Effect of Massive MIMO Technology on Energy Efficiency of the Wireless Cellular Network

Comparison with Standard MIMO Technology

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Introduction

As the world is rapidly adopting the fifth generation (5G) of wireless cellular networks, energy efficiency becomes an important design aspect of 5G systems to guarantee a sustainable development. These systems heavily rely on Massive Multiple Input - Multiple Output (Massive MIMO, MM) technologies to meet their specification requirements. In this work, we discuss the impact of MM technology on Energy Efficiency of the 5G networks and we draw à comparison with the older Standard MIMO technology through a MATLAB simulation.

5G networks are the fifth-generation cellular networks that came to succeed 4G and 3G technologies, with the vision to enable a new kind of network: massive 5G IoT. It is designed to connect virtually everyone and everything together including machines, objects, and devices. 5G New Radio (NR) is the submission of the industry standards group 3GPP to the IMT-2020 standard. There are 8 specification requirements:

- Up to 10Gbps data rate, which is 10 to 100x speed improvement over 4G and 4.5G networks
- 1-millisecond latency
- 1000x bandwidth per unit area
- Up to 100x number of connected devices per unit area (compared with 4G LTE)
- 99.999% availability
- 100% coverage
- 90% reduction in network energy usage
- Up to 10-year battery life for low power IoT device

Although these 5G specification requirements urge for a true technological breakthrough, they also set many challenges. Notably, **the energy efficiency trade-off.**

Energy Efficiency (EE) essentially means using less energy to get the same job done. In the context of cellular networks, it is the total bits successfully transmitted by consuming a Joule of energy, measured as bits-per-Joule.

$$EE = \frac{R}{P}\left(\frac{Bits}{Joule}\right) \qquad \textbf{(1)}$$

Where **R is the system throughput** and **P is the power spent to transmit R**.
We define **P** as the sum power consumption aggregated over Uplink (UL) and Downlink (DL) transmissions in an MM system:

$$P = Ppa + Pc + Psys \qquad \textbf{(2)}$$

Where $\mathbf{P_{pa}}$ is the total amplification power, $\mathbf{P_c}$ is the total circuit power consumed by the signal processing chain (filter, mixers,) and $\mathbf{P_{sys}}$ accounts for the remaining system power dependent on architecture specific factors (power supply, control equipment…).

Multiple Input and Multiple Output (**MIMO**) is an antenna technology meant for wireless networks. It is a method for multiplying the capacity of a radio link using multiple transmission and receiving antennas to exploit multipath propagation, as opposed to Single Input or Single Output transmission systems.

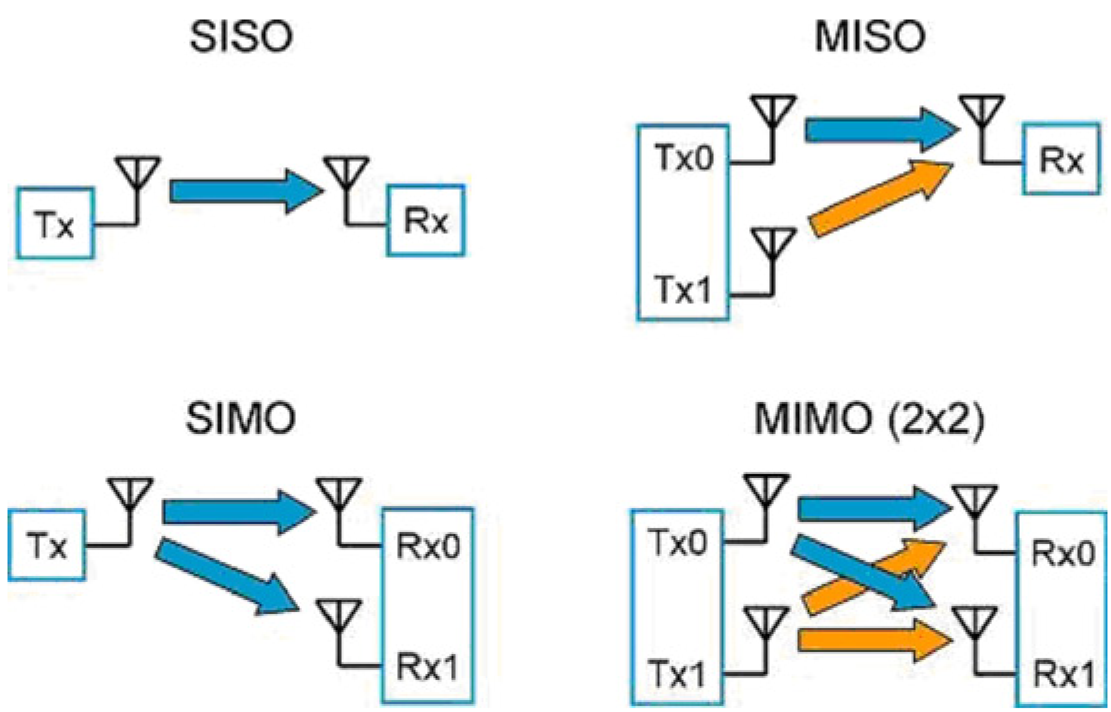

Fig1: Transmit and Receive configurations. Single Input Single Output (SISO), Multiple Input Single Output (MISO), Single Input Multiple Output (SIMO), and Multiple Input Multiple Output (MIMO).

MIMO ensures higher throughput and serving capacity compared to previous systems. It is usually found in configurations up to (8x8) Transmit and Receive antennas, and technologies like WiFi 6 and 4G LTE rely on it.

Massive MIMO is a Multi-User (MU) MIMO technology in which K single-antenna user equipments (UEs) are serviced on the same time-frequency resource by a base station (BS) equipped with a large number M of antennas: M >> K.

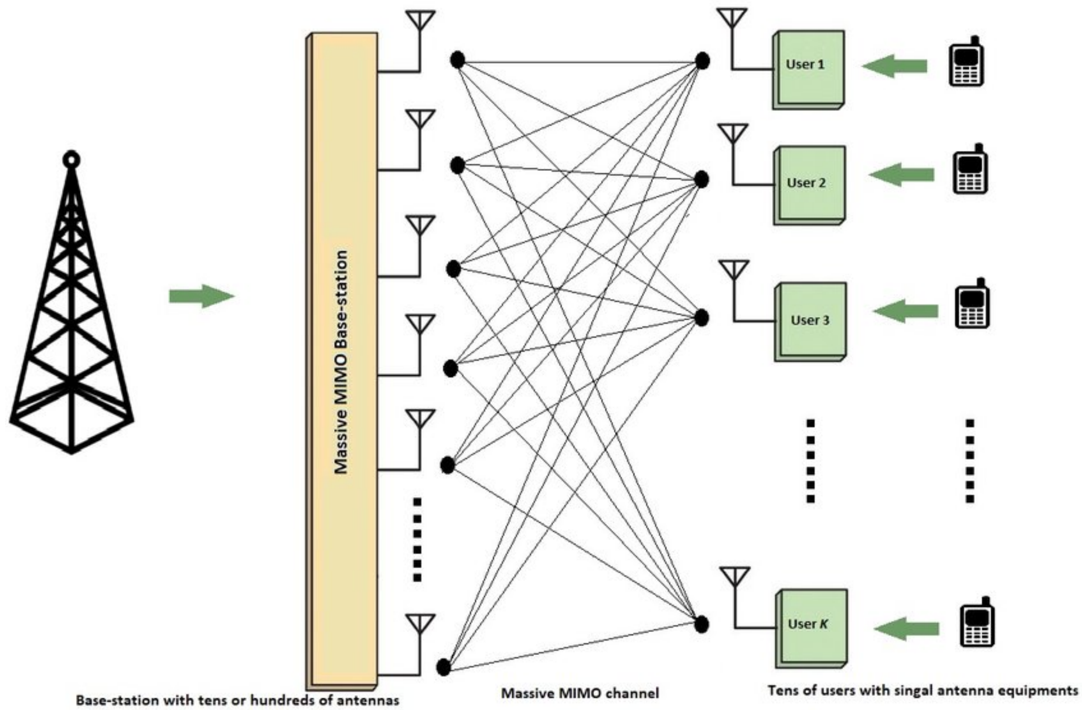

Fig2: Multi-User Massive MIMO model

MM is based on 3 key techniques: spatial diversity, spatial multiplexing, and beamforming.

A radio signal between transmitter and receiver is filtered by its environment, with reflections from buildings and other obstacles resulting in multiple signal paths. The various reflected signals will arrive at the receiving antenna with differing time delays, levels of attenuation and direction of travel.
For a single receiving antenna, this results in degradation of the received signal due to *Fast Fading*; an attenuation of the signal caused by *multipath propagation*.
But, when multiple receiving antennas are deployed, each antenna receives a slightly different version of the signal, which can be combined mathematically to improve the quality of the transmitted signal.
This technique is known as *spatial diversity,* since the receiver antennas are spatially separated from each other: the same message is received by multiple antennas and all versions are then correlated to reconstruct the message, improving the Bit Error Rate.

Whilst spatial diversity increases the *reliability* of the radio link, *spatial multiplexing* increases the *capacity* of the radio link by using the multiple transition paths as additional channels for carrying data. Spatial multiplexing allows multiple data streams of the same message for one user to be sent over multiple antennas, increasing the Data Rate.

Beamforming is a key enabler for MM. It uses advanced antenna technologies to focus the wireless signal in a specific direction, rather than broadcasting to a wide area. This technique reduces interference between beams directed in different directions, making possible the massive deployment of larger antenna arrays.

Effect of Massive MIMO on Energy Efficiency

1. **Challenges and expectations**

In the 5G era with millions more base stations and billions of connected devices, given the required 1000x increase in offered data rates and throughput, the network energy efficiency should be improved at least by the same factor, in order to maintain the whole energy consumption at today's level.

Energy consumption at network level depends largely on the number of installed radio base stations. In addition to the essential densification of Massive MIMO network nodes, integrating new systems upon the existing ones unavoidably increases the energy consumption, even if new systems are more efficient than the old ones (this happened by adding LTE on top of 2G/3G). Increased energy consumption means higher costs and a greater carbon footprint, since today mobile systems are present everywhere in the world. While planning for 5G networks, energy consumption becomes a critical concern because mobile communication networks contribute significantly towards the global carbon footprint. Trends suggest that the ICT sector would emit more than 250 million tonnes of greenhouse gas per annum by 2020. The European Commission (EC) recognized the need for further actions towards energy efficiency and green communications and introduced the Code-of-Conduct that regulates energy consumption and carbon dioxide emissions. Sustainable development has become a globally paramount issue and an aspiration of long-term civilization development of all human beings since the "Resolution 42/187 of the United Nations General Assembly" in December 1987. The Brundtland Commission of the United Nations (UN) has defined sustainable development as the one that "meets the needs of the present without compromising the ability of future generations to meet their own needs". From then on, several United Nations' conferences (from Rio de Janeiro-1992 to Copenhague-2009) continually confirmed this important issue, for which one of the most obvious aspects and challenges of sustainable development is the earth climate change and the ever-growing CO2 emission. Currently, 3.3% of the world-wide energy is consumed by the ICT (Information and Communications Technology) infrastructure, which causes about 2%-4% of the world-wide CO2 emissions and surprisingly is comparable to the world-wide CO2 emissions by all commercial airplanes.
As a result, there is a significant pressure on providers to deploy energy efficient 5G networks.

Besides, the 5G requirements also put constraints on energy consumption. In fact, the 5G network aims to serve the massive deployment of Internet of Things. But many IoT environment devices run on low power consumptions (like sensors). The 5G network component should make use of the provided low energy without significantly reducing Quality of Service. This explains the 5G specification requirement to guarantee up to 10-year battery life for low power IoT devices.
Another 5G requirement that targets energy efficiency is the explicit goal to reach 90% reduction in network energy usage.
It is also worth noting the inherent challenge to EE of balancing the trade-off between low energy consumption and high throughput capacity.

Therefore, to ensure sustainability, 5G networks deploying Massive MIMO should operate at low energy consumption levels while still achieving large capacity gains.

2. **Comparison with Standard MIMO:**
    a. **Theory**

In standard MU-MIMO, the transmitter simultaneously sends different streams to different users using the same time and frequency resource, thereby increasing the network capacity. Spectral efficiency and capacity can be improved by adding additional antennae to support more streams, up to the point where power sharing and interference between users result in diminishing gains and, eventually, losses.
M-MIMO includes all the advantages of standard Multi-User MIMO (MU-MIMO), and adds the advantages of massive deployment of antennas at the BS resulting in favourable propagation. In this propagation scenario, the channel becomes near-deterministic because the BS-UE radio links become nearly orthogonal to each other.
With favorable propagation, linear processing can achieve optimal performance. More explicitly, on the uplink, with a simple linear detector such as the matched filter, noise and interference can be canceled out. On the downlink, with linear beamforming techniques, the BS can simultaneously beamform multiple data streams to multiple terminals without causing mutual interference.
With a very large antenna array, things that were random before start to look deterministic. As a result, the effect of small-scale fading can be averaged out. Furthermore, when the number of BS antennas grows large, the random channel vectors between the users and the BS become pairwisely orthogonal. Thus, the effects of fast fading, intra cell interference, and uncorrelated noise disappear asymptotically in the large M regime.
Significant EE gains can be achieved under favourable propagation because multiple orders of multiplexing and array gains are realizable.
Furthermore, the power radiated by the terminals can be made inversely proportional to the square-root of the number of base station antennas with no reduction in performance. And on the BS side, we gain further enhancement in the effective energy by aiming the energy terminals with beamforming.

In short, systems can deliver all the attractive benefits of traditional MIMO, but at a much larger scale. More precisely, massive efficiency MIMO systems can provide high throughput, communication reliability, and high power with linear processing.

b. **Simulation**

In this simulation scenario, we explore the trade-off between Spectral Efficiency and Energy Efficiency in multiple MIMO models, and we compare the impact of Multiple BS Antennas in standard and Massive MIMO models.
The following equations are referenced from the book Massive MIMO by Björnson and al. (2020).

For this scenario, let’s consider 1 BS cell serving actuve UE (K=1). The number of BS antennas is M.
We defined the Energy Efficiency (EE) in the introduction in equation **(1)**. Let’s assume that the transmit power P component in EE, defined in equation **(2)**, is:

$$P = p/mu + P_{FIX}$$

Where p is the transmit power, mu is the Power Amplification efficiency, P_FIX accounts for a fixed value of P_SYS+P_C independent from M.
The transmit power p is given by:

$$p = \frac{\left(2^{\mathsf{SE}_0} - 1\right)}{(M-1)} \frac{\sigma^2}{\beta_0^0}$$

Where SE0 is a given Spectral Efficiency, σ 2 is the noise power, β 0 0 denotes the average channel gain of the active UE, and M the number of BS antennas.
The system throughput (data rate) component R in EE (1) is measured as by bits. It is equal to:

R = B * SE0

Where B is the system bandwidth (Hz) and SE0 is the Spectral Efficiency (bits/Hz).
EE is thus computed as:

EE = B * SE / (p/mu + P_FIX)

The theoretical maximum value of SE is given by:

$$\mathsf{SE}^{\star} = \frac{W\left((M-1)\frac{P_{\mathrm{FIX}}}{\nu_0 e} - \frac{1}{e}\right) + 1}{\log_e(2)}$$

Where W(.) is the Lambert mathematical function, and v0 provides the relation between SE and EE by:

$$\nu_0 = \frac{\sigma^2}{\mu \beta_0^0}.$$

The theoretical maximum of EE is given by:

EE = (M-1)*B*2^(-maxSE_theory(index1))/(nu_0*log(2))

In our simulation, we demonstrate that larger numbers of BS antennas M coincide with maximum EE-SE tradeoff both in practical simulation and in theoretical computation in Massive MIMO models.

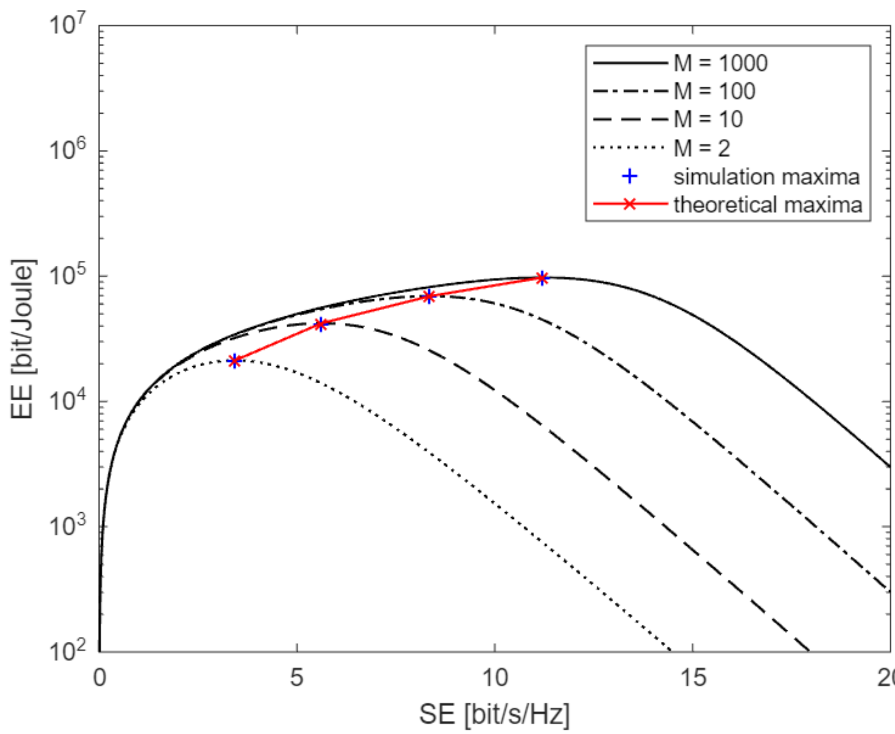

Fig3: EE and SE relation in for different values of M when PFIX = 10 W, B = 100kHz, σ^2/β0 = −6 dBm, and μ = 0.4. Both SE* and EE* increase as M grows large.

This figure illustrates the relation between EE (Energy Efficiency) and SE (Spectral Efficiency) for different values of M. We can clearly see that both SE* and EE* increase as M grows large. The red dots represent the points at each curve in which the EE achieves its maximum.

The code for this simulation was made with MATLAB. It is given as an annex to this report.

Conclusion

Massive multiple-input multiple-output (MIMO) is a promising technology for sustainable evolution towards 5G because it offers multiple orders of both Spectral and Energy Efficiency (EE & SE) gains over current LTE technologies. In this report we addressed the need for 5G networks to consider EE and the effect of Massive MIMO on EE compared to standard MIMO models.

Bibliography

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Annex: simulation MATLAB code

```
%% Impact of Massive MIMO on EE
close all;
clear;

%% Propagation and hardware parameters

%Communication bandwidth
B = 0.1*10^(6); %100 kHz
%PA efficiency
mu = 0.4;
%Range of number of BS antennas
Mrange = [1000 100 10 2];
%Fixed circuit power per BS (in Watt)
P_FIX = 10;
%Range of SE values (Spectral Efficiency)
SE = (0:0.0001:20)';
%Select ratio between noise power and beta_0^0
sigma2_beta = 10^(-6*0.1);
%beta_0^0 denotes the average channel gain of the active UE

%Compute nu_0 in (5.14)
nu_0 = sigma2_beta/mu;

%Prepare to save simulation results
EE = zeros(length(SE),length(Mrange));
maxEE = zeros(length(Mrange),1);
maxSE = zeros(length(Mrange),1);
maxEE_theory = zeros(length(Mrange),1);
maxSE_theory = zeros(length(Mrange),1);

%% Go through range of number of antennas
for index1 = 1:length(Mrange)
    %Extract number of antennas
    M = Mrange(index1);
    %Go through range of SE values
    for index2 = 1:length(SE)
```

```
        for index2 = 1:length(SE)
            %Compute transmit power using (5.12)
            p = (2^SE(index2) - 1)/(M-1)*sigma2_beta;
            %Compute the EE using (5.11)
            EE(index2,index1) = B*SE(index2)/(p/mu + P_FIX);
    %B bandwidth (Hz), SE spectral efficiency (bit/s/HZ)
    % --> Data rate: R=B.SE (bit/s)
    %p is transmit power, 1/mu amplification factor, P_FIX is Circuit Power (CP)
        end

        %Find the EE-maximizing point on each curve
        [max_value, index_max ] = max(EE(:,index1));
        maxEE(index1) = max_value;
        maxSE(index1) = SE(index_max);

        %Find the EE-maximizing pair of SE and EE values, using (5.18) and (5.19)
        argument  = (M-1)*P_FIX/(nu_0*exp(1)) - 1/exp(1);
        maxSE_theory(index1) = (lambertw(argument) + 1)/log(2);
```


```
    maxSE_theory(index1) = (lambertw(argument) + 1)/log(2);
```


```
    maxEE_theory(index1) = (M-1)*B*2^(-maxSE_theory(index1))/(nu_0*log(2));
end

%% Plot the simulation results
figure;
hold on; box on;
plot(SE,EE(:,1),'k','LineWidth',1);
plot(SE,EE(:,2),'k-.','LineWidth',1);
plot(SE,EE(:,3),'k--','LineWidth',1);
plot(SE,EE(:,4),'k:','LineWidth',1);
set(gca,'YScale','log');
xlabel('SE [bit/s/Hz]');
ylabel('EE [bit/Joule]');
axis([0 max(SE) 10^2 10^7])
plot(maxSE,maxEE,'b+','LineWidth',1);
plot(maxSE_theory,maxEE_theory,'rx-','LineWidth',1,'MarkerFaceColor','r');
legend('M = 1000','M = 100','M = 10','M = 2','simulation maxima', 'theoretical maxima' ,'Location','NorthEast');
```