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On the Energy Efficiency Gain of MIMO Communication under Various Power Consumption Models

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Abstract: Along with spectral efficiency (SE), Energy efficiency (EE) is becoming one of the main performance evaluation criteria in communication. These two criteria, which are conflicting, can be linked through their trade-off. As far as MIMO is concerned, a closed-form approximation of the EE-SE trade-off has recently been proposed and it proved useful for analyzing the impact of using multiple antennas on the EE. In this paper, we use this closed-form approximation for assessing and comparing the EE gain of MIMO over SISO system when different power consumption models (PCMs) are considered at the transmitter. The EE of a communication system is closely related to its power consumption. In theory only the transmit power is considered as consumed power, whereas in a practical setting, the consumed power is the addition of two terms; the fixed consumed power, which accounts for cooling, processing, etc., and the variable consumed power, which varies as a function of the transmit power. Our analysis unveils the large mismatch between theoretical and practical EE gain of MIMO over SISO system; In theory, the EE gain increases both with the SE and the number of antennas, and, hence the potential of MIMO for EE improvement is very large in comparison with SISO; On the contrary, the EE gain is small and decreases as the number of transmit antennas increases when realistic PCMs are considered.

Keywords: MIMO, energy efficiency, trade-off, power consumption model

1. Introduction

In communication, energy efficiency (EE) has mainly been studied for power-limited applications, such as battery-driven system [1], e.g. mobile terminal, under acoustic telemetry [2] or wireless ad-hoc networks [3]. However, in the current context of growing energy demand and increasing energy price, communication network operators drive the research agenda towards more energy efficient network as a whole in order to decrease their ever-growing operational costs. This trend can already be noticed in the current development of future mobile systems, e.g. long term evolution-advanced (LTE-A), which clearly contrast with the development of 3GPP systems, such as wideband code division multiple access (WCDMA), where the energy consumption issues have received little, if any attention.

The efficiency of a communication system is usually measured in terms of spectral efficiency (SE), which is directly related to the channel capacity in bits/s. This metric indicates how efficiently a limited frequency spectrum is utilized but does not provide any insight on how efficiently the energy is consumed. In a context of energy saving, this aspect becomes very important and, thus, it should be integrated in the performance evaluation framework by the means of EE metrics. For instance, the bit-per-joule capacity (bits/J), which has first been introduced in [2] and is simply defined as the ratio of the capacity to the rate of energy expenditure can be one of these metrics. Other EE metrics, such as the Joule-per-bit [3] and the traditional energy-per-bit to noise power spectral density ratio [4], i.e. E_b/N_0, have also been used in the literature. The EE of a system is obviously closely related to its power consumption and, thus, a power consumption model is required in addition to the EE metric for properly assessing its EE. In this regards, two different base station (BS) power consumption models have recently been proposed in [5] and [6]. The former is linear and related to GSM and UMTS, whereas the latter is non-linear and related to LTE.

Minimizing the EE while maximizing the SE are conflicting objectives and, consequently, they can be linked together through their trade-off. The concept of power-bandwidth trade-off or equivalently EE-SE trade-off has first been introduced in [4], where an approximation of this trade-off has been derived for the white and colored noise, as well as multi-input multi-output (MIMO) fading channels. This linear approximation is accurate in the low-SE regime but largely inaccurate otherwise. Recently in [7], we have proposed a closed-form approximation of this EE-SE trade-off for MIMO system over a Rayleigh fading channel, which is highly accurate for a wide range of SE values and antennas configurations.

In this paper, we first use our closed-form, which is presented in Section 2., for deriving the theoretical EE gain limits of MIMO over SISO system in the low and high-SE regimes in Section 3., in order to get an insight on the behavior of this gain as a function of the SE and number of antennas. We then introduce the PCMs of [5] and [6] in Section 4. and use them in conjunction with our closed-form approximation for obtaining practical EE gain results. These results are next compared with theoretical results in Section 4. and they show the disparity between the potential MIMO vs. SISO EE gain when either a theoretical PCM or realistic PCMs are considered. In theory, the EE increases linearly with the number of receive antennas in the low-SE regime and exponentially with the SE in the high-SE regime. In contrast, using a MIMO system with more than 2 transmit antennas at the BS is unlikely to provide any EE gain or can even be less efficient than SISO system when realistic PCMs are assumed. Conclusions are finally drawn in Section 5..

2. EE-SE Trade-off over the MIMO Rayleigh Fading Channel

In order to introduce the EE-SE trade-off concept itself, we first recall the work in [2] over the additive white Gaussian noise (AWGN) channel. Let us assume a single-user communication system where data is encoded at a rate R and transmitted with power P over a channel with bandwidth W. At the receiver, the signal is corrupted by an AWGN noise with power N_0W, where N_0 is the AWGN spectral density. The channel AWGN capacity is then expressed as

$$C = Wf(\gamma) = W\log_2(1+\gamma) \geq R, \tag{1}$$

where $\gamma = \frac{P}{N_0W}$ is the signal-to-noise ratio (SNR). The SE of the system S can then be simply defined as $S = R/W$, whereas the EE of the system can either be expressed in terms of the energy-per-bit E_b or bit-per-Joule capacity C_J, where $E_b = P/R$ and $C_J = R/P$, respectively. Thus, $\gamma = \frac{P}{N_0W}$ can be expressed as a function of the SE and EE such that $\gamma = \frac{P}{N_0W} = SE_b/N_0$ and (1) simplifies as $f(SE_b/N_0) \geq S$. At this stage, the EE-SE trade-off can simply be expressed in a closed-form as

$$E_b \geq N_0(2^S - 1)/S \tag{2}$$

by applying $f^{-1}(.)$, which is the inverse function of $f(.)$, on both side of the inequality $f(SE_b/N_0) \geq S$. Note that a similar method can be used for C_J instead of E_b. Equation (2) clearly indicates the trade-off between EE and SE for the rate R to be achieved. This example itself shows that the problem of finding a closed-form expression for the EE-SE trade-off boils down to obtaining a closed-form expression for $f^{-1}(.)$.

In the MIMO Rayleigh channel case, the Ergodic capacity is usually expressed as [8]

$$C \triangleq W\mathrm{E}_{\mathbf{H}}\left\{\log_2\left|\mathbf{I}_r + \frac{\gamma}{t}\mathbf{H}\mathbf{H}^{\dagger}\right|\right\}, \tag{3}$$

where $\mathbf{I}_r$ denotes a $r \times r$ identity matrix, $\mathbf{H} \in \mathbb{C}^{r\times t}$ is a random matrix having independent and identically distributed (i.i.d.) complex circular Gaussian entries with zero-mean and unit variance that characterizes the MIMO channel, $|.|$ is the determinant and $\mathrm{E}\{.\}$ stands for the expectation. Furthermore, it has been demonstrated in [9] that (3) can be approximated as

$$C \approx \widetilde{C} = Wg(\gamma) = -\frac{Wt}{\ln(2)}\left[(1+\beta)\ln(w) + q_0 r_0 + \ln(r_0) + \beta\ln\left(\frac{q_0}{\beta}\right)\right] \tag{4}$$

when assuming a large number of antennas t and r, however, the accuracy of (4) has been found to be acceptable even for small number of antennas [9], i.e. as long as t and $r \geq 2$. In equation (4), $\beta = r/t$ is the ratio between the number of receive and transmit antennas, $w = \sqrt{\frac{1}{\gamma}}$, $q_0 = \frac{\beta-1-w^2+\sqrt{(\beta-1-w^2)^2+4w^2\beta}}{2w}$ and $r_0 = \frac{1}{w+q_0}$. Using (4) instead of (3) as a starting point for our derivation, we have obtained in [7] a closed-form expression for the inverse function $g^{-1}(.)$ and have provided an accurate closed-form approximation of the EE-SE trade-off over the Rayleigh fading channel that is given by

$$E_b \geq E_{b,MIMO} = \frac{N_0\left(-1 + \left[1 + \frac{1}{W_0(g_t(S_t))}\right]\left[1 + \frac{1}{W_0(g_r(S_r))}\right]\right)}{2S(1+\beta)}, \tag{5}$$

where $W_0(.)$ is real branch of the Lambert W function [10],

$$g_a(S_a) = -e^{-\left(\frac{S_a}{a}+\frac{1}{2}+\ln(2)\right)}, \tag{6}$$

with $a = t$ or r, and

$$\begin{aligned} S_t &= \{S\ln(2) - \zeta\alpha\ln(1+\eta_0[\cosh(S\ln(2)/(\alpha\eta_1))^{\eta_2} - 1])\}/2 \\ S_r &= \{S\ln(2) + \zeta\alpha\ln(1+\eta_0[\cosh(S\ln(2)/(\alpha\eta_1))^{\eta_2} - 1])\}/2 \end{aligned}. \tag{7}$$

In addition, $\alpha = \min(t, r)$, $\zeta = -\mathsf{sign}(\ln(\beta))$, $\mathsf{sign}(x) = -1$, 0 or 1 if $x < 0$, $x = 0$ or $x > 0$, respectively, and the coefficients η_0, η_1, η_2 that are solely dependent of β can be found in Table I of [7]. Note that $\eta_0 = 1$ and $\eta_2 = \eta_1$ for $\beta \in (0, 1/2] \cup [2, +\infty)$. Furthermore $\zeta = 0$ for $\beta = 1$ and, hence, the closed-form approximation in (5) simplifies as

$$E_b \geq E_{b,MIMO} = \frac{N_0\left(-1 + \left[1 + \left(W_0\left(-2^{-\left(\frac{S}{2r}+1\right)}e^{-\frac{1}{2}}\right)\right)^{-1}\right]^2\right)}{4S} \tag{8}$$

when $t = r$.

3. Theoretical Energy Efficiency Gain in the Low and High-SE regimes

The EE gain of MIMO over SISO system can be defined as follows

$$G_{\text{EE}} = E_{b,MIMO}/E_{b,SISO}, \tag{9}$$

where $E_{b,MIMO}$ is given in (5) and (8) and $E_{b,SISO}$ can be numerically obtained by using the closed-form expression of the SISO SE in (2.46) of [11] for $r = 1$. In order to define the EE gain, we first need to obtain closed-form expressions of the EE-SE trade-off at low and high-SE regimes for both SISO and MIMO systems. As far as SISO is concerned, it can easily be proved that the EE-SE trade-off limits for $S \ll 1$ and $S \gg 1$ are expressed as $E^0_{b,SISO} = N_0 \ln(2)$ and $E^\infty_{b,SISO} = N_0 e^{S\ln(2)+\phi}/S$, respectively, by using (2.46) of [11], where $\phi = 0.577$ is the Euler-Mascheroni constant [12].

In the MIMO case, the EE-SE trade-off at low and high-SE regimes can be characterized by assuming that $S \ll 1$ and $\frac{S}{a} \gg 1$, $a = t$ or r, in (5). Let us first assume that $S \ll 1$ in (5), it then implies that

$$S_t \overset{S\to 0}{\sim} \left(\frac{S\ln(2)}{2}\right)\left[1 - \frac{\ln(2)\eta_0\eta_2}{2\alpha\eta_1^2}S\right], S_r \overset{S\to 0}{\sim} \left(\frac{S\ln(2)}{2}\right)\left[1 + \frac{\ln(2)\eta_0\eta_2}{2\alpha\eta_1^2}S\right] \tag{10}$$

by applying successively the following approximations of usual functions to S_t and S_r in (7): $\cosh(x) \overset{0}{\sim} 1 + x^2/2$, $\ln(1 + x) \overset{0}{\sim} x$ and $e^x \overset{0}{\sim} 1 + x$, where the notation $\cosh(x) \overset{0}{\sim} 1 + x^2/2$ means that $\cosh(x)$ is similar to $1 + x^2/2$ when x approaches zero. Considering only the first order approximations of S_t and S_r in (10), the latter equations further simplify as

$$S_t = S_r \overset{0}{\sim} S\ln(2)/2 \tag{11}$$

such that $g_a(S_a)$ in (6) can be re-expressed as follows

$$g_a(S_a) \overset{0}{\sim} -e^{-\left(\frac{S\ln(2)}{2a}+\frac{1}{2}+\ln(2)\right)} = -\frac{1}{2}e^{-\frac{S\ln(2)}{a}}e^{-\frac{1}{2}\left(1-\frac{S\ln(2)}{a}\right)}, \tag{12}$$

with $a = t$ or r. Moreover, we know that $e^{-x} \overset{0}{\sim} 1 - x$ such that $g_a(S_a)$ can be further reformulated as

$$g_a(S_a) \overset{0}{\sim} -\frac{1}{2}\left(1 - \frac{S\ln(2)}{a}\right)e^{-\frac{1}{2}\left(1-\frac{S\ln(2)}{a}\right)} \tag{13}$$

and, hence, $W_0(g_a(S_a))$ in (5) can then be approximated as

$$W_0(g_a(S_a)) \overset{0}{\sim} -\frac{1}{2}\left(1 - \frac{S\ln(2)}{a}\right). \tag{14}$$

After further simplifications of (5), we obtain that

$$\frac{E_b}{N_0} \geq \frac{-2r(t - S\ln(2)) - 2t(r - S\ln(2)) + 4rt}{2S(1+\beta)(t - S\ln(2))(r - S\ln(2))} \overset{0}{\sim} \frac{2S\ln(2)(t + r)}{2S(1+\beta)rt}, \tag{15}$$

which finally simplify as

$$E_b \geq E^0_{b,MIMO} = N_0 \ln(2)/r \tag{16}$$

when $S \ll 1$. Notice that this result is the same as the one in (213) of [4].

In the case that $\frac{S_a}{a} \gg 1$ in (5), then the function $g_a(S_a) \ll -1$, and, hence, $W_0(g_a(S_a)) \overset{g_a(S_a)\to 0}{\sim} g_a(S_a)$ since $W_0(x) \overset{0}{\sim} x$. Omitting the term N_0, the numerator of (5) can then be approximated as

$$\begin{aligned} -1+\left[1+\frac{1}{W_0(g_t(S_t))}\right]\left[1+\frac{1}{W_0(g_r(S_r))}\right] &\overset{S\to\infty}{\sim} -1+\left[1+g_t(S_t)^{-1}\right]\left[1+g_t(S_r)^{-1}\right] \\ &\overset{\infty}{\approx} g_t(S_t)^{-1}+g_r(S_r)^{-1}+g_t(S_t)^{-1}g_r(S_r)^{-1}. \\ &\overset{\infty}{\approx} -2e^{\frac{1}{2}}\left[e^{\frac{S_t}{t}}+e^{\frac{S_r}{r}}\right]+4e^{1+\frac{S_t}{t}+\frac{S_r}{r}} \end{aligned} \quad (17)$$

In addition, if both S_t/t and $S_r/r \gg 1$ then (17) further simplifies as $4e^{1+\frac{S_t}{t}+\frac{S_r}{r}}$ and, consequently, (5) can be reformulated as

$$E_b \geq E^{\infty}_{b,MIMO} = \frac{N_0 2e^{1+\frac{S_t}{t}+\frac{S_r}{r}}}{S(1+\beta)} \quad (18)$$

when $\frac{S_a}{a} \gg 1$, and where S_t and S_r in (7) are approximated by

$$S_t \overset{\infty}{\approx} \frac{S\ln(2)}{2}\left[1-\zeta\frac{\eta_2}{\eta_1}\right]+\frac{\zeta\alpha\eta_2}{2}\ln\left(2\eta_0^{-\frac{1}{\eta_2}}\right), \; S_r \overset{\infty}{\approx} \frac{S\ln(2)}{2}\left[1+\zeta\frac{\eta_2}{\eta_1}\right]-\frac{\zeta\alpha\eta_2}{2}\ln\left(2\eta_0^{-\frac{1}{\eta_2}}\right) \quad (19)$$

since $\cosh(x) \overset{\infty}{\approx} e^x/2$ and $\ln(1+x) \overset{\infty}{\approx} \ln(x)$.

Finally, the theoretical EE gain of MIMO against SISO system in the low and high-SE regimes, i.e G^0_{EE} and G^{∞}_{EE}, respectively, can be expressed as

$$\begin{aligned} G^0_{\text{EE}} &= r \\ G^{\infty}_{\text{EE}} &= \frac{(1+\beta)}{2}e^{(-1+\phi)}\left(2\eta_0^{-\frac{1}{\eta_2}}\right)^{\left[\frac{1}{2t}-\frac{1}{2r}\right]\zeta\alpha\eta_2} 2^{S\left[1-\frac{1}{2t\eta_1}(\eta_1-\zeta\eta_2)-\frac{1}{2r\eta_1}(\eta_1+\zeta\eta_2)\right]} \end{aligned} \quad (20)$$

by using (16) and (18). Notice that G^{∞}_{EE} simplifies as $G^{\infty}_{\text{EE}} = e^{(-1+\phi)}2^{S\left(1-\frac{1}{r}\right)}$ when $t=r$.

4. Realistic Power Consumption Models and Numerical Results

4.1 Realistic Power Models

As we previously explained in Section 2., the EE can be expressed as $E_b = P_{\text{T}}/R$ or $C_J = R/P_{\text{T}}$, where P_{T} is the total consumed power for transmitting data at a rate R. In theoretical analysis, it is assumed that $P_{\text{T}} = P$, where P is the transmitted power. However, in a practical setting, P is only one element of P_{T}. For instance in [5], P_{T} is defined as

$$P_{\text{T}} = N_{\text{Sector}}N_{\text{PApSec}}(P/\mu_{\text{PA}}+P_{\text{SP}})(1+C_{\text{C}})(1+C_{\text{PSBB}}), \quad (21)$$

where N_{Sector} is the number of sector, N_{PApSec} is the number of power amplifier (PA) per sector, μ_{PA} is the PA efficiency, P_{SP} is the signal processing overhead, C_{C} is the cooling loss and C_{PSBB} is the battery backup and power supply loss. This model is linear and simplifies as $P_{\text{T}} = P_{\text{F}} + P_{\text{V}}$, where $P_{\text{F}} = P_{\text{SP}}N_{\text{Sector}}N_{\text{PApSec}}(1+C_{\text{C}})(1+C_{\text{PSBB}})$ and $P_{\text{V}} = (P/\mu_{\text{PA}})N_{\text{Sector}}N_{\text{PApSec}}(1+C_{\text{C}})(1+C_{\text{PSBB}})$ are fixed and variable consumed power components, respectively. Whereas in [6] an even more comprehensive PCM has recently been proposed, which includes extra BS components such as the DCDC and ACDC converters on top of the ones already included in the PCM of [5]. In addition, this PCM takes into account the non-linearity of the PA.

4.2 Results and Discussions

In this section, we numerically compare the EE gain of MIMO over SISO system according to the theoretical PCM, i.e. $P_\text{T} = P$, and the PCMs in [5] and [6]. Note that we consider $N_\text{PApSec} = t$ in (21) for the PCM in [5].

Since the EE is a ratio between the rate and the power, the EE gain between two systems can either be the result of a system providing a better rate for a fixed transmit power, or a lower power consumption for a fixed rate than the other system for the same noise power. In other word, the EE gain is either due to an increase of SE or a decrease of consumed power. MIMO is already well-know to be very effective for the former [11], thus, we focus in our analysis on the latter, i.e. how efficient is MIMO for reducing the consumed power of the system.

In Fig. 1, we compare the theoretical EE gain of $r \times t$ MIMO over SISO system with the gain when realistic PCMs are considered at the transmitter. The theoretical results in the left side of Fig. 1 show that the gain increases exponentially (linearly in log-scale) with the SE when receive diversity is available, i.e. $r \geq 1$. If $r = 1$, G_EE^∞ in (20) tells us that if $\eta_1 = \eta_2$ and $\zeta = 1$, as it is the case for $\beta = 1/2$, then the gain at high SE will be independent of S and, hence, will reach at best $(1+\beta)e^{(-1+\phi)}\left(2\eta_0^{-\frac{1}{\eta_2}}\right)^{\left[\frac{1}{2t}-\frac{1}{2}\right]\zeta\alpha\eta_2}$. Moreover, the results also indicate that our limits for the EE gain at low and high SE in (20) are accurate, since $G_\text{EE} \geq G_\text{EE}^0$ and $G_\text{EE} \simeq G_\text{EE}^\infty$ for $S \geq 15$ bits/s/Hz.

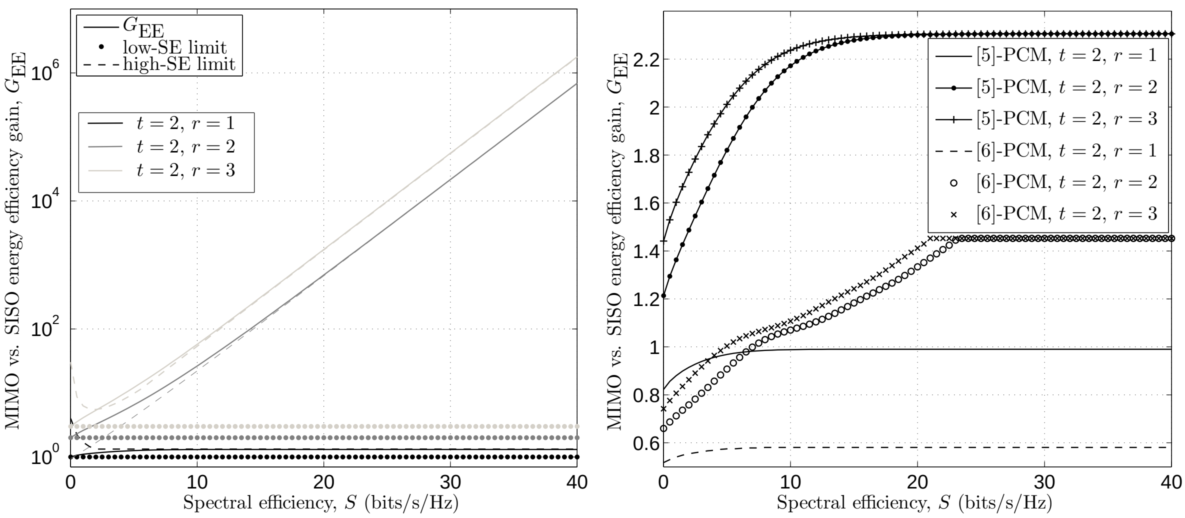

Figure 1: MIMO vs. SISO energy efficiency gain against spectral efficiency: Theoretical PCM (left), realistic PCMs (right).

In contrast, the results in the right side of Fig. 1 indicates that only a limited EE gain can be achieved, only in the high-SE regime, when using MIMO instead of SISO. In the case of $r = 1$, no EE gain is achieved, only loss. For the SISO case, the expression (2.46) of [11] provides the SE S for a given SNR γ. However, one can obtained the SNR γ for a given SE S by using this expression in conjunction with a simple line search algorithm. Using this approach, we have obtained γ_SISO for $S = 0$ to 40 bits/s/Hz with an increment step of 0.5 bits/s/Hz. Then, we have assumed a fixed transmit power $P_\text{SISO} = 49$ dBm for each S value and have computed the noise $N_\text{SISO}(\text{dB}) = P_\text{SISO}(\text{dB}) - \gamma_\text{SISO}(\text{dB})$. In the

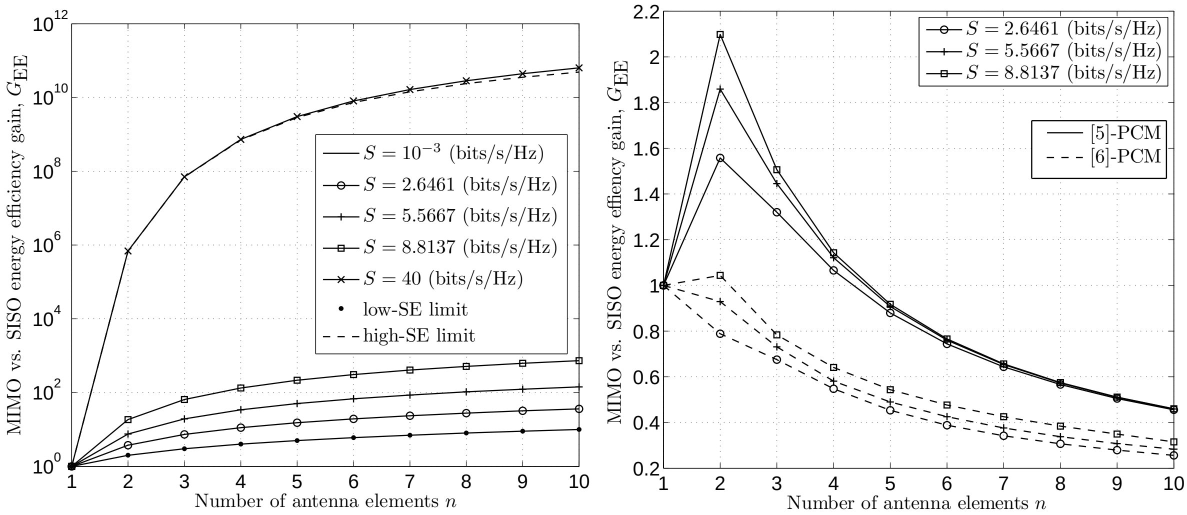

Figure 2: MIMO vs. SISO energy efficiency gain against the number of antenna elements: Theoretical PCM (left), realistic PCMs (right).

MIMO case, we have used our closed-form in (5) ($\gamma = S\frac{E_b}{N_0}$) to obtain γ as a function of S and then computed $P_{\text{MIMO}}(\text{dB}) = \gamma_{\text{MIMO}}(\text{dB}) + N_{\text{SISO}}(\text{dB})$. In other words, we have obtained the transmit power that is required by MIMO for achieving the same SE as SISO for a fixed noise power. This transmit power is always lower for MIMO than for SISO but the total consumed power is not always, as it can be seen in Fig.1. In the low-SE regime, the reduction of transmit power induces by MIMO is not sufficient ([6]-PCM) or just sufficient ([5]-PCM) to compensate for the increase of fixed power. In the high-SE regime, the transmit power that is required by MIMO for achieving the same SE as SISO goes to zero, the total consumed power becomes equivalent to the fixed power and, hence, the EE gain reaches its maximum and saturates. Notice that the variations of curvature for the results obtained with the [6]-PCM are due to the non-linearity (non-linear PA) of this PCM.

In Fig. 2, we compare the EE gain of a $n \times n$ MIMO over SISO system as a function of the number of antenna elements $n = t = r$ for different PCMs. Note that we have used the same approach as in Fig.1 for obtaining γ as a function of S in the SISO case. Moreover, we have used $P_{\text{SISO}} = 49$ dBm and the values of $S = 2.6461, 5.5667$ and 8.8137 bits/s/Hz correspond to $\gamma = 9, 19$ and 29 dB, respectively. As in Fig. 1, the right and left sides of Fig. 2 show the great disparity between theoretical and practical results. The theoretical results in the left side of Fig. 2 indicate that EE gain also increases with the number of antennas, however, more in a linear way (logarithmic in log-scale) than in an exponential way, as it is the case according to the SE S in Fig. 1. Whereas the results in the right side of Fig. 2 point out that the 2x2 setting provides the best EE gain and that this gain decreases with the number of antennas, contrarily to the theoretical case. One reason for explaining this phenomena is the fact that power amplifiers are usually optimized for a single input/output power, generally the maximum input/output value, hence, by reducing the transmit power as n increases, the amplifier efficiency decreases as well as the EE gain. Paradoxically, transmitting with less power means also being less EE. Otherwise, the accuracy of both our limits in (20) is again demonstrated since G^{0}_{EE} perfectly matched G_{EE} for $S = 10^{-3}$ and G^{∞}_{EE}

tightly fits G_{EE} for $S = 40$ when $n \leq 6$. Note that the condition $S/n \gg 1$ becomes weak as $n > 6$, which explains the increasing gap between G_{EE}^{∞} and G_{EE} for $S = 40$ as n further increases.

5. Conclusions

In this paper, we have analyzed the EE gain of MIMO over SISO system when various PCMs are considered at the transmitter. We have derived the theoretical EE gain limits in the low and high-SE regimes and their accuracy have been confirmed via simulation. These limits indicated that the EE gain grows exponentially with the SE in the high-SE regime and in a linear way with the number of receive antennas. We then have utilised two realistic PCMs for obtaining practical EE gain results. These results have been compared with theoretical ones and a large disparity between the theoretical and practical results have been shown. In theory MIMO has a great potential for EE improvement, to some extends even better than in terms of SE, but when realistic PCMs are assumed, using a MIMO system with more than 2 transmit antennas at the BS is unlikely to provide any EE gain. In the future, we would like to extend our EE analysis to distributed MIMO system.

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References

[1] K. Lahiri, A. Raghunathan, S. Dey, and D. Panigrahi, "Battery-driven system design: A new frontier in low power design,," in *Proc. Intl. Conf. on VLSI Design*, Bangalore, India, Jan. 2002, pp. 261–267.

[2] H. M. Kwon and T. G. Birdsall, "Channel Capacity in Bits per Joule," *IEEE Jour. Oceanic Engineering*, vol. OE-11, no. 1, pp. 97–99, Jan. 1986.

[3] C. Bae and W. E. Stark, "Energy and Bandwidth Efficiency in Wireless Networks," in *Proc. IEEE ICCCAS*, Guilin, China, Jun. 2006.

[4] S. Verdu, "Spectral Efficiency in the Wideband Regime," *IEEE Trans. Inf. Theory*, vol. 48, no. 6, pp. 1319–1343, Jun. 2002.

[5] O. Arnold, F. Richter, G. Fettweis, and O. Blume, "Power Consumption Modeling of Different Base Station Types in Heterogeneous Cellular Networks," in *Proc. ICT Future Network & Mobile Summit*, Florence, Italy, Jun. 2010.

[6] G. Auer and et al., "D2.3: Energy Efficiency Analysis of the Reference Systems, Areas of Improvements and Target Breakdown," INFSO-ICT-247733 EARTH (Energy Aware Radio and NeTwork TecHnologies), Tech. Rep., Nov. 2010. [Online]. Available: https://www.ict-earth.eu/publications/deliverables/deliverables.html

[7] F. Héliot, O. Onireti, and M. A. Imran, "An Accurate Closed-Form Approximation of the Energy Efficiency-Spectral Efficiency Trade-Off over the MIMO Rayleigh Fading Channel," in *Proc. IEEE ICC'11, 4th International Workshop on Green Communications*, Kyoto, Japan, Jun. 2011.

[8] I. E. Telatar, "Capacity of Multi-Antenna Gaussian Channels," *Europ. Trans. Telecommun. and Related Technol.*, vol. 10, no. 6, pp. 585–596, Nov. 1999.

[9] E. Biglieri and G. Taricco, *Transmission and Reception with Multiple Antennas: Theoretical Foundations*. Now Publishers Inc., 2004.

[10] R. M. Corless, G. H. Gonnet, D. E. G. Hare, D. J. Jeffrey, and D. E. Knuth, "On the LambertW Function," *Adv. Comput. Math.*, vol. 5, p. 329359, 1996.

[11] M. Dohler, "Virtual Antenna Arrays," Ph.D. dissertation, King's College London, University of London, Nov 2003. [Online]. Available: http://perso.rd.francetelecom.fr/dohler/theses/PhD.pdf

[12] "Wikipedia Website," [Online]. Available: http://en.wikipedia.org/wiki/Euler-Mascheroni_constant.