Joint Beamforming and PAPR Reduction in Massive MIMO: Analysis of Gain in Energy Efficiency

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***Abstract*—The main goal of this article is to accurately quantify the gain in energy efficiency that can be obtained by combining PAPR reduction techniques with beamforming in the context of massive MIMO communications. To this purpose, we first derive and analyze the expressions of sum capacity, power consumption, and energy efficiency for hybrid, digital and analog beamforming for massive MIMO systems in the millimeter wave frequency range. Then, we use these results to derive and quantify the gain in energy efficiency at system level that can be obtained by combining PAPR reduction for improved power amplifier efficiency with beamforming in massive MIMO systems. In addition, we derive the expressions allowing to determine the optimal amount of antennas M that should be connected to each RF chain in a partially connected hybrid beamforming scheme in order to maximize the systems energy efficiency. Evaluation of the derived expressions clearly show that a noticeable gain in the systems energy efficiency is obtained when PAPR reduction is added, and allows to analyze the advantages and disadvantages of each approach from an energy efficiency point of view.**

***Keywords*—Beamforming, PAPR reduction, Massive MIMO, Energy efficiency.**

I. INTRODUCTION

The feasibility of 5G NR systems and beyond partly relies on beamforming (BF) techniques in the context of massive multiple-input multiple-output (MIMO) communications at the millimeter waves (mm-waves) frequency band extending from 24 to 52 GHz [1]. These systems, which need to comply with very greedy specifications of data throughput, channel capacity and low latency, benefit from the large number of antennas in the massive MIMO regime [2] [3]. These large antenna arrays allow to efficiently use new large portions of the available spectrum and provide a practical tool to combat the severe channel path-loss effect present at mm-waves [4] [5]. When using a large number of transmit antennas ($N_T > 64$) at the Base Station (BS), narrow beams with high directivity can be emitted towards a very specific user equipment (UE) location, which results in a great enhancement in the signal-to-interference plus noise ratio (SINR) [6].

While this technology is considered key to enable higher performance in the latest generation of wireless communication networks, there are also several challenges and limitations that still remain to be solved, as reported for example in [7], [8]. Among these issues, a major concern is that power consumption may be dramatically increased due to the large amount of radio frequency (RF) chains needed to feed the signals to the antennas, particularly in a fully digital beamforming (DBF) architecture [4]. However, recent studies indicate that DBF is in fact the most globally energy efficient approach in terms of achievable system throughput per energy consumption unit [9]. Therefore, the search for improved energy efficiency (EE) should be addressed as a main system design parameter.

Following this principle, the EE of the partially connected hybrid beamforming (HBF) architecture is studied in [10]. There, the EE is optimized by varying both the number of RF chains and that of antennas connected to them. Then, the trade-off between EE and spectral efficiency (SE) is analyzed and a *green point* of operation is found. In [9], the EE at system level including a certain amount of UEs is computed and compared for the digital, analog and hybrid BF strategies, showing that DBF is the most globally energy efficient approach when considering the system as a whole.

In [11] and [12], we propose to combine DBF in the time domain with peak-to-average power ratio (PAPR) reduction based on tone reservation (TR) before the power amplifiers (PAs) as a means to enhance EE. In those articles, we show that not only PAPR reduction of the signals fed to the antennas is preserved, but also good performance in BF is attained with low distortion at a much lower computational cost when compared to frequency domain based BF. The used PAPR reduction method is an optimized TR approach presented in [13] and offering a very good trade-off between performance and complexity as shown in [14]. This method is compliant with the American and European standards for digital video broadcasting (DVB) ASTC3 and DVB-T2, and presents a very competitive latency-performance-complexity trade-off. The chosen BF strategy is based on phase control only, as it allows to bias all the PAs in the more energy efficient operation point near its saturation region, which is not possible in amplitude control based BF [5].

However, even if a significant gain in EE is intuitively expected in this context, to the best of the authors knowledge its expression has not been derived yet, neither its value quantified. The main goal of this work is then to derive the expressions for the gain in energy efficiency due to the combination of PAPR reduction with beamforming in massive MIMO for different architectures, and evaluate these expressions in order to accurately quantify it, as well as its impact on the system. To this purpose, we first derive the expressions of sum capacity, power consumption and EE for analog, hybrid, and digital BF. Then, we use these results to derive the expression of the achievable gain in EE that can be obtained through PAPR reduction when combined with each of the three BF architectures. Finally, we quantify the gain in EE in absolute and relative terms for all the considered cases. In addition, we derive the expressions allowing to determine the optimal number of antennas M per RF chain in a HBF scheme that maximize the EE. Evaluation of the derived expressions by MATLAB simulations allow compare the results for all the considered architectures and scenarios. In particular, the novel contributions introduced in this work can be summarized as follows:

- We derive the expressions allowing to quantify the gain in EE obtained by joint BF and PAPR reduction in massive MIMO systems. In addition, we provide a detailed analysis of the achievable gain in EE for the different available BF schemes and compare the results.
- We derive the expressions allowing to determine the optimal amount of antennas M that should be connected to each RF chain in HBF in order to maximize the EE.
- We provide evaluation of the derived expressions by numerical simulations and discuss the advantages and disadvantages of each BF approach from an EE point of view.

This work is organized as follows. The system model is introduced in Section II. The EE and the gain associated to the addition of PAPR reduction in a massive MIMO system are derived in Section III. In Section IV, the optimal configuration for EE in a partially connected HBF is studied. Evaluation of the derived expressions by numeric simulations are presented in Section V, and some conclusions are drawn in Section VI.

II. System model

In this section, we introduce the system model, its configuration, and its parameters. In particular, we describe the system structure in terms of the properties of the transmitted signal and its component blocks.

A. OFDM signal parameters

The parameters of the OFDM signal and their respective values are shown in Table I, which are chosen according to the specifications provided by the 3GPP group for future 5G NR standard in the release 15 [15]. The number of active carriers and bandwidth are expressed here in terms of their maximum value as they are flexible in 5G NR and determined by the new parameter bandwidth part (BWP) assigned to each UE [16].

TABLE I
OFDM parameters for 5G NR Release 15

Band [GHz]	Δf [kHz]	FFT size	Max. BW [MHz]
0.45-6	15	512-4096	5-50
	30	256-4096	5-100
	60	256-2048	10-100
24-52	60	1024-4096	50-200
	120	512-4096	50-400

B. System structure

Figure 1 shows the considered system structure for BF with PAPR reduction in the context of massive MIMO, assuming the classical frequency-domain implementation for the BF part. First, the signal is modulated and converted from serial to parallel. Then, a pre-coding matrix W performs the phase-shifting operation to the signal (and possibly weighting as well) in order to generate as many beam-formed signals as the number N_T of transmit antennas. Next, each phase-shifted signal is OFDM modulated and a PAPR reduction algorithm is applied to it. Finally, cyclic prefix is inserted to each signal, parallel-to-serial and digital-to-analog conversion is performed, and the signals are fed to the PAs and then to the antennas.

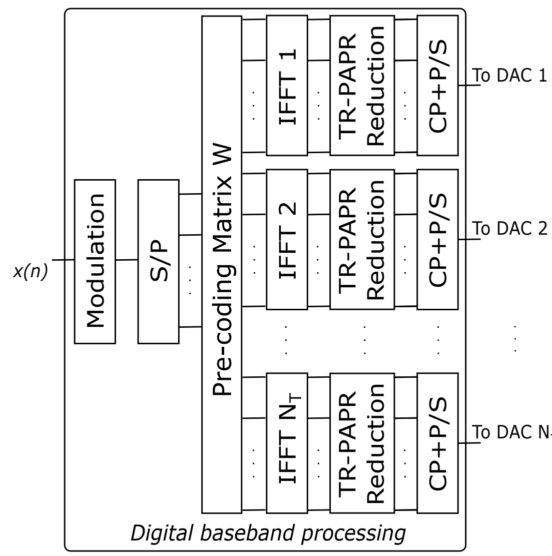

Fig. 1. Considered digital baseband processing for frequency-domain beamforming with PAPR reduction.

III. Gain in Energy Efficiency

In this section we analyze the energy efficiency of a beam-steering massive MIMO system based on OFDM signaling, with and without PAPR reduction of the signals before amplification at the input of the antennas. The idea is to quantify the EE gain that is possible to achieve by combining both beamforming and PAPR reduction.

A. Sum capacity, and spectral and energy efficiency

In [10], an analysis of EE is performed for the case of a partially connected hybrid BF architecture, where the number of antennas is $N_T = NM$. In such case, N is the number of RF chains which are assumed to serve N users, while M is the number of antennas connected to each RF chain. According to [10], the N user sum capacity for the partially connected hybrid structure can be written as

$$C_{\Sigma H} = WN \log_2 \left(1 + \frac{MP_{PA}\eta_{PA}}{WN_0}\right) \tag{1}$$

where W is the system bandwidth, P_{PA} is the total power consumption of the M PAs per transceiver, η_{PA} is the efficiency of the PAs and N_0 is the thermal noise density.

While this is a commonly used model when an additive white gaussian noise (AWGN) channel with negligible path loss is considered, we add an additional term to model the increased path loss at the mm-wave frequency range as introduced in [17] and [18]. Then, (1) becomes,

$$C_{\Sigma H} = WN\log_2\left(1+\frac{MP_{PA}\eta_{PA}P_L}{WN_0}\right) \tag{2}$$

where the received power $P_H^R = MP_{PA}\eta_{PA}P_L$ is the transmitted power $P_H^T = MP_{PA}\eta_{PA}$ as in (1) affected by an additional path loss term P_L approximated in dB by [18]

$$P_L^{dB}(d) = P_L(d_0) + \alpha 10\log_{10}(d/d_0) + X, X \sim N(0,\sigma_x) \tag{3}$$

where $P_L(d_0)$ is the path loss at free-space for a reference distance of $d_0 = 1$ m, whereas α and σ_x are the path-loss exponent and shadowing factor dependent on the frequency of operation and type of link (LOS, NLOS, indoor, outdoor).

For the case of a fully digital architecture, we may adapt the analysis *per user* considering $N = N_T, M = 1$, i.e., as many RF chains as transmit antennas connected in a one-to-one basis[1]. However, we consider a number of users $U << N_T$, as is also the case for the hybrid structure (where $U = N << NM = N_T$). Thus, considering U users each served using all N_T antennas, the sum capacity for the DBF approach can be expressed as

$$C_{\Sigma D} = WU\log_2\left(1+\frac{N_T P_{PA}\eta_{PA}P_L}{WN_0}\right) \tag{4}$$

whereas in the case of fully analog BF, only one RF chain uses all N_T antennas to serve one user, thus the capacity is

$$C_{\Sigma A} = W\log_2\left(1+\frac{N_T P_{PA}\eta_{PA}P_L}{WN_0}\right) \tag{5}$$

Now we can define the SE as $\eta_{SE} = C_\Sigma/W$, and the EE as $\eta_{EE} = C_\Sigma/P_T = W\eta_{SE}/P_T$, where P_T is the total power consumption. Note that for the case of analog beamforming (ABF), the sum capacity is just $C_{\Sigma A} = C_{\Sigma D}/U$.

B. Total power consumption

Continuing with the approach followed in [10], it is possible to compute an estimate of the total power consumption[2] for a partially connected HBF scheme as

$$P_T^H = N(MP_{PA} + P_{RF} + P_0) + P_{common} \tag{6}$$

where P_{RF} is the power consumption of each RF chain, P_0 is the static power consumption that depends on the number of transceivers, and P_{common} is the static power consumption in the BS independent of the number of transceivers. For the case of a fully digital architecture the number of transceivers (RF chains) is the same as the number of transmit antennas. Then, introducing some modifications in (6) to adapt it for the fully digital architecture, the total power consumption in that case reduces to

$$P_T^D = N_T(P_{PA} + P_{RF} + P_0) + P_{common} \tag{7}$$

In the ABF case, as only one RF chain is available, we get

$$P_T^A = N_T P_{PA} + P_{RF} + P_0 + P_{common} \tag{8}$$

Thus, the EE can now be computed as the ratio between the sum capacity and the total power consumption P_T for each architecture as $\eta_{EE} = C_\Sigma/P_T$.

C. Energy efficiency gain due to PAPR reduction

In this section we analyze the gain in EE. The PA efficiency is given by

$$\eta_{PA} = \bar{P}_{out}/P_{PA} \tag{9}$$

where $\bar{P}_{out}$ is the PA average output power. Then, PAPR reduction leads to an increased $\bar{P}_{out}$ by lowering the required IBO operation point to obtain certain acceptable signal distortion according to linearity metrics such as MER or EVM. For instance, the EE of a class A PA can be approximated as a function of PAPR by [19] [20]

$$\eta_{PA} = 0.5/PAPR \tag{10}$$

Then, according to (1)-(5), lower PAPR allows for an increased sum capacity C_Σ due to a larger SNR leading to higher EE. Let us now quantify the achievable gain in EE. To that purpose, we consider the increased PA efficiency after PAPR reduction as

$$\hat{\eta}_{PA} = G\bar{P}_{out}/P_{PA} = G\eta_{PA} \tag{11}$$

Then, considering the total power consumption roughly unchanged[3], replacing (11) in (1)-(5), and dividing by the total power consumption of each structure, we can express the new energy efficiency for each architecture as

$$\begin{aligned}\hat{\eta}_{EE}^H &= \frac{WN}{P_T^H}\log_2\left(1+\frac{MP_{PA}G\eta_{PA}P_L}{WN_0}\right)\\ &\cong \frac{WN}{P_T^H}\log_2\left(\frac{G[MP_{PA}\eta_{PA}P_L]}{WN_0}\right)\\ &\cong \hat{G}_{EE}^H + \eta_{EE}^H\end{aligned} \tag{12}$$

$$\begin{aligned}\hat{\eta}_{EE}^D &= \frac{WU}{P_T^D}\log_2\left(1+\frac{N_T P_{PA}G\eta_{PA}P_L}{WN_0}\right)\\ &\cong \frac{WU}{P_T^D}\log_2\left(\frac{G[N_T P_{PA}\eta_{PA}P_L]}{WN_0}\right)\\ &\cong \hat{G}_{EE}^D + \eta_{EE}^D\end{aligned} \tag{13}$$

$$\begin{aligned}\hat{\eta}_{EE}^A &= \frac{W}{P_T^A}\log_2\left(1+\frac{N_T P_{PA}G\eta_{PA}P_L}{WN_0}\right)\\ &\cong \frac{W}{P_T^A}\log_2\left(\frac{G[N_T P_{PA}\eta_{PA}P_L]}{WN_0}\right)\\ &\cong \hat{G}_{EE}^A + \eta_{EE}^A\end{aligned} \tag{14}$$

[1] Similarly, the analysis can also be carried out for the fully analog beamforming case by taking $N = 1$ and $M = N_T$.

[2] At the transmitter side or base station, considering the consumed power at the receiver terminal negligible in comparison.

[3] Any increment in the PA power consumption due to a lower IBO (as a result of a lower PAPR in the input signal) can be considered as a slightly lower gain G in $\hat{\eta}_{PA}$.

where the additive gain in EE is:

- $\hat{G}_{EE}^{H} = (WN/P_T^H)\log_2(G)$ for HBF.
- $\hat{G}_{EE}^{D} = (WU/P_T^D)\log_2(G)$ for DBF.
- $\hat{G}_{EE}^{A} = (W/P_T^A)\log_2(G)$ for ABF.

Note that all the gain terms are positive numbers since $G > 1$.

IV. Optimal partially connected hybrid beamforming

In this section we derive the optimal number of antennas M that should be connected to each RF chain in a partially connected HBF scheme in order to maximize the EE. We recall from (1) and (6) that

$$\eta_{EE}^{H} = \frac{C_{\Sigma}^{H}}{P_T^H} = \frac{WN\log_2\left(1+\frac{MP_{PA}\eta_{PA}P_L}{WN_0}\right)}{N(MP_{PA}+P_{RF}+P_0)+P_{common}} \quad (15)$$

Then, defining $\tilde{P}_{common} = P_{common}/N$ and $P_{ST} = P_{RF} + P_0 + \tilde{P}_{common}$, we can rewrite (15) as

$$\eta_{EE}^{H} = \frac{W\log_2\left(1+\frac{MP_{PA}\eta_{PA}P_L}{WN_0}\right)}{MP_{PA}+P_{ST}} \quad (16)$$

Now we can find the derivative of (16) w.r.t. M and compute under which conditions it equals zero. To that purpose, we first define $f = W\log_2\left(1+\frac{MP_{PA}\eta_{PA}P_L}{WN_0}\right)$. Then,

$$\frac{d\left(\eta_{EE}^{H}\right)}{dM} = \frac{\frac{W\left(\frac{P_{PA}\eta_{PA}P_L}{WN_0}\right)(MP_{PA}+P_{ST})}{\left(1+\frac{MP_{PA}\eta_{PA}P_L}{WN_0}\right)\ln(2)} - fP_{PA}}{(MP_{PA}+P_{ST})^2} \quad (17)$$

$$\frac{d\left(\eta_{EE}^{H}\right)}{dM} = \frac{\frac{W\left(\frac{P_{PA}\eta_{PA}P_L}{WN_0}\right)(MP_{PA}+P_{ST})}{\left(\frac{WN_0+MP_{PA}\eta_{PA}P_L}{WN_0}\right)\ln(2)} - fP_{PA}}{(MP_{PA}+P_{ST})^2} \quad (18)$$

$$\frac{d\left(\eta_{EE}^{H}\right)}{dM} = \frac{\frac{W(P_{PA}\eta_{PA}P_L)(MP_{PA}+P_{ST})}{(WN_0+MP_{PA}\eta_{PA}P_L)\ln(2)} - fP_{PA}}{(MP_{PA}+P_{ST})^2} \quad (19)$$

Clearly, (19) is zero when its numerator is, i.e.,

$$\log_2\left(\frac{WN_0+MP_{PA}\eta_{PA}P_L}{WN_0}\right) = \frac{\eta_{PA}P_L(MP_{PA}+P_{ST})}{(WN_0+MP_{PA}\eta_{PA}P_L)\ln(2)} \quad (20)$$

Note that a closed form expression for M can not be obtained as (20) is a transcendental equation. However, this expression will be used in the following section for numerical simulation.

V. Performance evaluation

In this section we present the simulation results of the expressions derived in section III following the system model described in section II, motivated by the discussion in section I. In particular, we present:

- The sum capacity with and without PAPR reduction as a function of the number of antennas for digital, hybrid and analog BF.
- The total power consumption for the three architectures.
- The energy efficiency with and without PAPR reduction as a function of the number of antennas.

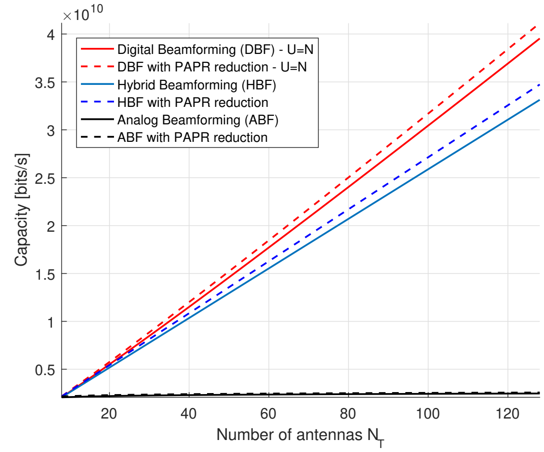

Fig. 2. Sum capacity with and without PAPR reduction as a function of the number of antennas for digital, hybrid and analog BF.

- The actual gain in energy efficiency.

We also consider the natural case where the number of users served by the DBF approach is larger than that of HBF. For the HBF case, we consider $M = 16N$ such that each RF chain is connected to $M = 16$ antennas, and that the number of users is equal to the number of RF chains N. Then, in this simulation set-up, an increment of the number of RF chains (and therefore of transmit antennas) is equal to the increment of the number of users.

For consistency and comparison purposes, we chose the parameters used in [10] to compute the power consumption and sum capacities:

- $\eta_{PA} = 0.375$.
- $W = 100 \times 10^6$ [Hz].
- $N_0 = 1 \times 10^{-17}$ [dBm/Hz].
- $P_{PA} = 5$, $P_0 = 1$, $P_{common} = 50$, $P_{RF} = 1$ [W].

In addition, we include the path-loss model for mm-waves considering a distance of $d = 100$ m, and an operation frequency of 29 GHz with parameters $\alpha = 2.4$ and $\sigma_x = 6.5$ taken as the average values of the table in [18]. We also consider the power amplifier efficiency could be doubled after PAPR reduction as suggested in [20], such that $G = 2$. Although this may be quite optimistic, we take it as an upper bound for achievable performance.[4]

Figure 2 shows the sum capacity for the three architectures. Here, we can see that DBF has a slightly higher performance over HBF when the number of users is the same. However, note from equation (4) that increasing the number of users U in the fully digital scheme results in a linear increment of the sum capacity independently of the number of antennas, which results in an additional shift w.r.t. the vertical axis.

Figure 3 shows the total power consumption for the three studied cases. As expected, the power consumption of the digital structure is higher than that of the hybrid scheme. However, it is worth to note that the power consumption of

[4] In [13], measurement results indicate a 10% gain in the PA EE under the condition of keeping the same level of distortion in the amplified signal, such that $G = 1.1$.

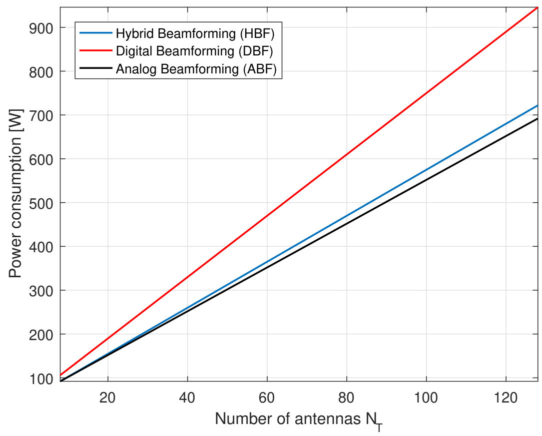

Fig. 3. Total power consumption for the three architectures.

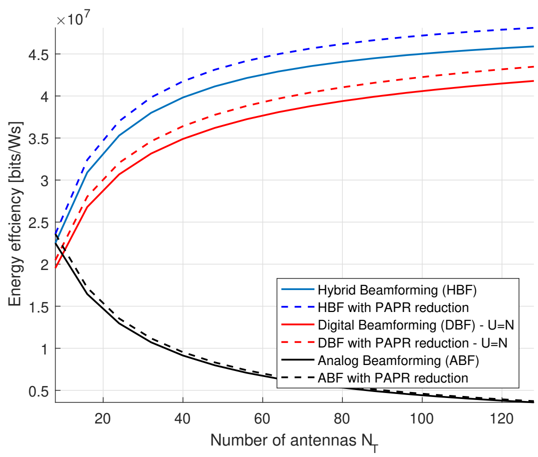

Fig. 4. Energy efficiency with and without PAPR reduction as a function of the number of antennas.

the analog approach is roughly the same when compared to the power consumption of the hybrid scheme, which proves that ABF is not convenient neither from the point of view of performance nor power consumption savings. It is also worth noticing from equation (7) that the total power consumption in the fully digital architecture is independent of the number of users. As a consequence, increasing the number of users in the digital scheme produces a significant impact in the EE.

Figures 4 and 5 show the energy efficiency with and without PAPR reduction and the actual gain in EE, respectively. There, it can be seen that there is a noticeable gain in EE, although it is more evident in Figure 5. Interestingly, it can also be seen that the EE increment for $N_T > 120$ has a very low slope. This is due to the fact that the increment in capacity is compensated by the respective increment in power consumption. As expected, ABF is the least energy efficient solution. On the other hand, the EE can be further improved for the DBF structure by allowing more users, as capacity grows linearly but the power consumption remains unchanged.

Figure 6 shows the EE for the HBF scheme as a function of the number of antennas M connected to each RF chain. In this case, it can be seen that the EE decreases monotonically

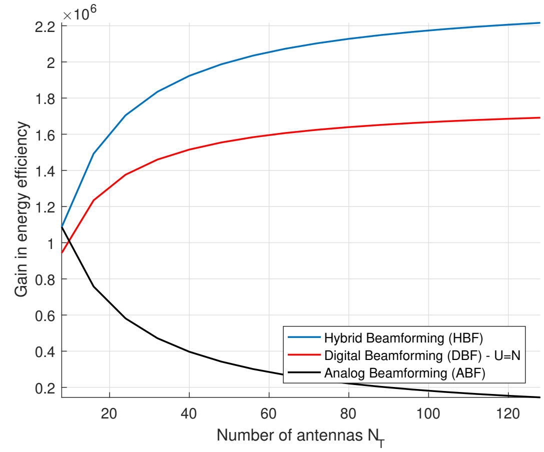

Fig. 5. Actual gain in energy efficiency.

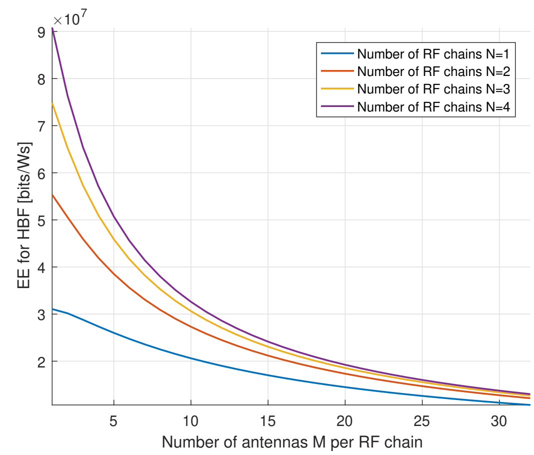

Fig. 6. Energy efficiency for HBF as a function of the number of antennas M per RF chain.

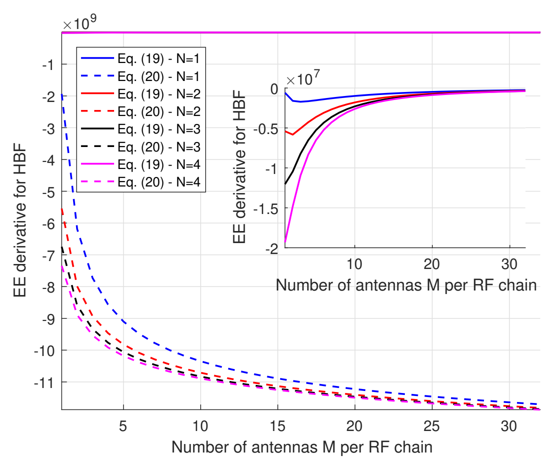

Fig. 7. Derivative of Energy efficiency in HBF as a function of the number of antennas M connected to each RF chain for $P_{common} = 50$ [W].

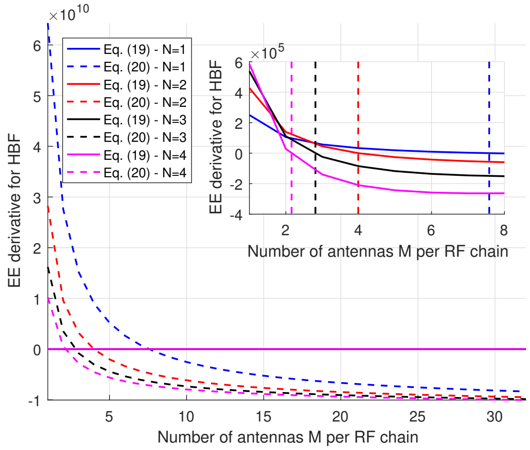

Fig. 8. Derivative of Energy efficiency in HBF as a function of the number of antennas M connected to each RF chain for $P_{common} = 500$ [W].

as the number of antennas per RF chain increases. This means that the EE of a HBF is always below that of a DBF structure at system level when no restriction on the number of users is provided. In fact, as the number of RF chains N increases, so does the number of users and the systems EE. This effect can be confirmed by also analysing the derivative of the EE.

Figures 7 and 8 are the plots of equation (19) and its numerator (20), showing the derivative of the EE for the HBF scheme as a function of the number M of antennas connected to each RF chain for two scenarios, i.e., with $P_{common} = 50$ and $P_{common} = 500$ W. We can see in figure 7 that although there are no zero crossings, the numerator (20) approaches zero as M approaches 1. That is, the EE increases when HBF becomes DBF. In Figure 8, the zero crossings are not only present and coincide, but they also indicate that when the number of RF chains N increases, the optimal number of antennas M connected to them that maximize the energy efficiency also tends to 1. Interestingly, this confirms that DBF is in fact the most energy efficient approach at system level when no restrictions on the number of users is introduced, independently of the total power consumption.

VI. Conclusions

In this work, we first derive the expressions of the sum capacity, power consumption, and EE for three BF structures. These are the analog, digital, and the partially connected hybrid BF schemes. Then we derive the expressions of the gain in EE that can be obtained in each case when combining BF with PAPR reduction for energy efficient power amplification. Next, we analyze the EE for the HBF architecture as a function of the number of antennas M connected to each RF chain. Simulation results show that the EE can be significantly enhanced by PAPR reduction, and allow to compare the advantages and disadvantages of each of the considered BF structures from an EE point of view. In the case of partially connected HBF, results indicate that reducing the number of antennas connected to each RF chain produces an increment in the systems EE when no restrictions on the number of users is introduced. This presents an interesting trade-off between power consumption, hardware complexity and EE.

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