Power Amplifier Switching (PAS) for Energy Efficient Systems

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***Abstract*—We propose a power amplifier (PA) switching/selection (PAS) method to improve the energy efficiency (EE) of a transmit antenna selection and maximum ratio combining (TAS-MRC) system. A PAS transmitter has a PA bank consisting of multiple dissimilar PAs, which operate with different output power levels, and selects the most efficient PA and its power level that satisfies a target rate. If there is no PA supporting the target rate, the transmitter is set to an off-mode (i.e., all PAs are turned off). The receiver feeds back the choice of PA and its power level to the transmitter, similar to the feedback in a conventional power control system with a single PA. Numerical results show that the system EE can be improved by using the PAS. This letter is the first study to investigate and verify the potential capability of PAS for the system EE improvement in wireless communications.**

***Index Terms*—Energy efficiency, power amplifier bank, power amplifier switching, power amplifier selection.**

I. INTRODUCTION

ENERGY efficiency (EE) has been studied widely to resolve the conflict between high demands of quality-of-service (QoS) and energy saving in wireless communication technologies (e.g., [1]–[3]). Power amplifier (PA) is a major power consumer for wireless communications, with around 50% of the transmitter's total power consumption [3]. Thus, imperfect efficiency (i.e., lower than 100%) and nonlinearity of the PA have been carefully examined to design high EE systems in [4], [5]. A tradeoff between spectral efficiency (SE) and EE has been analyzed for *single* antenna systems under the assumptions of *full* channel state information at the transmitter (CSIT) and of *identical* efficiencies of PAs, and a PA switching/selection (PAS) method has been proposed to expand the Pareto-optimal SE-EE tradeoff region in [4], [5]. In many practical wireless communication systems, however, full CSIT is unavailable. Moreover, the PA efficiency varies according to the PA type and the PA output power. Due to the overheating of the PAs, PA power consumption $P_{\rm PA}$ is a function of PA input power $P_{\rm in}$ (equivalently PA output power $P_{\rm out}$) and depends on the silicon technology with around 30% efficiency on average [5]. Thus power control with a single PA is inefficient in terms of *system* EE because PA efficiency decreases drastically as $P_{\rm out}$ decreases [6].

In this letter, we propose a PAS with multiple dissimilar PAs for a transmit antenna selection and maximum ratio combining (TAS-MRC) system to improve its average system EE. The average system EE is defined as [4], [5]

$$\mathsf{EE} \triangleq \frac{\Omega \mathsf{TP}}{P_c(\Omega)} \ \ \mathrm{b/J}, \tag{1}$$

where TP represents an average system throughput per unit time and frequency $(\mathrm{b/s/Hz})$, and $P_c(\Omega)$ is an average transmit power consumption (W) over the system bandwidth $\Omega\,\mathrm{Hz}$. In other words, EE in (1) is the total amount of reliably decoded bits normalized by the energy $(\mathrm{b/J})$. For practical scenarios, we consider a *partial* CSIT (feedback) and a *power dependent* efficiency of PAs. Instead of a single PA with multiple power levels as in conventional power control systems, the proposed transmitter employs multiple dissimilar PAs, in which each power level matches the output power of the most efficient PA that can support a target rate with the least power consumption. Since each output power level corresponds to the highest PA efficiency by selecting the most efficient PA and its power level, the average efficiency of PAs can be increased. As a consequence, the average system EE in (1) can also be improved compared to the conventional power control systems with a single PA. The PA switching probability is derived analytically, and it is used to obtain TP, $P_c(\Omega)$, and EE in closed-form expressions. Numerical results illustrate the potential capability of the multiple PAs for EE improvement, using the partial CSIT for the PAS.

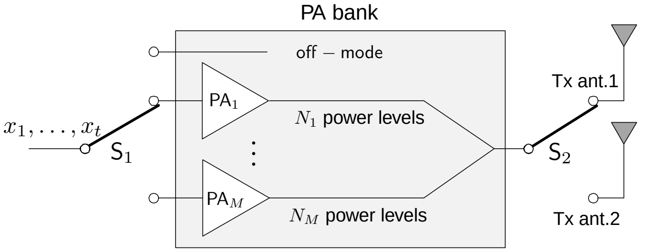

Fig. 1. Proposed PA switching (PAS) transmitter model with a PA bank having M PAs, in which PA_m has N_m power levels. Switch S_1 selects a PA and switch S_2 selects a transmit antenna (Tx ant.1 or Tx ant.2).

II. PROPOSED SYSTEM MODEL

Two transmit and two receive antennas are considered for the TAS-MRC systems. The proposed scheme in the letter applies readily to any number of transmit and receive antennas, including the special case of a single transmit and single receive antenna system. The actual number of antennas to use can be decided based on a tradeoff of performance versus complexity, depending on the implementation scenario. As illustrated in Fig. 1, we propose a PAS with a PA bank consisting of M dissimilar PAs, denoted by PA_m where $m \in \{1, \ldots, M\}$ in ascending order of PA's maximum output power, i.e., PA_1 is the weakest PA and PA_M is the strongest PA. The PA_m operates with *distinct* and *consecutive* N_m output power levels in the linearly amplifying region. Thus, in total $N = \sum_{m=1}^{M} N_m$ non-zero power levels are available for

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the transmission.

Let us define $P_{\mathrm{out}}^{\max} \triangleq \overline{P_{\mathrm{out}}^{\max}} 10^{-\frac{\mathsf{OBO}}{10}}$ that is the maximum *operating* output power of the strongest PA, i.e., PA_M, where OBO is an output backoff (OBO) in dB from the maximum output power $\overline{P_{\mathrm{out}}^{\max}}$. The OBO is required for avoiding nonlinear amplification of broadband signals having a high peak-to-average power ratio. Then, without loss of generality (w.l.o.g.), we can express the nth largest output output power as $\mu_n P_{\mathrm{out}}^{\max}$, where $n \in \{1, \ldots, N\}$, μ_n is a relative scaling factor for different power levels of different PAs, and $0 < \mu_1 < \cdots < \mu_N = 1$ for the distinct output power levels. Accordingly, regardless of the selected power level and PA, the maximum transmit power is restricted to $P_{\mathrm{out}}^{\max}$ subject to regulatory constraints. Note that PA_m operates optimally (i.e., with maximum efficiency) only at its own maximum output power.

We transmit $R\,\mathrm{b/s/Hz}$ of information via a packet with symbols $x_1, \ldots, x_t$, where t is a time index, see Fig. 1. We assume that $\mathrm{E}\,|x|^2 = 1$ where E is the expectation operation, and we drop the time index for notational convenience. Here, we choose x to be a Gaussian distribution. The transmit symbol x is amplified by the PA_m selected by the first switch S_1 and transmitted by the transmit antenna i, $i \in \{1, 2\}$, selected by the second switch S_2. If the ith transmit antenna is selected, the corresponding channel vector is represented as $\sqrt{A}\boldsymbol{h}_i \in \mathbb{C}^{2\times 1}$, where $\sqrt{A}$ is an attenuation factor including the path loss effects of shadowing and large scale fading; and $\boldsymbol{h}_i$'s jth element $h_{j,i}$ is a channel gain between the transmit antenna i and the receiver antenna $j \in \{1, 2\}$ and it is zero-mean complex Gaussian random variables with a unit variance. We assume that the channel variation over time is ergodic (not necessarily independent).

III. POWER AMPLIFIER SWITCHING STRATEGY

Noting that exclusive and consecutive N_m power levels are mapped to PA_m, selecting the power level n includes switching the corresponding PA. We derive the probability $f_n(R)$ that PA_m is activated at the output power level n for given target rate R. For further notational simplicity, we represent $f_n(R)$ by f_n for all $n \in \{1, \ldots, N\}$, and use f_0 for the off-mode. Using the probabilities $\{f_n\}$ and f_0, we can further derive TP and $P_c(\Omega)$ of the proposed PAS TAS-MRC system later.

According to the selected PA PA_m and the selected antenna i from PAS and TAS, respectively, the received signal vector is written as

$$\boldsymbol{y} = \sqrt{A}\boldsymbol{h}_i g_n x + \boldsymbol{z} \in \mathbb{C}^{2\times 2}, \tag{2}$$

where g_n is an amplification factor at the kth power level of PA_m, and $\boldsymbol{z}$ is an additive white Gaussian noise (AWGN) vector whose elements are i.i.d., with variance σ_z^2. Since PA_m amplifies the input signal to one of its operating output power levels, i.e., $\mu_n P_{\mathrm{out}}^{\max}$, we can model g_n as

$$g_n \triangleq \sqrt{\mu_n P_{\mathrm{out}}^{\max}}. \tag{3}$$

Using (3) in (2), the received signal is rewritten by

$$\boldsymbol{y} = \boldsymbol{h}_i \sqrt{A\mu_n P_{\mathrm{out}}^{\max}}\, x + \boldsymbol{z}. \tag{4}$$

Since TAS does not affect the power consumption, the receiver always selects the stronger channel so that the received signal-to-noise ratio (SNR) is maximized; therefore, the SNR after an MRC can be derived as a function of power level n as follows:

$$\mathsf{SNR}_n = \frac{\lambda}{\sigma_n^2}, \tag{5}$$

where λ and σ_n^2 are the equivalent channel gain and noise variance after the TAS and MRC, given by

$$\begin{aligned} \lambda &\triangleq \max\left(\|\boldsymbol{h}_1\|^2, \|\boldsymbol{h}_2\|^2\right), \\ \sigma_n^2 &\triangleq \frac{\sigma_z^2}{A\mu_n P_{\mathrm{out}}^{\max}}. \end{aligned} \tag{6}$$

From (4), the receiver can correctly decode the packet at rate $R\,\mathrm{b/s/Hz}$ if

$$R_n \triangleq \log_2\left(1 + \mathsf{SNR}_n\right) \geq R, \tag{7}$$

where R_n is the achievable rate with power level n corresponding PA PA_m under the assumption that the PA output signal has a Gaussian distribution, assuming a sufficiently high OBO. This assumption allows the PA input signal to be linearly amplified with high probability and the output signal also has a Gaussian distribution with high probability. Among the PAs that satisfy (7), we select one PA which consumes the smallest power. More precisely, the power level n (i.e., the corresponding PA_m) is selected if $R_n \geq R$, while $R_{n-1} < R$. Accordingly, using (5), we can formulate the selection probability f_n of power level n at PA_m for given R as follow where $n \in \{1, \ldots, N\}$:

$$\begin{aligned} f_n &= \Pr\left(R_{n-1} < R \leq R_n\right) \\ &= \Pr\left(\left(2^R - 1\right)\sigma_n^2 \leq \lambda < \left(2^R - 1\right)\sigma_{n-1}^2\right). \end{aligned} \tag{8}$$

The probability density function (pdf) of λ in (6) is denoted by $f_\Lambda(\lambda)$, and by using order statistics it is given by the maximum over $u_i \triangleq \|\boldsymbol{h}_i\|^2 = |h_{1,i}|^2 + |h_{2,i}|^2$ where $i = 1, 2$ [7]. Thus, $f_\Lambda(\lambda) = 2F_U(u)f_U(u)$, where $f_U(u)$ and $F_U(u)$ are the pdf and cumulative density function of sample u, respectively. Since $|h_{j,i}|$ is Rayleigh distributed with the parameter $\frac{1}{\sqrt{2}}$, u has a gamma distribution $\Gamma(2, 1)$, and $f_U(u) = ue^{-u}$ and $F_U(u) = 1 - e^{-u}(1 + u)$, respectively [8]; therefore, (8) can be derived as follows:

$$\begin{aligned} f_n &= \int_{(2^R-1)\sigma_n^2}^{(2^R-1)\sigma_{n-1}^2} f_\Lambda(\lambda)d\lambda \\ &= \left(\Upsilon_{n-1}(R) - \Upsilon_n(R)\right)\left(\Upsilon_{n-1}(R) + \Upsilon_n(R) - 2\right), \end{aligned} \tag{9}$$

where

$$\Upsilon_n(R) \triangleq \left(\left(2^R - 1\right)\sigma_n^2 + 1\right) e^{-\left(2^R-1\right)\sigma_n^2}.$$

Here, we define $\Upsilon_0 = 0$ for consistency. Using the probabilities $\{f_n\}$ derived in (9), we can readily obtain the off-mode probability f_0 as

$$f_0 = 1 - \sum_{n=1}^{N} f_n. \tag{10}$$

A tradeoff exists for the choice of M, the number of PAs. A larger M allows us to choose more energy efficient PA so as to achieve a higher system EE. However, increasing M leads to increasing manufacturing cost and form factor of the circuit. Similarly, a tradeoff exists for the choice of N, the number of power levels. Increasing N leads to better system EE but also an increased number of feedback bits. Both tradeoffs require knowledge of the specific system to be implemented, which is beyond the scope of this paper. Nevertheless, we shall study the EE performance difference between a system with a small M and N and that with a large M and N, see Fig. 5 in Section V.

IV. ENERGY EFFICIENCY ANALYSIS

To obtain EE in (1), we first derive the average throughput TP. For the given rate $R\,\mathrm{b/s/Hz}$, the system throughput can be derived by using (9) and (10) as follows:

$$\begin{aligned} \mathsf{TP} &= 0 \times f_0 + R \sum_{n=1}^{N} f_n \\ &= R\,(1 - f_0)\,. \end{aligned} \tag{11}$$

Next, we model the average transmit power consumption $P_c(\Omega)$. For the power level n, the total transmitter power consumption can be modeled as [9]

$$P_{\mathrm{Tx},n}(\Omega) = cP_{\mathrm{PA},n} + P_{\mathrm{fix}}(\Omega), \tag{12}$$

where c is a system dependent power coefficient which can be empirically measured and obtained; $P_{\mathrm{PA},n}$ is power consumption at level n of the corresponding PA PA_m; and $P_{\mathrm{fix}}(\Omega)$ is a PA independent power consumption that is a function of bandwidth Ω. In (12), $P_{\mathrm{PA},n}$ depends on the PA efficiency. In the PA date sheets, the power-added efficiency (PAE) is commonly used, defined by $\mathsf{PAE} \triangleq \frac{100(P_{\mathrm{out}} - P_{\mathrm{in}})}{P_{\mathrm{PA}}}\%$. Since P_{in} is small (by several orders) compared to P_{out} in our applications, $\mathsf{PAE} \simeq \frac{100 P_{\mathrm{out}}}{P_{\mathrm{PA}}} \triangleq \eta$, known as a drain efficiency. Denoting the drain efficiency at power level n as η_n, we can model $P_{\mathrm{PA},n}$ as follows:

$$P_{\mathrm{PA},n} = \begin{cases} 0, & \text{if } n = 0 \text{ (off-mode)}, \\ \frac{100\mu_n P_{\mathrm{out}}^{\max}}{\eta_n}, & \text{if } n = 1, \dots, N. \end{cases}$$

Note that the PA efficiency depend on PA and the output power level (equivalently μ_n) as depicted in Fig. 2. From Fig. 2, we also see that the efficiency drop rapidly as the output power decreases. For example of PA_3, the PAE drops from 60% at D to 43%, 32%, and 9% at C, F, and E, respectively.

Following the PAS strategy in the previous section, the total transmit power consumption of the proposed system, $P_c(\Omega)$, can be now formulated by using (9), (10), and (12) as

$$P_c(\Omega) = \sum_{n=0}^{N} P_{\mathrm{Tx},n}(\Omega) f_n. \tag{13}$$

Using (11) and (13) in (1), we eventually get

$$\mathsf{EE} = \frac{\Omega R (1 - f_0)}{\sum_{n=0}^{N} P_{\mathrm{Tx},n}(\Omega) f_n}.$$

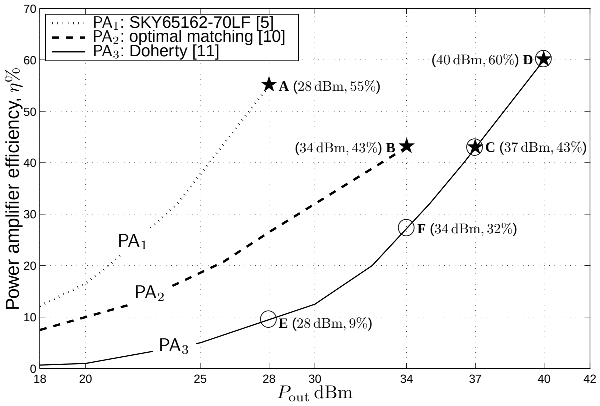

Fig. 2. PA efficiency $\eta\%$ versus PA output power P_{out}. Points A–D depicted by '★' are PAs' operating points of PAS system. Points C–F depicted by '○' are PA's operating points of conventional system.

V. NUMERICAL RESULTS

For simplicity of the proposed PAS system, we consider four power levels $\{28, 34, 37, 40\}\,\mathrm{dBm}$ assuming an $8\,\mathrm{dB}$ OBO, and employ three PAs, PA_1, PA_2, and PA_3, operating at A, B, and $\{\mathsf{C}, \mathsf{D}\}$, respectively, depicted by '★' in Fig. 2, i.e., $M = 3$, $N_1 = 1$, $N_2 = 1$, and $N_3 = 2$. The notation $\mathsf{PAS}[M; N]$ is used to represent various PAS configurations later. Insertion loss of switch S_1 for the PAS is negligible because switching is performed before the signal amplification; while the insertion loss of switch S_2 for antenna selection is assumed to be $1\,\mathrm{dB}$ in our simulations. The channel attenuation A is modeled as $A\,\mathrm{dB} = G - 128 + 10\log_{10}(d^{-\alpha})$ [12], where G includes the transceiver feeder loss, switch insertion loss, and antenna gains; and $d^{-\alpha}$ is the path loss where d is the distance in kilometers between a transmitter and a receiver and α is a path loss exponent. In our simulations, we set $G = 5\,\mathrm{dB}$, $\alpha = 3.76$, $d = 0.6\,\mathrm{km}$, and $\sigma^2 = -174\,\mathrm{dBm\,/\,Hz}$ to model practical wireless communication systems. The bandwidth is set to $10\,\mathrm{MHz}$. For the power consumption model, we set $P_{\mathrm{fix}} = 40\,\mathrm{W}$ and $c = 4.7$ [5].

Fig. 3 shows the PAS probabilities $\{f_n\}$ of $\mathsf{PAS}[3; 4]$. As we can see, the lowest output power PA, i.e., PA_1, is turned on with a high probability f_1 when R is low. As R increases, f_1 decreases, while f_2 increases because PA_1 cannot support R bits transmission, yet PA_2 can. Similarly, f_3 and f_4 increase and then decrease as R increases. Eventually, the off-mode probability f_0 increases and approaches to one as no PA can support the high R.

In Fig. 4, we show the throughput and power consumption of $\mathsf{PAS}[3; 4]$; for each figure of merit, we normalize them by their respective maximum values. As expected, the throughput increases as R increases up to a point where the highest output power PA, i.e., PA_3, is used most frequently, and then starts to decrease as the probability of off-mode increases. Eventually, the throughput approaches zero when R is very high. The power consumption behaves similarly, except that the minimum power consumption in off-mode is non-zero due to the fixed overhead power P_{fix} which is around 40% of the peak power consumption in the simulations.

We compare the EE of $\mathsf{PAS}[3; 4]$ and the conventional

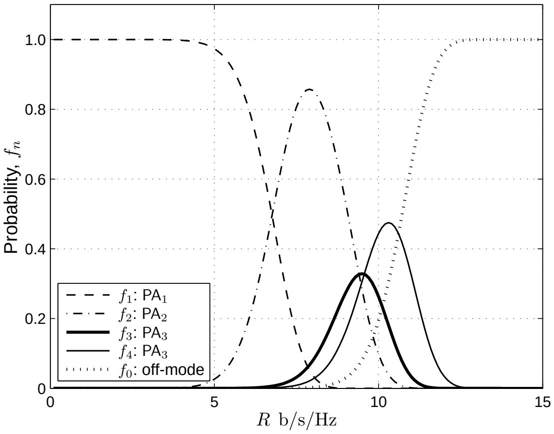

Fig. 3. PAS probabilities of the proposed PAS system.

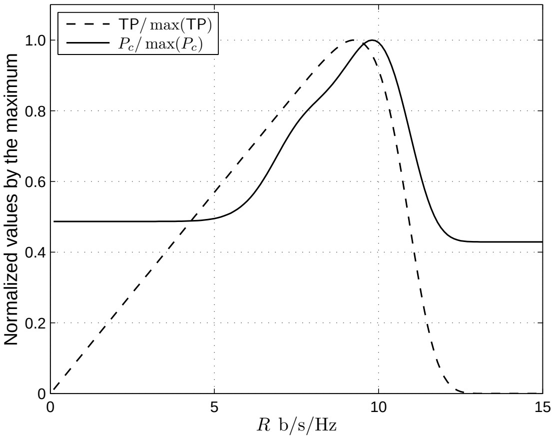

Fig. 4. Normalized throughput and normalized power consumption.

system that performs four-level power control. For fair comparison, the conventional power control system employs PA PA$_3$ in Fig. 2 which operates at C–F depicted by ‘$\bigcirc$.’ Besides, the conventional power control system is equivalent to the PAS$[3;4]$ in terms of feedback (FB) amount, i.e., one-bit FB for antenna selection and two-bit FB for power control. However, note that η’s of the conventional system are reduced. For the sake of comparison, we consider three TAS-MRC systems with extreme conditions. The first one is PAS$[100;100]$ with fixed efficiency by $\eta = 60\%$, whose maximum output power vary from $0.1\,\mathrm{W}$ to $10\,\mathrm{W}$ in steps of $0.1\,\mathrm{W}$. From numerical results omitted in the paper, we observe that the PAS$[100;100]$ is almost ideal as EE improvement is marginal with more than 100 PAs. The second one is a PAS$[3;100]$. The third one is a TAS-MRC system without power control, i.e., the transmitter always transmits with its maximum power at D.

In Fig. 5, we observe that PAS$[3;4]$ achieves a high EE close to its bound EE within 5% gap if $R \leq 6$ or if $R \geq 11$. To reduce an EE gap between PAS$[100;100]$ and PAS$[3;100]$, more efficient PAs, i.e., *hardware load*, are required; while to reduce an EE gap between PAS$[3;100]$ and PAS$[3;4]$, more power levels (FB), i.e., *network load*, is needed. In general, we see that i) power control can improve the conventional system’s EE, and ii) the proposed PAS method with multiple PAs can further improve the system EE significantly.

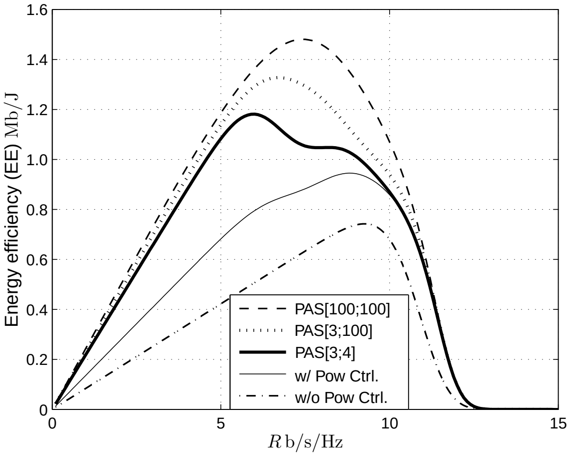

Fig. 5. Energy efficiency (EE) comparison of the proposed PAS systems with PAS$[M;N]$ and the conventional systems with and without power control (Pow Ctrl).

VI. CONCLUSION

We propose a power amplify switching (PAS) method to improve a system energy efficiency (EE). To enable an efficient PA and power level selection in the PAS system, we employ a PA bank consisting of multiple dissimilar PAs, whose output power levels and efficiencies are different. Numerical results verify that the proposed PAS method can improve the system EE compared to the conventional systems that performs transmit power control with a single PA.

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