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Energy Efficiency of a Massive MIMO System

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Abstract- **The information traffic in wi-fi networks is growing constantly. It follows Cooper's regulation, wherein the traffic is doubled every 2 and half years, and it will likely continue for many years to come. The data transmission is highly related with the electricity consumption within the electricity amplifiers, transceiver hardware, and baseband processing. The relation can be obtained by way of the energy efficiency measured in bit/Joule, which describes how lots power is consumed in step with efficiently received bits. While the information charge is basically limited by means of the channel capacity, there is no clear information regarding the power-efficiency of a conventional massive MIMO system.**

1.INTRODUCTION

A new wireless technology generation is introduced every decade and the standardization is guided via the International Telecommunication Union (ITU), which provides the minimal overall performance necessities. For example, 4G turned into designed to fulfill the IMT-Advanced necessities on spectral efficiency, bandwidth, latency, and mobility. Similarly, the brand new 5G standard is supposed to satisfy the minimum necessities of being an IMT-2020 radio interface. In addition to more stringent necessities in the mentioned categories, a brand new metric has been noticed in energy efficiency (EE). A simple definition of the EE is

$$\mathrm{EE}\left[\frac{\mathrm{bit}}{\mathrm{Joule}}\right] = \frac{\text{Data rate}\left[{}^{\mathrm{bit}}/_{\mathrm{s}}\right]}{\text{Energy consumption}\left[{}^{\mathrm{Joule}}/_{\mathrm{s}}\right]} \quad (1)$$

This is a ratio and the electricity intake time period consists of transmit strength and dissipation inside the transceiver hardware and baseband processing. A general situation is that higher information fees can simplest be achieved through consuming extra strength; if the EE is regular, then 100 higher facts price in 5G is associated with a 100 higher energy consumption. This is an environmental problem due to the fact wi-fi networks are usually no longer powered from renewable green sources. It is ideal to massively boom the EE in 5G, but IMT-2020 affords no measurable objectives for it, however claims that better spectral efficiency can be sufficient. There are fundamental approaches to improve the spectral efficiency: smaller cells and huge multiple-input and multiple-output (MIMO). The former gives substantially higher SNRs via lowering the propagation distances and the latter permits for spatial multiplexing of many users and/or higher SNRs. Since these profits are done by using deploying extra transceiver hardware consistent with km 2, better spectral efficiency will not necessarily improve the EE; the EE first grows with smaller cellular sizes and extra antennas, however there may be an particular factor wherein it starts decaying instead. The bandwidth is x in these earlier works, however many other parameters are optimized for maximum EE. There are other non-trivial tradeoffs, such as the reality that transceiver hardware turns into extra efficient with time, so the energy consumption of a given network topology regularly reduces.

While the Shannon capacity manifests the maximal spectral efficiency over a channel and the rate of light limits the latency, the corresponding upper limit on the EE is unknown. A comprehensive look at of the EE of 4G base stations shows that a macro website online delivering 28Mbit/s has an strength intake of 1.35kW, leading to an EE of 20kbit/Joule. Recent papers file EE numbers in the order of 10Mbit/Joule while thinking about destiny 5G deployment scenarios and the use of estimates of contemporary transceivers electricity intake. There is also several papers that recall normalized setups (e.g., 1Hz of bandwidth) that give no insights into the EE that may be achieved in exercise. The purpose of this paper is to analyze the physical EE limits in some different cases and, particularly, give almost relevant numbers on the most possible EE.

II. AN ULTIMATE LIMIT ON THE ENERGY EFFICIENCY:

In this segment, we derive remaining top restriction at the EE. We expect that the channels are deterministic and a outcome of this assumption is that perfect CSI is available. The general models for small-scale fading, includes the Rayleigh fading model, which does not have any upper bounds at the channel gain. However, any bodily channel may have a finite-valued "best" attention due to the fact one cannot receive greater electricity that was transmitted. We will not forget two cases: Single-antenna structures and multiple-antenna structures. In both instances, we count on that the communication takes place over a bandwidth of B Hz, the total transmit energy is denoted by PW, and N_0 W/Hz is the noise energy spectral density. We treat B and P as layout variables.

A. Single-antenna Systems Without Interference

We begin by thinking about a single-antenna machine. The channel is represented by a scalar coefficient $h \in \mathbb{C}$ The acquired signal $\mathcal{Y} \in \mathbb{C}$ is given with the aid of

$$\mathcal{Y} = hx + n \qquad (2)$$

Where $x \in \mathbb{C}$ is the transmit signal with power P and is $n \sim \mathcal{N}_{\mathbb{C}}(0, BN_0)$ is AWGN. Since best CSI is to be had, the potential of the channel is [12]

$$C = B\log_2\left(1 + \frac{P\beta}{BN_0}\right) \quad \left[\frac{\text{bits}}{\text{s}}\right] \qquad (3)$$

Where $\beta = |h|^2$ denotes the channel benefit. The ability is completed by $x \sim \mathcal{N}_{\mathbb{C}}(0, P)$ .When the transmit strength is the best factor contributing to the strength intake, an upper sure at the EE in (1) is

$$\frac{B\log_2\left(1+\frac{P\beta}{BN_0}\right)}{P} \qquad (4)$$

that is a monotonically increasing feature with admire to B/P . Hence, the EE is maximized as $P/B \to 0$, which can be performed through taking the transmit power $P \to 0$, taking the bandwidth $\beta \to \infty$, or a aggregate thereof. The limit is simple to compute with the aid of considering a Taylor expansion of the logarithm around $\left(1 + \frac{P\beta}{BN_0}\right) = 0$:

$$\frac{B\log_2\left(1+\frac{P\beta}{BN_0}\right)}{P} = \frac{B\log_2(e)}{P}\left(\frac{P\beta}{BN_0} - \sum_{n=2}^{\infty}(-1)^n\frac{\left(\frac{P\beta}{BN_0}\right)^n}{n}\right) \to \frac{\log_2(e)\beta}{N_0} \quad as\ P/B \to 0, \qquad (5)$$

Where e denotes Euler's quantity. We apprehend this as the reciprocal of the classical minimum energy-per-bit $N_0/\log_2(e) = N_0\ln(2)$ for an AWGN channel [16], with the simplest distinction that a deterministic channel gain β has been protected. To quantify the EE that may be done on this case, we use the everyday noise power spectral density $N_0 = -\frac{174\text{dBm}}{\text{Hz}}$ in room temperature and bear in mind a practical range of channel gains β from -110dB to -50dB . The ensuing EE is shown in Fig.1 and degrees from 3 Gbit/Joule to 3.10^6 Gbit/Joule= 3 Pbit/Joule. These numbers are the EE limits in single-antenna systems with typical channel gains and are in reality away from what is accomplished by way of modern day systems.

The channel gain is seldom higher than50dB. This cost is achieved while communicating over 2.5m in the 3GHz band in free-space propagation, the usage of lossless isotropic antennas. The cost will decrease at better provider frequencies and when considering longer propagation distances.

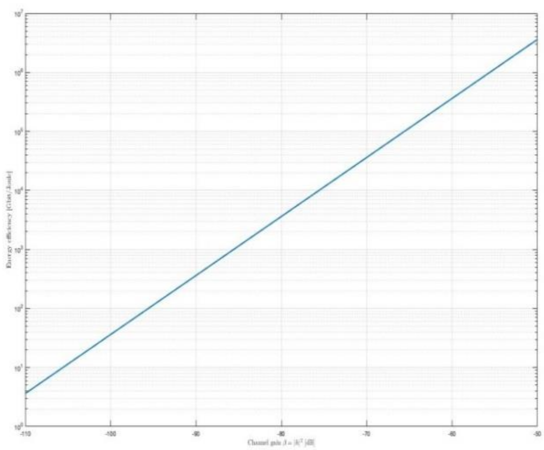

Fig. 1: The Energy Efficiency in a single-antenna relies upon on the channel gain.

B. Single-antenna Systems With Interference

We will now add interference to the gadget. The interference is as a result of one or a couple of structures which can be also operating with most EE as intention. Hence, each transmitter makes use of the equal transmit power P and we denote the sum of the channel gains from all the interfering transmitters, main to a total obtained interference energy of P. By treating interference as noise, the EE in (4) will become

$$\frac{B\log_2\left(1+\frac{P\beta}{BN_0+P\alpha}\right)}{P} \qquad (6)$$

which is still an increasing function of B/P. Hence, an top sure at the EE is performed by way of letting $P/B \to 0$, which leads to

$$\frac{\log_2(e)\beta}{N_0} \qquad (7)$$

This expression is unbiased of and, therefore, coincides with the restrict in (5) for interference-free systems. This demonstrates that it turned into top of the line to treat interference as noise in this case. Notice that we did not purposely forget the interference, but the EE is maximized inside the low SNR regime $P/B \to 0$ where the system is noise limited, not interference limited.

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C. Multiple-antenna Systems

Suppose the transmitter is prepared with M antennas and the receiver is equipped with N antennas, that is a MIMO system. The deterministic channel is now described by means of the channel matrix $\mathrm{H} \in \mathbb{C}^{N\times M}$. If we expect that there's no interference, the received signal $\mathrm{y} \in \mathbb{C}^{N}$ is

$$y = \mathrm{Hx} + n \qquad (8)$$

where $\mathrm{x} \in \mathbb{C}^{M}$ is the transmit sign and $n \sim \mathcal{N}_{\mathbb{C}}(0, BN_0\mathrm{I}_N)$ is AWGN. The channel capability of this MIMO device is [17]

$$C = \max_{k\geq 0:(k)\leq p} B\log_2 det\left(\mathrm{I}_N + \frac{1}{BN_0}\mathrm{HKH}^H\right) \qquad (9)$$

and is completed by $x \sim \mathcal{N}_{\mathbb{C}}(0, \mathrm{K})$ where in the superb semidenite correlation decided on primarily based at the waterlling algorithm. An top certain at the capability is obtained when all the singular values of Hare equal to the most singular value max(h) of the matrix. We then obtain

$$C \leq \sum_{i=1}^{\min(M,N)} B\log_2\left(1 + \frac{P}{MBN_0}\sigma_{max}^2(\mathbf{H})\right) = \min(M,N)B\log_2\left(1 + \frac{P}{MBN_0}\sigma_{max}^2(\mathbf{H})\right) \qquad (10)$$

When the transmit power is the handiest component contributing to the energy intake, an upper bound at the EE in (1) is

$$\frac{\min(M,N)B\log_2\left(1 + \frac{P}{MBN_0}\sigma_{max}^2(\mathbf{H})\right)}{p} \leq \frac{\min(M,N)}{M}\frac{\sigma_{max}^2(\mathbf{H})}{N_0} \qquad (11)$$

where the upper restriction is performed by using letting $P/B \to 0$ as inside the single-antenna case. The first term $\frac{\min(M,N)}{M}$ is upper bounded with the aid of one and this bound is tight while the receiver has as a minimum as many antennas as the transmitter.

A greater complicated query is how $\sigma_{max}^2(\mathbf{H})$ depends on M and N. Since we have assumed that every one the non-zero singular values of H are same, it follows that

$$\sigma_{max}^2(\mathbf{H}) = \frac{\|\mathbf{H}\|_F^2}{\min(M,N)'} \qquad (12)$$

Where $\|.\|_F$ is the Frobenius norm. Suppose all of the elements of H have a consistent magnitude $\sqrt{\beta} > 0$, then $\sigma max2\mathbf{H} = \beta MN\min(M,N) = \beta\max(M,N)$,which goes to infinity as the quantity of transmit and/or acquire antennas grow. This a common place channel model inside the Massive MIMO literature [5],[8]-[10] where it is utilized to demonstrate that the received signal energy grows proportionally to the wide variety of antennas. This scaling behaviour makes experience for realistic number of antennas, but not asymptotically; if the transmit energy is P, the regulation of conservation of power manifests that the receiver can never get hold of more sign power than P, irrespectively of how many antennas are used. Hence, the bodily upper restriction at the singular values is one

$$\sigma_{max}^2(\mathrm{H}) \leq 1 \qquad (13)$$

The top restriction can be executed by means of enclosing the transmitter by using a sphere and then masking the surface of that sphere with get hold of antennas. When the floor is completely covered, all the transmitted strength might be captured by means of the acquire antennas, assuming that these are ideal (lossless).Suppose the sphere has radius r and each lossless antennas has area A, as illustrated in Fig.2,then we need $4\pi r^2/A$ antennas to over the surface. For example, if $r = 10\mathrm{m}$ and isotropic antennas designed for the 3GHz band are used, then $A = 0.1^2/(4\pi)$ and, consequently, we want 1.6 million antennas to cover the surface. This massive quantity explains why the asymptotic analysis in the Massive MIMO literature makes sense even in extreme realistic cases Receive antenna with area A with thousands of antennas.

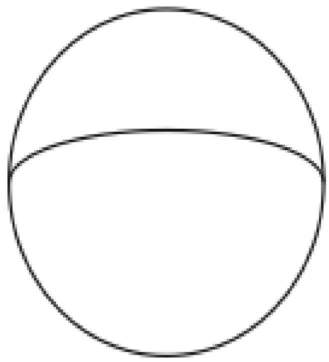

Fig. 2: All the transmitted signal power may be captured through enclosing the transmit antenna. We need $4\pi r^2/A$ antennas to do this, where A is the place of an antenna and r is the radius.

If we eventually need more than $4\pi r^2/A$ antennas, we want to make the floor larger by using increasing r. The result is that is decreased as $1/r^2$ and, therefore, we need to cowl the larger floor of the brand new sphere with extra antennas to seize the identical energy.

In practice, we will maximum likely have $\sigma_{max}^2(\mathbf{H}) \ll 1$, however we are able to see to attain the fina $\sigma_{max}^2(\mathbf{H}) = 1$ EE restriction. Hence, the EE of a multiple-antenna gadget is upper bounded as

$$\mathrm{EE} \leq \frac{log_2(e)}{N_0} \qquad (14)$$

which is similar to the EE restriction for single-antenna systems in (5), but the key distinction is that the channel gain β has now been changed with its higher sure: 0 dB. If we insert the noise electricity spectral density into this

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expression, we acquire the ultimate EE restrict: $10^{20.6}$ bit/Joule = 398 Ebit/Joule.

III. ENERGY EFFICIENCY INCLUDING CIRCUIT POWER

The previous segment demonstrated several ways to attain excessive EE. The most is finished when $P/B \to 0$. From an EE perspective, the evaluation indicates that it doesn't matter if $P \to 0$ or $B \to \infty$, but in phrases of the records price in (3) it makes a large distinction:

$$C=B\log_2\left(1+\frac{P\beta}{BN_0}\right) \to \begin{cases} 0, & p \to 0, \\ \frac{\log_2(e)p\beta}{N_0} & B \to \infty \end{cases} \quad (15)$$

For example, we get 0 bit/s if $P \to 0$ or 1 Tbit/s if $B \to \infty$, (with P = 20 dBm, β = 75 dB, and N_0 =174 dBm/Hz). A communication system with zero ability is almost worthl ess, even if it's far power-efficient from a only mathematical perspective. One purpose for this weird end result is that we taken into consideration the strength consumption version where simplest the transmit power is blanketed, but this may be generalized below. Fig. 3 indicates how the EE procedures its restrict as $B \to 1$ when P= 20 dBm and N_0 =174 dBm/Hz. Different values of are taken into consideration and those are determining how quick we met hod the EE restrict. For the cell-part case of $\beta = -110$dB, the restrict is reached already at B = 1GHz, at the same time as we need 100 × more bandwidth every time β is increased via 20dB.

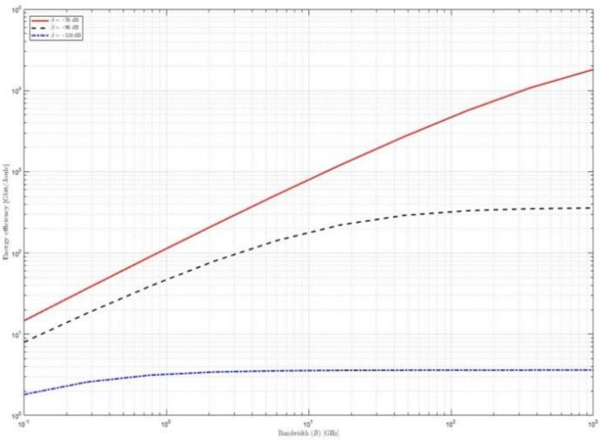

Fig. 3: The EE increases with the bandwidth. The restrict and the convergence rely strongly at the channel advantage.

A. Constant Circuit Power

A greater sensible electricity intake model is $P + \mu$, in which $\mu \geq 0$ is the circuit power the electricity dissipated inside the analog and virtual circuitry of the transceivers. When communicating over long distances, it's miles not unusual to have $P + \mu \approx P$, but in future smalls cells it is possible that $\mu > P$. In the single-antenna case with out interference, the EE in (4) can now be generalized and higher bounded as

$$\text{EE} = \frac{B\log_2\left(1+\frac{P\beta}{BN_0}\right)}{P+\mu} \leq \frac{\log_2(e)\frac{P\beta}{N_0}}{P+\mu} \leq \frac{\log_2(e)\beta}{N_0} \quad (16)$$

Where (a) follows from noting that the EE is an increasing function of B and letting B! 1, while (b) follows from letting P! 1. Another manner to view it is that *P* and *B* are going together to infinity, but B has a substantially better convergence speed such that P=B!0. Interestingly, the upper sure in (16) is similar to in (5), for that reason the inclusion of the circuit power did now not alternate the EE limit, however handiest made the conditions for attaining it stricter and more realistic. Note that was no longer purposely removed inside the bounding, however made negligible via taking P! 1.

B. Varying Circuit Power

The reality that we treated as steady when changing B and P implies that no extensive changes to the hardware are needed when converting those variables. This simplication is tough to justify whilst taking the variables to infinity. The sampling price is proportional to B and the power consumption of analog-to-digital and virtual-to-analog converters is proportional to the sampling charge (i.e., behaves as B for some constant), and the identical applies to the baseband processing of these samples. The strength consumption of data encoding/interpreting is (at best) proportional to the information fee .An alternative EE expression capturing those properties is

$$\text{EE} = \frac{B\log_2\left(1+\frac{P\beta}{BN_0}\right)}{P+vB+\eta B\log_2\left(1+\frac{P\beta}{BN_0}\right)} \quad (17)$$

Where $v \geq 0$ and $\eta \geq 0$ are hardware-characterizing constants.

$$\text{EE} = \frac{x\log_2(e)}{N_0\frac{e^x-1}{\beta}+v+\eta x\log_2(e)} \quad (18)$$

Since this EE is executed by means of any values of *P* and *B* having the ratio in (18), we have the freedom to choose B to reap any desired information price

$$C = Bx\log_2(e) \quad (19)$$

The corresponding EE-maximizing value of *P* is acquired. In other words, there's no tradeoff between EE and rate-except if *P* and *B* are limited by external factors.

These effects are illustrated in Fig. 4 for $\beta = -80$ dB,$N_0 = -174$ dBm/Hz, $v = 10^{-14}$ J , and $\eta = 10^{-15}$ J/bit. The latter values are decided on futuristically based totally at the essential bound on computing electricity : the Landauer restrict is approximately 10^{-18}logic operations in line with Joule. Hence, v corresponds to ten thousand good judgment operations in step with sample and η to a thousand common sense operations in step with bit. Fig. 4(a) shows how the EE is maximized for sure combinations of *P* and *B*, which can be marked by means of a line. All these factors offer the maximum EE of 3 Tbit/Joule, however they offer massively different records charges, as proven in Fig. 4(b). In the considered parameter intervals, the EE-maximizing price degrees from 0.3 Gbit/s to 3Tbit/s. The EE-maximizing ratio P/B , supplied

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by Theorem 1, gives an most desirable SNR $\frac{P\beta}{BN_0} = -6$dB of and a spectral efficiency of zero.3bit/s/Hz. A binary modulation scheme with channel coding can reap this bit/s/Hz in a practical implementation. For example, LDPC decoding can be implemented with 10^{16}J/bit [18] that's below the considered value of η .

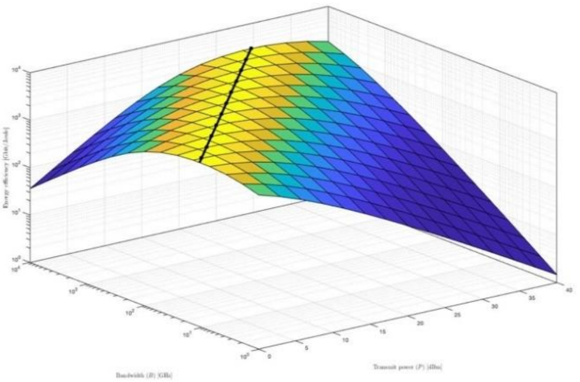

Fig 4(a)

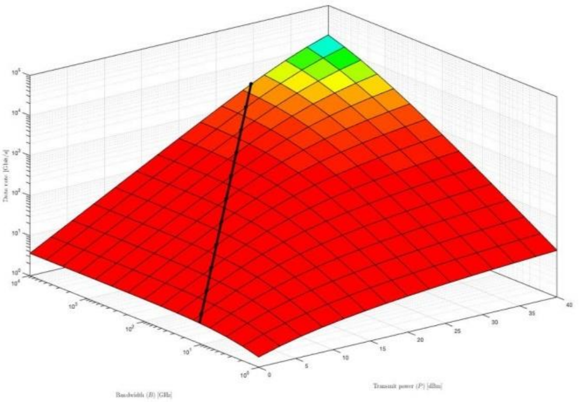

Fig 4(b)

Fig. 4: The EE in (a) and facts price in (b) vary with the transmit electricity and bandwidth. The most EE is executed while the ratio is filled and we are able to then range the strength and bandwidth (alongside the thick line) to gain any statistics charge wished.

C. Multiple-antenna Systems

We can amplify the evaluation to MIMO structures. For brevity, we count on that both the transmitter and receiver are prepared with M antennas. An plausible top certain at the potential is given in (10) and the corresponding EE is

$$\text{EE} = \frac{MB\log_2\left(1+\frac{P}{MBN_0}\sigma_{max}^2(\mathbf{H})\right)}{\text{p+vBM+}\eta\text{xlog}_2\left(1+\frac{P}{MBN_0}\sigma_{max}^2(\mathbf{H})\right)} \quad (20)$$

wherein the first term within the denominator is the full transmit strength, the second time period is the power consumption of processing M parallel alerts at the transmitter and receiver, and the third time period is the power intake of encoding/decoding.

IV. CONCLUSION

The energy efficiency of a massive MIMO system can purely depends on which parameter values can be decided on in practice and the electricity consumption modeling. If it is modeled to seize the most essential hardware characteristics, the best EE is done for a particular ratio of the transmit power P and bandwidth B, which typically corresponds to a low SNR. Any statistics fee may be accomplished by means of collectively increasing P and B while preserving the most reliable ratio. The physical higher restrict on the EE is round 1Pbit/Joule. For sensible number of antennas and channel profits, we will instead wish to reach EEs in the order of some T bit/Joule (as in Fig. 4) in future systems.

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