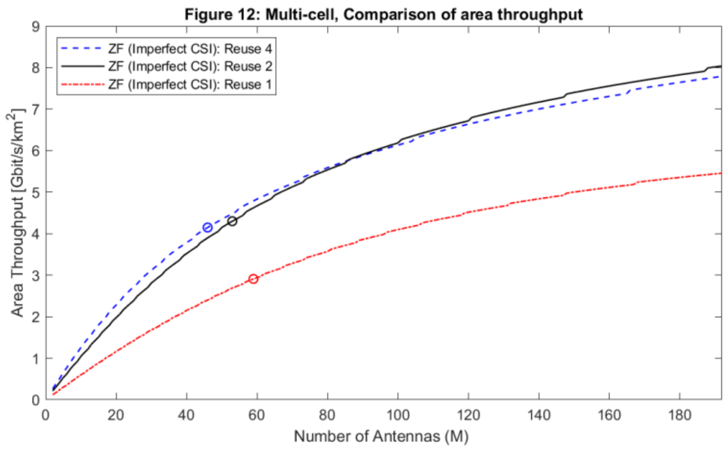

Figure 12. Area throughput at the energy efficiency maximizing solution in the multi-cell scenario for different numbers of BS antennas.

Figure 13 provided a better view of utilizing a smaller number of antennas, but the energy efficiency is still optimal. Utilizing different values of M and K with a pilot re-use factor of $\tau^{(UL)} = 4$, resulted in higher energy efficiency. This outcome has almost the same concave in Figure 3, but the earlier has a much higher energy efficiency value. With multi-user and more re-use factors, inter-cell interference is experienced, forcing each cell to sacrifice some user camping to the network. Nevertheless, we conclude that we need to optimize some parameters in 5G massive MIMO to achieve optimal architecture to deliver Energy efficiency.

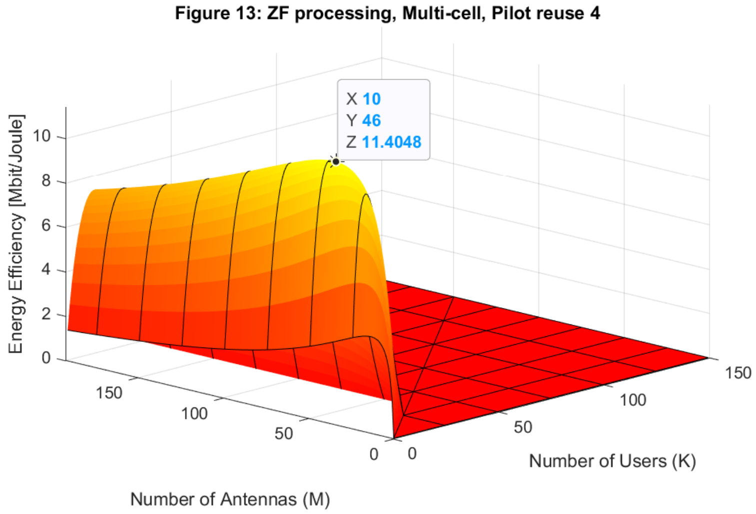

Figure 13. Energy efficiency (in Mbit/Joule) with ZF processing in the multi-cell scenario with pilot re-use 4.

Table 3 below shows the comparative results between the original paper on utilizing massive MIMO in a 4G network and with a 5G network. It clearly shows that using a ZF processing in the single-cell with a perfect CSI scenario yielded higher Energy Efficiency.

Table 3. Optimal Energy Efficiency Comparison between 4G and 5G with the Different Processing Schemes

Processing Schemes	x Number of Antennas (M)		y Number of Users (K)		z Energy Efficiency (Mbit/Joule)	
	4G LTE	5G	4G LTE	5G	4G LTE	5G
ZF processing in the single-cell, perfect CSI scenario	165	46	104	24	30.70	51.32
MRT/MRC processing in the single-cell, perfect CSI scenario	77	46	81	21	9.83	16.74
ZF processing in the single-cell scenario with imperfect CSI	185	50	110	24	25.88	43.5
ZF processing Multi-Cell, Pilot Re-use 4	123	46	40	10	7.57	11.5

Note: The reference 4G values were derived from the original paper (Björnson et al., 2015).

Conclusion

Based on the simulation, results showed a significant impact on energy efficiency when deploying 5G massive MIMO. Several parameters were considered in the simulation process: the number of BS antennas (M), the frequency used, wider transmission bandwidth, higher fixed power consumption, channel coherence bandwidth, channel coherence time, coherence block, a fraction of downlink transmission, a fraction of uplink transmission and the type of antenna being used to which are all based on 3GPP standard Release 15 for 5G network. There were noticeable impacts on the energy efficiency of the different processing schemes based on the changes made in the simulation parameters. These are as follows: a) changing the number of active base station antennas (M) with the consideration of having a 3-sector antenna with 64T x 64R configuration per cell, b) increasing the transmission bandwidth from 20MHz to 60MHz based on 3GPP Release 15, c) increasing the channel coherence bandwidth based on 5G's subcarrier spacing and subcarriers per resource block, d) decreasing the channel coherence time which affects the coherence blocks, e) improving the total noise power, f) adhering to 5G TDD configuration using FORMAT31 which changes now both the values of the fraction of downlink transmission and the fraction of uplink transmission into 80/20 respectively, and g) the increased fixed power consumption based on the actual antenna configuration.

In an energy-efficient 5G network, a high SNR is required with the proper interference-suppressing processing technique like ZF, which works well compared to an MRT/MRC processing which is an interference-ignoring system. Using 5G massive MIMO works well on both ZF processing in the single-cell, perfect CSI and imperfect CSI scenario, yielding high energy efficiency values. Based on the simulation, MMSE processing did not contribute much to the energy efficiency improvement, unlike MRT/MRC processing. Because of the wider bandwidth, the network was opened up to more UE's but statistically selected those with less interference to camp to the network at a higher throughput to limit the possibility of creating interference from within. The incremental power induced to the network due to more RF chains has affected the power consumption and impacted the overall Energy efficiency.

Recommendations

Several factors need to be reconsidered in the simulation process. It is highly recommended to explore further other 5G parameters and simulate different optimization principles to achieve Energy efficiency. Also, future researchers should look into the end-to-end power consumption of not just the antenna and radio units but also consider external ancillaries that can affect the overall power consumption. Lastly, consider revising the model based on updated 5G equipment configurations.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Acknowledgements or Notes

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References

3GPP Global Initiative. (2021). *"3rd generation partnership project; technical specification group radio access network; NR; User Equipment (UE) radio transmission and reception*; Part 1: Range 1 Standalone (Release 17)". 3GPP TS 38.101-1 V17.2.0 (2021-06). (pp. 24).

3GPP Global Initiative. (2017). "*3rd generation partnership project; technical specification group radio access network; Evolved Universal Terrestrial Radio Access (E-UTRA)*; Further advancements for E-UTRA physical layer aspects (Release 9)". 3GPP TR 36.814 V9.2.0 (2017-03)

Björnson, E., Sanguinetti, L. Hoydis, J., & Debbah, M. (2015, June). "Optimal design of energy-efficient multi-user MIMO systems: Is massive MIMO the answer?" *IEEE Transactions on Wireless Communication., 14*(6), (pp. 3059–3075).

Björnson, E., Sanguinetti, L., & Kountouris, M. (2016, April). "Deploying dense networks for maximal energy efficiency: small cells meet massive MIMO". *IEEE Journal on Selected Areas in Communications, 34*(4), 832-847.

Chatzipapas, A., Alouf, S., & Mancuso, V. (2011). "On the minimization of power consumption in base stations using on/off power amplifiers". *In IEEE Online Conference on Green Communications (pp. 18-23). IEEE.*

European Telecommunications Standards Institute (ETSI) (2019). *ETSI TS 138 104 V15.5.0 (2019-05), "5G; NR; Base Station (BS) radio transmission and reception* (3GPP TS 38.104 version 15.5.0 Release 15)". (pp. 28-31).

Environmental and Energy Study Institute (2023). *Energy efficiency*. https://www.eesi.org/topics/energy-efficiency/description.

Huawei Technologies Co., Ltd. (2017). *5G spectrum: public policy position*. https://www-file.huawei.com/-/media/CORPORATE/PDF/public-policy/public_policy_position_5g_spectrum.pdf, (pp. 6).

Huawei Technologies Co., Ltd. (2022, Oct.). AAU5636w V100R018C10 technical specifications. https://www.huawei.com/en/

International Telecommunication Union, Radio Communication Sector (ITU-R). (2015, Sept.). Recommendation ITU-R M.2083-0, "IMT vision – framework and overall objectives of the future development of IMT for 2020 and beyond". M Series, Mobile, radiodetermination, amateur, and related satellite services". (pp 4-5), (pp. 11- 12).

Osseiran, A., Monserrat, J.F., & Marsch, P. (2016). "*5G mobile and wireless communications technology"*, Cambridge University Press, ISBN 978-1-107-13009-8

Qualcomm. (2022). *"What is 5G? Everything you need to know about 5G".* https://www.qualcomm.com/5g/what-is-5g.Qualcomm Technologies.

Parker M. (2009). "*High-performance floating-point implementation using FPGAs*," in Proc. IEEE MILCOM, (pp. 1–5).

Pizzo, A., Verenzuela, D., Sanguinetti, L., & Björnson, E. (2015, Sept.). "Network deployment for maximal energy efficiency in uplink with multislope path loss". *IEEE Transactions on Green Communications and Networking, 2*(3).

Yang, H., & Marzetta, T. (2013). "Total energy efficiency of cellular large-scale antenna system multiple access mobile networks". 2013 IEEE Online Conference on Green Communications (OnlineGreenComm), 27-32.

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