Energy Efficiency Optimization for 5G Wireless Communication Systems.

Attougbré Franck Igor Djanan[1], Diaby Moustapha[2], Adama Coulibaly[3]

[1]*Boigny Houphouet Felix University Abidjan, Cote d'Ivoire*
[2]*African High School of ICT Abidjan, Cote d'Ivoire*
[3]*Boigny Houphouet Felix University Abidjan, Cote d'Ivoire*

Abstract - *The importance of energy efficiency (EE) in wireless networks is growing growth. Hence the interest in giving consideration to this metric whose long-term trend follows Cooper's law, where traffic is growing every year, and it is certain that continues for years to come. This is linked to data transmission and energy consumption in power amplifiers with an amplification coefficient, baseband material and processing. The relation is made up of the notion of energy efficiency, measured in bit/Joule, which defines the ratio of the amount of energy consumed by information bit received. It must be indicated that the data rate is limited by the capacity of the channel, thus the energy efficiency of a communication system wireless can be defined in several forms depending on the goal you want to achieve. Current survey documents generally present values in the order of 10Mbit/Joule, yet previous generations of wireless networks have operated well with energy efficiencies in the order of 10kbit/Joule. Can the same work for future power management systems (5G and beyond) become, or are we, far from the physical limits? These issues are addressed in this paper, by studying the limiting value of energy efficiency when the bandwidth becomes large. We look at a different case representing a potential future system deployment and system related characteristics.*

Key Words: **Energy efficiency(e), spectral efficiency(s), optimization, Interference, MIMO**.

1.INTRODUCTION

We are witnessing in recent years new performances of wireless technology and the certification is led by the International the Telecommunications Union (ITU), which provides minimum performance recommendations. For example, 4G was manufactured to meet IMT-Advanced requirements [1] on spectral efficiency, bandwidth, energy efficiency and mobility. As well the new standard of 5G [2] must meet the minimum needs to be an IMT-2020 radio interface [3]. The table below shows the different frequencies used today and the corresponding standard. The 2G band focuses on the 900 and 1800 MHz bandwidths. Some operators also operate 4G on 1800 MHz. The 3G is used on the 900 and 2100 MHz bandwidth. 4G works on the 800, 1800 and 2600 bandwidths

MHz and more recently on the 700 band. The arrival of 5G in a few years will be based on the 700 and 3500 MHz bandwidth initially [17]. What will be the impact of the evolution of the bandwidth on energy efficiency, spectral and other in the future?

Bandwidth	[frequence min, frequence max]	Standard
700 MHz	[694 – 790] MHz	4G/5G
800 MHz	[791 – 862] MHz	4G
900 MHz	[880 – 960] MHz	2G/3G
1800 MHz	[1710 – 1880] MHz	2G/4G
2100 MHz	[1920 – 2170] MHz	3G
2600 MHz	[2500 – 2690] MHz	4G
3500 MHz	[3500 – 3700] MHz	5G

Energy efficiency is a necessity for the future (5G, etc.) because it is not taken into account by 2G, 3G and 4G. The more we have more stringent requirements in four generations, a new metric has been associated in [3]: energy efficiency (EE). A fundamental definition of EE is [4], [5]

$$EE(b/J)= \frac{Data\ rate(^{b}/_{s})}{\text{Energy Consumption}(^{J}/_{s})} \qquad (1)$$

Energy efficiency (1) is measured in bit/joule, this metric is thus measured as a function of the amount of data corrected by Joule energy consumed This metric showed the benefit-cost ratio and the amount of energy consumption. contains transmit power and dissipation in the transceiver hardware and baseband processing [5], [6]. One of the common concerns is that higher data rates can only be achieved when there is more consumption energy; if the EE remains constant, then we will have 100 times more data rate more important in 5*G* is pegged to 100 times higher energy consumption. We are faced with a fundamental and environmental question due to the fact that wireless networks are mostly not supplied from renewable green sources. It recommendable to exaggerate to increase the EE in 5*G*, but IMT 2020 does not set measurable goals for her, but assumes that more spectral efficiency will be necessary. We have two main ways to improve spectral efficiency: on the one hand we consider the smaller cells [6], [7] and on the other hand massive multiple inputs and multiple outputs (MIMO) [8], [9]. In this work we fix the transmitted power, but many other important variables such as bandwidth, channel gain are optimized to obtain maximum EE. We have other compromises to consider, including the fact that the transceiver hardware improves more efficiently with time [6]; [11], which results in energy consumption of a chosen network the topology decreases as it is measured. However the capacity of Shannon [12] describes the maximum spectral efficiency on a channel and shows that speed of light limit the latency, the upper limit associated on the EE not known. A study conducted on the baseline 4G EE stations is described in [13]. This proves that a macro site giving 28 Mbps has a power consumption of 1.35kW, which provides an EE of 20kbit/joule. Recent research gives EE figures in the order of 10Mbit/Joule[5]; [14]; [15] taking into account future 5G deployment scenarios and using approximations of power consumption of transceivers. The main objective of this article is to study the physical limits of EE in special cases and, in addition, give values on the suitable maximum EE.

2. EXPRESSION OF THE LIMIT ON ENERGY EFFICIENCY

In this part, we derive an important limit on the EE. We consider that the channels are deterministic and a consequence linked to this hypothesis is that the suitable state of the canal information (CSI) is accessible to all (this means that it can be evaluated with a given and with a negligible additional cost). Also note that the capacity of a fading channel to be considered can be limited by a deterministic channel having the channel feasibility from the fading distribution that optimizes mutual information. We study two major cases: systems with a single antenna and multiple antenna systems. In each of the two cases presented, we consider that the communication is evaluated on a bandwidth of B Hz, the total the transmit power is denoted by P W , and $N_0 W/Hz$ identifies the noise power spectral density[6]. In our work we assume B as one of the design variables and P will be taken as a constant.

2.1 The limit value for energy efficiency (EE) with only one antenna.

We are working in this particular case with only one antenna in the system. We consider that the channel is defined by a scalar coefficient $h \in C$. The received signal $y \in C$ is expressed by:

$$y = hx + n \quad (2)$$

we have $x \in C$, which is the transmit signal with power P and n $\sim N_C$ (0, BN_0) is AWGN. The CSI being perfectly available, the capacity of the channel is defined by: [12]

$$C = B\log_2(1+\frac{Ph^2}{N_0 B}) = B\log_2(1+\frac{P\beta}{N_0 B}) \quad (3)$$

where $\beta = h^2$ defines the gain of the channel. The capacity is identified by $x \sim N_C$ (0, P). The operational and fundamental meaning of energy efficiency can be defined by taking into account an additive Gaussian white noise (AWGN) channel. In this case, the capacity of the channel will be considered as a measure. system benefit, energy efficiency can be defined as:

$$\frac{B\log_2(1+\frac{P\beta}{N_0 B})}{\mu P+P_c} \quad (4)$$

Where $\mu = \frac{1}{\lambda}$ with λ which represents the efficiency of

the transmission power amplifier, while P_c represents the power dissipated in all the other circuits of the transmitter and receiver to operate the terminals. Therefore, the EE is maximized by considering the bandwidth B→ ∞. The limit is calculated by taking a Taylor expansion of the logarithm around $\frac{P\beta}{N_0 B} = 0$:

$$\frac{B\log_2(1+\frac{P\beta}{N_0 B})}{\mu P+P_c} = \frac{B\log_2(e)}{\mu P+P_c}\left(\frac{P\beta}{N_0 B} - \sum_{n=2}^{\infty}(-1)^n\frac{(\frac{P\beta}{N_0 B})^n}{n}\right)$$

$$\rightarrow \frac{P\beta\log_2(e)}{N_0(\mu P+P_c)} \text{ as } B\rightarrow\infty \quad (5)$$

To optimize the EE that can be achieved by in this case we take the typical noise power spectral density N_0 = 125dBm/Hz with an ambient temperature and carry out a practice β channel gain for values 60 dB, 100 dB and 120dB. To always measure the EE which can be carried out by in this case, we take the circuit power P_c = 0.1 and μ = 10^{-14}. These results are compared with the results obtained in the work of Emil Bjrnson and Erik G. Larsson[19]. In these works the maximum EE is a function of β while our results obtained show that the maximum EE is a function of the transmitted power P, β, μ and P_c. These results are the EE limits in single antenna systems with channel gains and are far from what is obtained by the present systems.

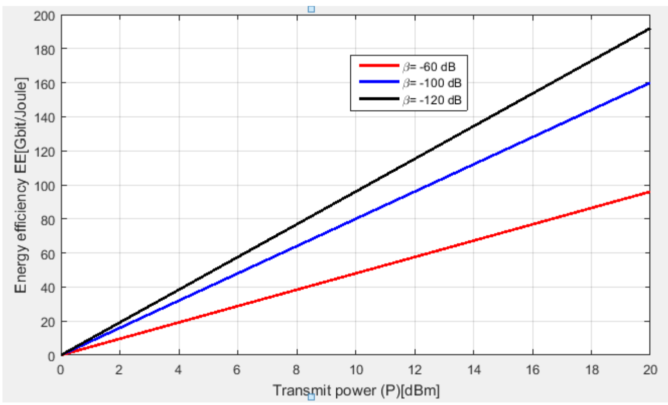

Fig.1 The maximum EE in a single antenna system is a function of transmitted power P in the canal for different values of β.

Here we note the more the propagation loss decreases, the more the curve of the maximum EE evolves, which is normal in reality.

2.2 Wireless communication systems has a single antenna with interference

Interference is not necessarily independent of input x and channel h. The exact capacity of the interference channels is largely unknown, however, practical lower limits can be achieved

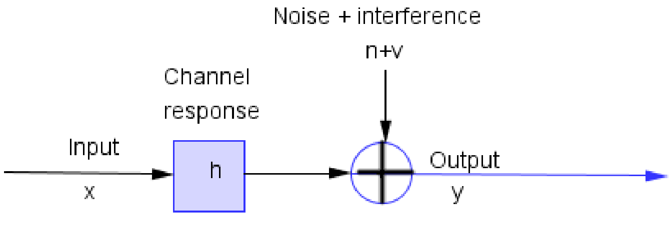

Fig. 2 A discrete memory less interference channel with input x and output $y = hx + v + n$, where h is the channel response, n is independent Gaussian

noise, and v is the interference, which is uncorrelated with the input and the channel.

So we define the following expression:

$$SINR = \frac{\overbrace{Ph^2}^{\text{Received signal power}}}{\underbrace{Pv}_{\text{Interference power}} + \underbrace{\sigma^2}_{\text{Noise power}}} \quad (6)$$

which can be analyzed as the signal-to-interference-plus-noise ratio (SINR), where $\sigma^2 = BN_0$. Formally, it is only an SINR when we have h and pv are deterministic; the expression is otherwise random. We begin by considering a single-antenna system. The channel is represented by a scalar coefficient $h \in C$. The received signal $y \in C$ is given by

$$y = hx + v + n \quad (7)$$

where $x \in C$ is the transmit signal with power and $n \in N_C(0, BN_0)$ is AWGN. Since perfect CSI is available, and $v \in C$ is random interference[12] We will now add EE as goal. Therefore, the transmit power P is

used by each transmitter and we take $v > 0$ denote the sum of the channel gains of all transmitters with noise, leading to a total received interference power of $P v$. We are considering interference like

$$\frac{B \log_2(1 + \frac{P\beta}{N_0 B + Pv})}{\mu P + P_c} \quad (8)$$

which is still an increasing function of B. Hence, an upper bound on the EE is achieved by letting B → ∞, which leads to

$$\frac{P\beta \log_2(e)}{N_0(\mu P + P_c)} \quad (9)$$

The expression obtained is independent of v, and therefore, merges with the limit in (5) to systems without interference. This proves that it was optimal to consider interference as noise in this Context. We understood the interference, but the EE is optimized, i.e. maximized in the low SINR regime B → ∞ where the system is considered in noise and not in interference.

2.3 Multiple antenna systems in wireless networks.

Let us assume that the transmitter is composed of antennas M and the receiver is made up of N antennas, which makes a MIMO system. Then the deterministic channel is realized by the channel matrix $H \in C^{N \times M}$ If we asked that there is no interference, then the received signal $y \in C^N$ is as follows:

$$y = Hx + n \quad (10)$$

where $x \in C^M$ represent the transmit signal and $n \sim N_C(0, BN_0 I_N)$ is AWGN. Also the channel capacity of this MIMO system is given by [17]

$$C = B \log_2 |I_N + \frac{1}{BN0} HPH^H| \quad (11)$$

We receive that the optimization variable is not defined as a scalar power but a P matrix with N dimensions and is achieved by $x \in N_C(0, P)$ where we have the positive semi-definite the correlation matrix P is chosen in relation to the water filling algorithm. Consequently, this can be realized for multiple input multiple output (MIMO) system with P representing the transmission covariance matrix. Thus taking into account the capacity as a function of efficiency, we received the level by $\sigma^2$the noise power of the receiver, and by H the MIMO channel matrix, the definition of energy efficiency is as follows:

$$EE = \frac{B \log_2 |I_N + \frac{1}{BN0} HPH^H|}{\mu tr(P) + P_C} \quad (12)$$

With $tr(P) \leq P_{max}$ also an upper bound on the capacitance is realized when all the singular values of H are equal to the maximum singular value $\sigma_{max}(H)$ of the matrix. We then have

$$C = \sum_{i=1}^{\min(M,N)} B \log_2 \left(1 + \frac{P}{MBN0} \sigma^2_{\max}(H)\right) \quad (13)$$

$$C = \min(M, N)\, B \log_2 \left(1 + \frac{P}{MBN0} \sigma^2_{\max}(H)\right)$$

When the transmission power and the power of the circuits are the only factors involved in energy consumption, an upper bound on the EE in (1) is obtained

$$\frac{\min(M,N)\, B \log_2\left(1+\frac{P}{MBN_0}\sigma^2_{\max}(\mathrm{H})\right)}{\mu tr(P)+P_C} \leq \frac{\min(M,N)}{M}\frac{P\log_2(\mathrm{e})\sigma^2_{\max}(\mathrm{H})}{\mu P_{max}N_0} \quad (14)$$

where we have the upper limit when $B \to \infty$ like in the situation with an antenna. The term $\frac{\min(M,N)}{M}$ is bounded by one and this bound is reached when the receiver has at least as many antennas as the transmitter. One concern is how $\sigma^2_{\max}(\mathrm{H})$ depends on M and N. Since we have assumed that all non-zero the singular values of H are equal, then we have

$$\sigma^2_{\max}(\mathrm{H}) = \frac{\|\mathrm{H}\|_F^2}{\min(M,N)} \quad (15)$$

Where $\|.\|_F$ is the Frobenius norm. We consider that all the elements of H has a constant magnitude $\sqrt{\beta} > 0$; then $\sigma^2_{\max}(\mathrm{H}) = \frac{\beta MN}{\min(M,N)} = \beta \max(M,N)$ whichtends to infinity if the number of transmitting and / or receiving antennas increased. This a channel model is mentioned a lot in the Massive MIMO literature [5], [8]-[10], when highlighted to show that the signal strength increased as a function of the number of antennas. Also the upper limit on singular values is defined by:

$$\sigma^2_{\max}(\mathrm{H}) \leq 1 \quad (16)$$

In reality, we will have $\sigma^2_{\max}(\mathrm{H}) \leq 1$, but we can set

$\sigma^2_{\max}(\mathrm{H}) = 1$ in order to get the limit EE. So, the EE of a system with several antennas is increased, that is to say we have:

$$EE \leq \frac{P\log_2(\mathrm{e})}{\mu N_0 P_{max}} \quad (17)$$

which is similar to the EE limit for single-antenna systems in (5), but the key difference is that the channel gain has now been replaced with its upper bound: 0dB, circuit power P_C is not.

3. ENERGY EFFICIENCY INCLUDING CIRCUIT POWER IN WIRELESS COMMUNICATION SYSTEMS

In the previous paragraph we have shown several ways to reach high EE. Thus the maximum is reached when $B \to \infty$. From an EE perspective, the analysis shows that it has no interest if $B \to \infty$, but concerns the data rate in (2) there is a difference :

$$C = B\log_2\left(1 + \frac{P\beta}{BN_0}\right) \to \frac{P\beta \log_2(\mathrm{e})}{N_0}, B \to \infty \quad (18)$$

For a communication system worthless capacity is obviously without important, even if it is beneficial in energy from a purely mathematical point of view perspective.

3.1 Constant Circuit Power and transmit power.

During communication over long distances it is usual to have $\mu P + P_C \approx \mu P$, but in future small cells it is possible that $\mu P > P_C$ [6]; [15]. In the mono-antenna unit without interference, the EE in (4) can be upper bounded as

$$\frac{B\log_2(1+\frac{P\beta}{N_0B})}{\mu P+P_c} \leq \frac{B\log_2(\mathrm{e})\frac{P\beta}{N_0B}}{\mu P+P_c} \leq \frac{\log_2(\mathrm{e})\,\beta}{\mu N_0} \quad (19)$$

Here we assume that B has a significantly higher value speed of convergence such that $B \to \infty$. Another interesting fact is the limit found in (5) is different from that obtained in (19), because the power of the circuits is not taken into account.

3.2 Modifying the power of the circuit

In this part we are interested in a special metric of energy efficiency. This means that we take $P_C = \nu B + \eta B\log_2\left(1 + \frac{P\beta}{N_0B}\right)$. This modification is difficult to demonstrable when one considers the variables at infinity. The sampling rate is proportional to the bandwidth B and the power consumption of the analog-to-digital and digital-to-analog converters is proportional to the sampling rate, and so is the baseband processing of these samples. Thus the energy consumption of the encoding/decoding of the data is proportional to the data rate. An EE expression associated with these properties is given by

$$EE = \frac{B\log_2(1+\frac{P\beta}{N_0B})}{\mu P+\nu B+\eta B\log_2(1+\frac{P\beta}{N_0B})} \quad (20)$$

where $\nu > 0$ and $\eta > 0$ are hardware-characterizing constants.

Definition [16]

The Lambert W function is denoted by $W(x)$ and defined by the equation $x = W(x)exp^{W(x)}$ for any $x \in C$.

Lemma [16]

Consider the optimization problem :

$$maximize_{z>-\frac{a}{b}} \frac{g\log_2(\mathrm{a}+\mathrm{bz})}{c+dz+h\log_2(\mathrm{a}+\mathrm{bz})} \quad (21)$$

with constant coefficients $a \in R, c.h \geq 0$; and $b; d; g > 0$. The unique solution to is :

$$z^* = \frac{e^{W\left(\frac{bc}{de}-\frac{a}{e}\right)+1} - a}{b} \quad (22)$$

Theorem 1: The EE in (20) is maximized for any values of P and B such that

$$\frac{P}{B} = N_0 \frac{\exp(x) - 1}{\beta} \qquad (23)$$

Where $x = W\left(\frac{\beta\nu}{N_0\,\mu e} - \frac{1}{e}\right) + 1 \qquad (24)$

And $W(:)$ denotes the Lambert W function [10].

Proof

With $z = P/B$ can be expressed as:

$$EE = \frac{\log_2(1 + \frac{\beta}{N_0} z)}{\nu + \mu z + \eta \log_2(1 + \frac{\beta}{N_0} z)} \qquad (25)$$

and can be optimized using (Lemma). This theorem shows

that the maximum EE is reached when B is of non-zero finite value, in the practical case of $\nu > 0, \eta > 0$; and $\mu > 0$. We observe that the optimal ratio obtained depends on the propagation conditions (via β/N_0) and the transceiver hardware (via ν). In particular, there is no dependency that shows that the the power consumption of encoding/decoding does not affect the optimal values of B, but especially the maximum value of the EE. Hence, it is the term νB in (20) that fundamentally changes the behavior as compared to the previous subsections. By inserting (23) into (20), the maximum EE is obtained as

$$EE = \frac{x \log_2(e)}{\mu N_0 \frac{\exp(x)-1}{\beta} + \nu + \eta x \log_2(e)} \qquad (26)$$

Thus this EE is realized by all the values of B and P having the ratio in (18), we can choose B in order to achieve any desired data rate:

$$C = x \log_2(e) \qquad (27)$$

The associated maximization value EE of P is determined of the theorem 1. Otherwise, there is no compromise between EE

and rate unless P and B are controlled by external factors. These results are illustrated in Fig. 3 for $\beta = -60$dB; $N_0 = 125$dBm/Hz; ν = 10^{-10}J; and; η = 10^{-17}J=bit; μ=2: The last two values are chosen in the future based on the fundamental bound on the computing power [6]: note that the Landauer limit is equal to 10^{-18} of logical operations per Joule. Also, ν corresponds to 10, 000 logical operations per sample while η to 1000 logical operations

per bit. Fig. 3 and Fig.4 describe how the EE reaches its maximum value for certain combinations of B and P. All these points give the maximum EE of 3Tbit/Joule. Also in the considered parameter ranges, the EE maximization rate ranges from 0.3Gbit/s to 3Tbit/s. The ratio EE-maximizing P/B, given by the theorem 1, provides a Optimal SNR of $\frac{P\beta}{N_0 B} = -3$dB and a spectral efficiency of 0.3bit/s/Hz. A comparative study carried out in the work of Emil Bjrnson and Erik G[19]. Larsson shows that the maximum EE that we found is also well improved with the amplifier coefficient.

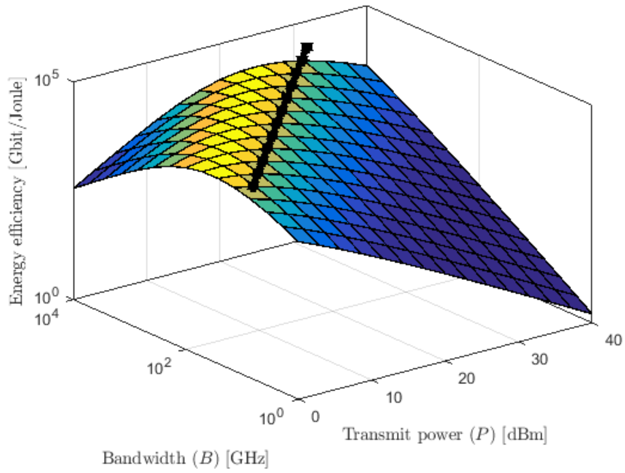

Fig. 3 The EE vary with the bandwidth and transmit power. The maximum EE is carried out when the condition in (23) is observed and we can in this case vary the bandwidth and the transmitted power (along the thick line) to satisfy the necessary data rate.

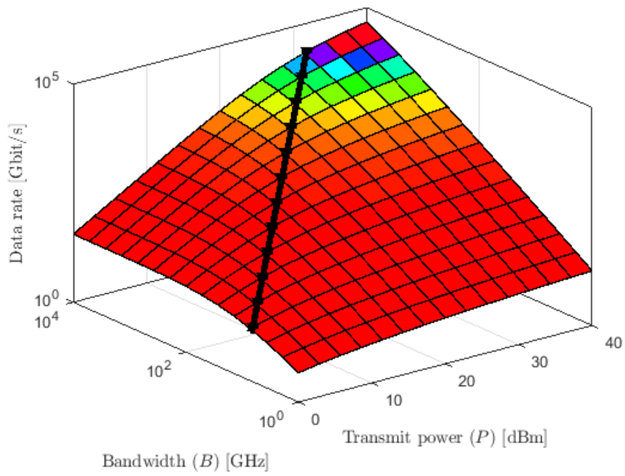

Fig. 4 The data rate vary with the bandwidth and transmit power. The maximum EE is carried out when the condition in (23) is observed and we can in this case vary the bandwidth and the transmitted power (along the thickline) to satisfy the necessary data rate.

3.3 Multiple-antenna in wireless communication Systems

To make the job more interesting we extend the analysis to cover MIMO systems. In addition, we consider that the transmitter and the receiver are equipped with N antennas. Then an upper limit achievable on the the capacity is obtained

in (13) and the corresponding EE is

$$EE = \frac{\mathrm{N}\,B\,\log 2\left(1 + \frac{P}{MBN_0}\,\sigma^2_{\max}(\mathrm{H})\right)}{\mu P + \nu B + \mathrm{N}\,B\,\log 2\left(1 + \frac{P}{MBN_0}\,\sigma^2_{\max}(\mathrm{H})\right)} \quad (28)$$

in this case the first term of the denominator represents the total transmitted power, the second term is the energy consumption of the treatment N signals parallel to the transmitter and receiver, and the the third term is the encoding /decoding energy consumption. Corollary 1: The EE in (28) is maximized for all values of P and B such that

$$\frac{P}{B} = N_0\frac{\exp(\hat{x})-1}{\beta} \text{ with } \hat{x} = W\left(\frac{\sigma^2_{\max}(\mathrm{H})\nu}{N_0\,\mu e} - \frac{1}{e}\right) + 1 \quad (29)$$

Proof

we take $\frac{P}{NB}$, the EE has the same form as in (25) and can be optimized as in Theorem 1. As a result maximum EE is reached. Also by adding more antennas we can increase this channel gain $\sigma^2_{\max}(\mathrm{H})$ around 1. With the same values ν and η as in the previous subsection, the ultimate EE is 0.6Pbit/Joule.

4. CONCLUSIONS

In this article, we looked at optimizing EE by varying the bandwidth. It strongly depends on which the parameter values can be selected in reality and also modeling of energy consumption. If it is modeled as a function the most essential material characteristics, optimal EE is reached for a particular value of the bandwidth *B* and considering the transmitted power as a constant, which particularly corresponds to a low SNR. As well the data rate can reach the maximum value by simultaneously increasing *B* and *P* while keep the optimal ratio. The higher physical value on the EE is around 1*P bit/Joule*. For the number of antennas and the value of a few Tbit/Joule in future systems.

REFERENCES

[1] ITU "Minimum requirements related to technical performance for IMT 2020 radio interfaces", ITU-R M.2410-0,Tech.Rep.,Nov.2017.

[2] X. Xia, K. Xu, Y. Wang, and Y. Xu, "A 5G-Enabling Technology: Benefits, Feasibility, and Limitations of In-Band Full-Duplex mMIMO," IEEE Vehicular Technology Magazine, vol. 13, no. 3, pp. 81-90, Sep. 2018.

[3] ITU, "Requirements related to technical performance for IMT advanced radio interfaces" ITU-R M.2134,Tech.REP.,2008.

[4] Bjrnson, E., Larsson, E.G., Debbah, M.: "Massive MIMO for maximal spectral efficiency: how many users and pilots should be allocated?", IEEE Trans. Wirel. Commun., 2016; 15; (2), pp. 1293 – 1308.

[5] Y Luo, Z Shi, F Bu, J Xiong, "Joint Optimization of Area Spectral Efficiency and Energy Efficiency for Two-Tier Heterogeneous Ultra-Dense Networks", IEEE Access, vol. 7, pp.12073 - 12086; 2019.

[6] Y Mao, B Clerckx, VOK Li, "Rate-Splitting for Multi-Antenna Non-Orthogonal Unicast and Multicast Transmission: Spectral and Energy Efficiency Analysis", IEEE Transactions on Communications, vol. 67, pp.8754 - 8770; 2019.

[7] Randa Jaouadi. "Energy and spectral efficiency tradeoff for autonomous communicating objects". UNIVERSITE DE NANTES, France2017.

[8] Mohammed, S.K.: "Impact of transceiver power consumption on the energy efficiency of zero-forcing detector in massive MIMO systems", IEEE Trans. Commun., 2014; 62; (11), pp. 3874 – 3890.

[9] Y. Liu and L. Dong, "Spectrum sharing in MIMO cognitive radio networks based on cooperative game theory," IEEE Trans. Wireless Commun., vol. 13, no. 9, pp. 4807 - 4820, Sep 2014.

[10] X. Gao, O. Edfors, F. Rusek, and F. Tufvesson, "Massive MIMO in real propagation environments," IEEE Trans. Wireless Commun., 2014; submitted. [Online]. Available: http://arxiv.org/abs/1403:3376.

[11] Mili, M.R., Hamdi, K.A., Marvasti, F., et al.: "Joint optimization for optimal power allocation in OFDMA femtocell networks", IEEE Commun. Lett., 2016; 20; (1), pp. 133 – 136.

[12] S. H. Yeung, A. Garcia-Lamperez, T. Kumar Sarkar, and M. Salazar-Palma, "A thin and compact high gain planar antenna integrated with a CMRC compact filter," in Wireless Symposium (IWS), 2014 IEEE International, Mar. 2014; pp:1 - 4:

[13] S. F. Yunas, M. Valkama, and J. Niemla, "Spectral and energy efficiency of ultra-dense networks under different deployment strategies," IEEE Commun. Mag., vol. 53, no. 1, pp. 90 - 100, Jan. 2015.

[14] E. Bjrnson and E. A. Jorswieck. "Optimal resource allocation in coordinated multi-cell systems". Now Publishers: Foundations and Trends in Communications and Information Theory, pp: 113 - 381, January 2013.

[15] C. Jiang and L. Cimini, "Energy-efficient transmission for MIMO interference channels," IEEE Trans. Wireless Commun, vol. 12, no. 6, pp. 2988 - 2999, June 2013.

[16] E. Bjornson, L. Sanguinetti, J. Hoydis, and M. Debbah, "Optimal design of energy-efficient multi-user mimo systems: Is massive mimo the answer?" IEEE Trans. Wireless Commun., vol. 14, no. 6, pp. 3059 -3075; 2015.

[17] Li, C., Zhang, J., Letaief, K.B.: "Throughput and energy efficiency analysis of small cell networks with multi-antenna base stations", IEEE Trans. Wirel. Commun., 2014; 13; (5), pp. 2505 – 2517.

[18] Zujun Liu, Weimin Du, Dechun Sun, "Energy and Spectral Efficiency Tradeoff for Massive MIMO Systems with Transmit Antenna Selection" IEEE Transactions on Vehicular Technology, vol. 66, pp.4453 - 4457; 2016.

[19] Emil Bjrnson and Erik G. Larsson "How Energy-Efficient Can a Wireless Communication System Become? Department of Electrical Engineering (ISY), 2019.