Abstract—We propose a power amplifier (PA) switching/selection (PAS) method to improve energy efficiency (EE) of a multiple-input multiple-output (MIMO) system. The proposed system consists of multiple dissimilar low maximum-output (MaxOut) PAs in addition to multiple identical high-MaxOut PAs. We select the most energy efficient PAs among all PAs and the corresponding power level such that a target rate is supported. The average EE of the MIMO system is improved compared to the case of using identical PAs whether with or without power control, especially in the regime of low target rate where the low-MaxOut PAs is most energy efficient in. Numerical results verify the efficacy of the proposed PAS with respect to MIMO systems with identical PAs with the same amount of feedback for PAS.

Index Terms—Energy efficiency (EE), power amplifier switching/selection (PAS), multiple-input multiple output (MIMO).

I. INTRODUCTION

Recently, green wireless communications have been studied extensively taking into account a practical power amplifier (PA) model [1], [2]. Since the PA is a major power consumer in wireless communications, a high-efficiency PA is preferably used to save energy consumption. In [1], [2], the improvement of the energy efficiency (EE) have been considered from three perspectives, namely, the PA, signal, and network design perspectives. For each of the respective perspectives, solutions considered in the literature include (i) circuit design (including PA design), (ii) signal processing techniques, such as input backoff (IBO), peak-to-average power ratio (PAPR) reduction, and linearization using feedback/feedback/distortion, and (iii) network protocol design, such as discontinuous transmission [3], coordinated multipoint transmission [4], and coordinated napping [5].

From the circuit-design perspective, a switch bias control circuit has been studied for a PA switching/selection (PAS) [6], in which either a low or high maximum-output (MaxOut) PA is selected based on the desired output power. In addition, the comparison of the EE with a PAS between a traditional PA and an envelope tracking PA has been evaluated in [7]. The PAS method has also been studied based from the signal processing perspective, for a single-antenna system with full channel state information at the transmitter (CSIT) in [8], [9] and for a transmit antenna selection (TAS) and maximum ratio combining (MRC) system with partial CSIT in [10]. In the PAS systems, the most efficient PA is switched on for transmission while satisfying the required spectral efficiency (SE); as a result, the EE of the network can be improved.

In a conventional multiple-input multiple-output (MIMO) system, multiple information streams are typically transmitted through multiple identical high-MaxOut PAs. As an example, Fig. 1 illustrates a two-transmit and two-receive (2-by-2) antenna system that transfers two data streams, \( x_1 \) and \( x_2 \), through two identical PAs, denoted by \( PA_1 \). The conventional MIMO transmitter may reduce the transmission power via power control to save power consumption if it can support the given target rate. To do this, the receiver sends the power to be used by a feedback channel. In the example, 2 bits are fed back from the receiver to the transmitter to inform one of four-power levels to be used, as well as a null feedback where no feedback is sent to indicate the PA is turned off and hence there is no transmission, as shown in Table I. However, when the transmission power is reduced to much smaller than the MaxOut, the PA efficiency \( \eta \) can drop significantly, as measured by the power-added efficiency (PAE) given by

\[
\eta = \frac{P_{\text{out}} - P_{\text{in}}}{P_{\text{PA}}} \approx \frac{P_{\text{out}}}{P_{\text{PA}}},
\]

where \( P_{\text{out}} \), \( P_{\text{in}} \), and \( P_{\text{PA}} \) are PA's output power, input power, and power consumption, respectively. The approximation of PAE to a drain efficiency in (1) is valid, because \( P_{\text{in}} \) is

![Fig. 1. Conventional 2-by-2 MIMO system.](image-url)

<table>
<thead>
<tr>
<th>Level</th>
<th>PA</th>
<th>( P_{\text{out}} )</th>
<th>( \eta % )</th>
<th>Feedback</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>two PA1's</td>
<td>2 \times 0.345 W (25 dBm)</td>
<td>5%</td>
<td>00</td>
</tr>
<tr>
<td>P2</td>
<td>two PA1's</td>
<td>2 \times 1.25 W (31 dBm)</td>
<td>15.5%</td>
<td>01</td>
</tr>
<tr>
<td>P3</td>
<td>two PA1's</td>
<td>2 \times 5 W (37 dBm)</td>
<td>42%</td>
<td>10</td>
</tr>
<tr>
<td>P4</td>
<td>two PA1's</td>
<td>2 \times 10 W (40 dBm)</td>
<td>60%</td>
<td>11</td>
</tr>
<tr>
<td>P5</td>
<td>off</td>
<td>0</td>
<td>0</td>
<td>null</td>
</tr>
</tbody>
</table>
relatively small compared to $P_{\text{out}}$ and $P_{\text{PA}}$ in generic wireless communications. The efficiency degradation is severe as shown over various PAs in Fig. 2. The PAEs of PA3 for particular transmit power levels are summarized in Table I. As a result of the PAE degradation, the system EE is reduced significantly as well, as will be shown analytically and numerically in the subsequent sections.

In this paper, to reduce the amount of EE degradation, we propose the use of identical high-MaxOut PAs as well as dissimilar low-MaxOut PAs at the transmitter, as illustrated in Fig. 3. Each of the low-MaxOut PAs is designed to achieve the maximum efficiency at some chosen low-power level. Based on this proposed MIMO system with multiple PAs, we employ PAS such that data is successfully delivered to a receiver at a target rate. Herein, we focus on a system-level approach, focusing on when to switch and which PA to switch to. To this end, we choose the PAs that can support the target rate with the minimum energy. As an example, we consider a MIMO system that performs a four-level transmit power control (excluding no transmission) with PA3. Compared to the conventional MIMO system in Fig. 1 with two PAs (say PA1), we have two additional PAs, PA1 and PA2, to transmit at power levels $P_1$ and $P_2$, respectively. The power levels and the corresponding efficiencies shown in Table II is obtained from [2], [10], shown also in Fig. 2. Since PA1 and PA2 can achieve higher PAE than PA3 at power levels $P_1$ and $P_2$, we expect the system EE to be improved if PA1 and PA2 is chosen to be used appropriately. To determine the appropriate PA to use, we define three modes of the PAS MIMO communications: a PAS-MRC mode which corresponds to a single-input multiple-output (SIMO) transmission mode, a MIMO mode with CSI at the receiver (CSIR), and an off mode. The proposed PAS can be directly extended to more than two transmit antennas, and also to multiple low-MaxOut PAs, but will lead to larger form factor and higher cost due to more antennas and PAs for implementation, and also require more feedback bits. For simplicity, we set two transmit antennas to describe the MIMO PAS system throughout the paper. A spatial diversity methods, such as TAS and space-time block code, are not considered in this work.

Our contributions are as follows. We propose the following PAS scheme in this paper. We use the PAS-MRC mode that uses only one antenna and choose the PA with the smallest MaxOut to support the target rate, if possible. If the PAS-MRC mode cannot support the target rate, the MIMO mode is used which employs two antennas with two high-MaxOut PAs. In the event that the target rate still cannot be satisfied, the off mode is used in which all PAs are switched off with no transmission; this saves energy as the receiver cannot be served at the target rate. Since the transmitter selects the most efficient PAPAs to satisfy the target rate (if possible) with the least power consumption, the system EE is improved compared to the conventional MIMO system employing identical PAs. We also analytically and numerically obtain the EE for the proposed PAS scheme. Numerical results quantify the EE gain of the proposed PAS with respect to MIMO systems with identical PAs employing the same amount of feedback bits for antenna switching.

The rest of the paper is organized as follows. In Section II, the proposed PAS MIMO system is introduced. Section III presents a mode selection criterion. In Sections IV, the EE of the proposed PAS MIMO is analyzed. Section V is devoted to verify the proposed PAS through computer simulation. After discussing future work and remaining issues for energy efficient wireless communications, we conclude this paper in Section VI.

## II. PROPOSED PAS MIMO SYSTEM MODEL

We consider a 2-by-2 MIMO system in this paper for simplicity, as shown in Fig. 3. The number of transmit and receive antennas can be readily generalized. We assume there are $M+2$ antennas, where $M$ is the number of additional antennas deployed over the conventional MIMO system. We label the...
mth PA as \( \text{PA}_m, m = \{1, \ldots, M+2\} \), such that the maximum output power within the linearly amplifying region is given by \( \mu_m P_{\text{out}}^\text{max} \), where \( P_{\text{out}}^\text{max} \) is a normalized power value and \( \mu_m \) is a relative amplification factor and we assume, without loss of generality (w.l.o.g.), that \( 0 < \mu_1 \leq \cdots \leq \mu_{M+2} \). Let OBO be an output backoff (OBO) in dB corresponding to an IBO, which is a factor used to avoid the nonlinear amplification of a fluctuating input signal with a high PAPR. Taking into account the OBO, the maximum operating MaxOut is \( \mu_m P_{\text{out}}^\text{max} \), where \( P_{\text{out}}^\text{max} - \text{OBO} = P_{\text{out}}^\text{max} \). In our system, there are two identical high-MaxOut PAs, \( \text{PA}_{M+1} \) and \( \text{PA}_{M+2} \), also known as the main PAs. We let \( \mu_{M+1} = \mu_{M+2} = 1 \), w.l.o.g. In addition, there are \( M \) dissimilar low-MaxOut PAs, \( \text{PA}_1, \ldots, \text{PA}_M \), also known as auxiliary PAs.

We consider the three modes of operation separately, namely, the MIMO mode, PAS-MRC mode, and the off mode. In the MIMO mode, we employ the two main PAs, one for each antenna. In the PAS-MRC mode, we employ one main PA for one antenna, and one PA chosen from any of the auxiliary PAs. In the off mode, the PAs are all turned off and there is no transmission.

The three modes can be activated by using two switches, denoted by \( S_0 \) and \( S_1 \). For the switch \( S_1 \), we set the switch variable \( s_1 \) as an integer as depicted on the dashed lines in Fig. 3, namely \( s_0 \in \{0, 1\} \) and \( s_1 \in \{1, \ldots, M+1\} \).

In PAS-MRC mode, \( s_0 = 0 \) and \( s_1 \in \{1, \ldots, M+1\} \) for \( S_0 \) and \( S_1 \), respectively. Accordingly, a single data symbol stream \( x_1 \) is amplified by \( \text{PA}_s \), and then transmitted by the first transmit antenna as illustrated in Fig. 4(a). The transmitter switches on \( \text{PA}_s \), which is the lowest MaxOut PA that can support a target rate \( R \text{ bits/sec/Hz} \) through the first transmit antenna. Namely, \( \{\text{PA}_1, \ldots, \text{PA}_{s-1}\} \) cannot support the target rate, while \( \{\text{PA}_s, \ldots, \text{PA}_{M+1}\} \) can. The receiver detects \( x_1 \) through MRC with two receive antennas. Hence, the PAS-MRC mode has \( M+1 \) transmission power levels according to the selected PA, namely \( \text{PA}_1, \ldots, \text{PA}_{M+1} \). Here, w.l.o.g., we assume that \( \mathbb{E}[|x_1|^2] = 1 \) where \( \mathbb{E} \) is the expectation operation. We assume \( x_1 \) to be Gaussian distributed for the purpose of calculation of teh mutual information in the next section.

If no single PA in PAS-MRC mode can support the target rate, \( s_0 = 1 \) for \( S_0 \) and \( s_1 = M+1 \) for \( S_1 \), then the MIMO mode is activated to support the target rate as illustrated in Fig. 4(b). Accordingly, two data streams, \( x_1 \) and \( x_2 \), are transmitted through \( \text{PA}_{M+1} \) and \( \text{PA}_{M+2} \), respectively, which are the main PAs.

Due to severe fading, the MIMO mode may still not be able to support the target rate, despite being able to provide the highest achievable rate among three modes. In this case, the off mode is activated so as not to save energy. Thus, both \( s_0 \) and \( s_1 \) are set to be zero, and all PAs are switched off, as illustrated in Fig. 4(c).

A proper mode is determined at the receiver and is fed back to the transmitter. We assume that the off mode can be activated by not sending any feedback. Hence, \( \log_2(M+2) \)-bit feedback is required to inform the selected mode with \( M \) auxiliary PAs. \( M \) should be carefully designed by balancing between the EE improvement and the feedback link overhead and the system-level cost. For the case of \( M = 3 \), we summarize the activated PAs, the feedback information, and the switch status in Table III.

### III. Mode Selection

In this section, we specify the mode selection criteria with more details. Let a received signal at receive antenna \( i \) be \( y_i \).
The generic, received signal vector \( \mathbf{y} = [y_1 \ y_2] \) is then written as
\[
y = \sqrt{A} \begin{bmatrix} h_2 & h_1 \end{bmatrix} \begin{bmatrix} g_{M+2} & 0 & f_2 \\ 0 & g_{M} & f_0 \end{bmatrix} \begin{bmatrix} z_2 \\ z_1 \end{bmatrix} + z,
\]
(2)
where \( \sqrt{A}h_j \in \mathbb{C}^{2 \times 1}, j = \{1, 2\} \), is a channel vector; \( A \) is an attenuation factor including the path loss effects of shadowing and large scale fading; \( h_j \)’s \( i \)th element \( h_{i,j} \) is a channel gain between the transmit antenna \( j \) and the receiver antenna, \( i \in \{1, 2\} \); the elements \( \{h_{i,j}\} \) are independent, identically distributed (i.i.d.) and zero-mean complex Gaussian random variables with a unit variance; \( g_m \) is an amplification factor of PA\(_m\); and \( z = [z_2 \ z_1] \) is an additive white Gaussian noise (AWGN) vector whose element \( z_i \)’s are i.i.d., with variance \( \sigma_i^2 \). With a high IBO, we can assume that the PA input signal is linearly amplified and the PA output signal obeys a Gaussian distribution. Accordingly, we can further assume that the receiver can correctly decode \( R \)-bit information per unit frequency and time if \( R_m \geq R \) bits/sec/Hz, where \( R_m \) is the achievable rate of (2). We derive \( R_m \) of each mode.

In the PAS-MRC mode, PA\(_{M+2}\) is deactivated as illustrated in Fig. 4(a). Thus, the received signal vector of the PAS-MRC mode is derived from (2) by setting \( g_{M+2} = 0 \). Since PA\(_m\) amplifies the input signal to its MaxOut, i.e., \( \mu_m P_{\text{out}}^{\text{max}} \), we can model \( g_m \) as \( g_m \overset{\Delta}{=} \sqrt{\mu_m P_{\text{out}}^{\text{max}}} \), and the effective noise variance is defined as
\[
\sigma_m^2 \overset{\Delta}{=} \sigma_2^2 (A \mu_m P_{\text{out}}^{\text{max}})^{-1}.
\]
The achievable throughput at PAS-MRC mode with PA\(_m\) is then derived as
\[
R_m = \log_2 \left( 1 + \frac{\mathbf{SINR}_m}{\sigma_m^2} \right), \quad m \in \{1, \ldots, M + 1\},
\]
where the signal-to-noise ratio (SNR) after MRC is obtained from (2) with \( g_{M+2} = 0 \) as a function of PA index \( m \) as
\[
\mathbf{SINR}_m = \| \mathbf{h}_m \|^2 \sigma_m^{-2}.
\]
(5)

In the MIMO mode, the received signal model is obtained from (2) by setting \( m = M + 1 \). Since the two activated PASs are identical to each other, we have the achievable rate, denoted by \( R_{M+2} \), under the CSIR assumption as (refer to [11])
\[
R_{M+2} = \log_2 \det \left( \mathbf{I} + 0.5 \begin{bmatrix} h_2 & h_1 \end{bmatrix} \begin{bmatrix} h_2 & h_1 \end{bmatrix}^H \sigma_{M+2}^{-2} \right),
\]
(6)
where the superscript \( H \) is Hermitian transpose.

Based on knowledge of the PAS’ MaxOut \( \mu_m \) and the CSI, the receiver can compare the achievable rate \( R_m \) and the target rate \( R \), and determine the mode that supports the target rate with the smallest transmit power. The feedback information \( s_0 \) and \( s_1 \) for switches \( S_0 \) and \( S_1 \), respectively, are selected specifically as follows:
\[
(s_0, s_1) = \begin{cases} (0, m) : \text{PAS}, & \text{if } R_{m-1} < R \leq R_m, \\ (1, M+1) : \text{MIMO}, & \text{if } R_{M+1} < R \leq R_{M+2}, \\ (0, 0) : \text{off}, & \text{if } R > R_{M+2}, \end{cases}
\]
(7)
where \( m \in \{1, \ldots, M + 1\} \) and \( R_0 \) = 0 for notational consistency.

IV. ANALYSIS OF ENERGY EFFICIENCY

We first derive a probability \( f_m(R) \) of selecting mode \( m \) for given target rate \( R \). For notational simplicity, we denote \( f_m(R) \) by \( f_m \). Specifically, \( \{f_m\} \) where \( m \in \{1, \ldots, M + 1\} \), \( f_{M+2} \), and \( f_{M+3} \) represent a PAS-MRC mode, a MIMO mode, and an off mode, respectively. Using the probabilities \( \{f_m\} \), we obtain the average achievable throughput, average power consumption, and energy efficiency, of the proposed PAS MIMO system.

A. PAS-MRC Mode

Following the PA switching criteria in (7), the probability \( f_m \) that PA\(_m\) is switched on for given target rate \( R \) is written as
\[
f_s \overset{\Delta}{=} \Pr (R_{m-1} < R \leq R_m), \quad m \in \{1, \ldots, M + 1\}.
\]

(8)

Since \( |h_{i,1}| \) is Rayleigh distributed with the parameter \( \frac{\sqrt{2}}{\sigma} \),
\[
\begin{aligned}
f_s &\overset{\Delta}{=} |h_{i,1}|^2 = |h_{1,1}|^2 + |h_{2,1}|^2 \text{ has a gamma distribution} \\
&\Gamma(2, 1), \text{ and thus the probability density function (pdf) of } u = f_{U}(u) = e^{-u} \text{ and the cumulative density function (cdf) of } u \text{ is } F_{U}(u) = 1 - e^{-u}(1 + u) \text{ [12]; therefore, using (4) to (8), we can further derive } f_m \text{ as }
\end{aligned}
\]
\[
\begin{aligned}
f_m &= f_{U}((2R - 1)\sigma_m^2 \leq u < (2R - 1)\sigma_{m-1}^2) \\
&= F_{U}((2R - 1)\sigma_{m-1}^2) - F_{U}((2R - 1)\sigma_m^2) \\
&= \Upsilon_m(R) - \Upsilon_{m-1}(R),
\end{aligned}
\]
where
\[
\Upsilon_m(R) = \frac{1 + (2R - 1)\sigma_m^2}{e^{(2R - 1)\sigma_m^2}}.
\]

(10)

Herein, we define \( \Upsilon_0(R) = 0 \) for consistency.

B. Off Mode and MIMO Mode

Following (7), the off mode is activated if two high-MaxOut main PASs, i.e., PA\(_{M+1}\)’s, cannot support \( R \) in a MIMO mode. Hence, the off-mode probability \( f_{M+3} \) can be defined for the given effective noise variance \( \sigma_{M+1}^2 = \sigma_{M+2}^2 \) as
\[
f_{M+3} \overset{\Delta}{=} f_{C}(x < R|\sigma_{M+1}^2) = F_{C}(R|\sigma_{M+1}^2),
\]
(11)

where \( f_{C}(x|\sigma_{M+1}^2) \) is the pdf of \( R_{M+2} \) in (6), and \( F_{C}(x|\sigma_{M+1}^2) \) is the cdf. From [11], we can derive \( F_{C}(x|\sigma_{M+1}^2) \) of the MIMO mode with two PA\(_{M+1}\)’s as
\[
\begin{aligned}
F_{C}(x|\sigma_{M+1}^2) &= \int_{-\infty}^{\infty} \left[ \int_{0}^{\infty} g(\tau, u) d\tau \right] \left( 1 - \frac{e^{2\pi u x}}{j2\pi u} \right) du
\end{aligned}
\]
(12)

where \( g(\tau, u) = e^{-\tau}(1 + 0.5\tau\sigma_{M+1}^2)^{-\frac{\tau u}{\sigma_{M+1}^2}} \). Using (12), we get \( f_{M+3} \) in (11) numerically. Note that there is no closed form expression of the integrations in (12). The probability of the MIMO mode is then readily obtained as
\[
f_{M+2} = 1 - \sum_{m=1}^{M+1} f_m - f_{M+3}.
\]
(13)
C. Energy Efficiency

Following [2], [8]–[10], [13], we define the system EE as

\[ \text{EE} \triangleq \frac{\text{TP}}{P_c} \text{ bits/J}, \]

(14)

where TP and \( P_c \) represent the total system throughput per unit time (bits/sec) and the corresponding total power consumption (W) at the transmitter, respectively. To obtain EE, we derive TP and \( P_c \).

Given \( R \), TP over a bandwidth of \( \Omega \) Hz is written by using \( \{f_m\} \) as

\[ \text{TP} = \Omega \left( 0 \times f_{M+3} + R \sum_{m=1}^{M+2} f_m \right) = \Omega R(1 - f_{M+3}), \]

(15)

where \( \Omega \) is the used bandwidth.

Using the transmitter’s power consumption models in [10] and [14], we can model the power consumption in mode \( m \) as follows:

\[ P_{\text{Tx},m} = \begin{cases} 
  P_{\text{ant},m} + P_{\text{sp1}} \Omega + P_{\text{fix}}, & \text{if } m = 1, \ldots, M + 1, \\
  2P_{\text{ant},m} + P_{\text{sp1}} \Omega + P_{\text{fix}}, & \text{if } m = M + 2, \\
  P_{\text{fix}}, & \text{if } m = M + 3, 
\end{cases} \]

(16)

where \( P_{\text{ant},m} \) is the power consumption of PA\(_m\) for using one transmit antennas; \( P_{\text{sp1}} \) is a signal processing related power consumption per unit frequency which is independent of the number of transmit antenna \( N_T \); \( P_{\text{fix}} \) is a fixed power consumption which is independent of MaxOut, \( N_T \), and \( \Omega \), such as a power supply, a direct current converter, and an active cooling system. More precisely, \( P_{\text{ant},m} \) can be modeled as (refer to [15])

\[ P_{\text{ant},m} = c \mu_m P_{\text{out}}^{\text{max}} / \eta(\mu_m) + P_{cc} + P_{\text{sp2}} \Omega, \]

(17)

where \( c > 0 \) is a system dependent power loss coefficient which can be empirically measured and obtained; the factor \( \eta(\mu_m) \), where \( 0 < \eta(\mu_m) < 1 \), is the PA efficiency that depends on the input power (or equivalently PA output power); \( P_{cc} \) is an RF circuit power consumption which is proportional to \( N_T \); and \( P_{\text{sp2}} \) is a signal processing related power consumption per bandwidth.

Following the mode switching strategy in (7), the total transmit power consumption of the PAS MIMO system is expressed with \( \{f_m\} \) and \( \{P_{\text{Tx},m}\} \) as

\[ P_c = \sum_{m=1}^{M+3} P_{\text{Tx},m} f_m. \]

(18)

Using (15) and (18) in (14), eventually we get the EE of PAS MIMO as

\[ \text{EE} = \frac{\Omega R(1 - f_{M+3})}{\sum_{m=1}^{M+3} P_{\text{Tx},m} f_m}. \]

(19)

V. PERFORMANCE EVALUATION AND DISCUSSION

We consider 2-by-2 MIMO systems in Figs. 1 and 3. For the proposed PAS MIMO system, two auxiliary PAs are considered, i.e., \( M = 2 \). The power profiles and PA efficiencies follow Tables I and II. The channel attenuation

\[ A \]

is modeled as \( A \text{dB} = G - 128 + 10 \log_{10}(d^{-\alpha}) \) following [16], where \( G \) includes the transceiver feeder loss and antenna gains; and \( d^{-\alpha} \) is the path loss where \( d \) is the distance between a transmitter and a receiver and \( \alpha \) is a path loss exponent. In our simulations, we set \( G = 5 \text{dB}, \alpha = 3.76, d = 0.6 \text{ km}, \) and \( \sigma^2 = -174 \text{dBm}/\text{Hz}. \) Power consumption model follows the long-term evolution system setup in [15], [17]: 5 MHz bandwidth with 512 FFT size (300 subcarriers), \( c = 2.63, P_{cc} = 66.4 \text{ W}, P_{\text{fix}} = 36.4 \text{ W}, P_{\text{sp1}} = 1.28 \mu\text{W/Hz}, \) and \( P_{\text{sp2}} = 3.32 \mu\text{W/Hz}. \) Since switching is performed before the signal amplification, the insertion loss for the switch is assumed to be negligible. All results are obtained by varying \( R \) from 0.1 to 24 bits in steps of 0.1 bit.

A. Switching Probability

Fig. 5(a) shows the mode switching probabilities \( \{f_m\} \) of the proposed PAS MIMO system. The lowest output power PA, i.e., PA\(_1\), is switched on with a high probability \( f_1 \) when the target rate \( R \) is low. As \( R \) increases, \( f_1 \) decreases, while \( f_2 \) increases because PA\(_2\) is starting to be unable to support the transmission, while PA\(_3\) still can do so. Similarly, \( f_3 \)
increases and then decreases as $R$ increases, while $f_4$ continue to increase. Eventually, $f_4$ decreases, while the off-mode probability $f_2$ increases. The off-mode probability approaches to one as even the MIMO mode cannot support the high $R$.

For benchmarking, Fig. 5(b) shows the probability $f_{\ell}^{\text{pow}}$ of selecting power level $P_{\ell}$ in the conventional MIMO system so as to support the target rate with minimum power. The probability $f_{\ell}^{\text{pow}}$ can be numerically obtained as follows:

$$f_{\ell}^{\text{pow}} = F_{C}(R|\sigma_{\ell}^2) - F_{C}(R|\sigma_{\ell-1}^2),$$

(20)

where $\sigma_{\ell}^2 \triangleq \frac{\sigma_{\ell}^2}{A_{P_{\ell}}} \text{ and } P_{\ell}^{\text{out}}$ is the output power of level $\ell$. Probability $f_{\ell}^{\text{pow}}$ behaves similarly to $f_{\ell}$.

B. EE Comparison

We evaluate EEs of three MIMO transmitters: two conventional MIMO transmitters employing two high-MaxOut PAs with and without power control, respectively, and the proposed MIMO transmitter employing low-MaxOut PAs with PAS. Fig. 6 shows the EE improvement of the proposed PAS MIMO transmitter in percentage compared with two conventional MIMO transmitters.

From the results, we see that EE improvement is significant, especially, when $R$ is low because the low-MaxOut PA, which yields high EE improvement, is switched on with a high probability when $R$ is low. For example, when $R < 8 \text{ bits/sec/Hz}$, the proposed PAS can achieve more than 120% EE improvement compared to the conventional MIMO transmitter without (with) power control. However, the EE improvement of PAS compared with the conventional MIMO transmitters diminishes as $R$ increases. Eventually, the EE improvement of the PAS compared to the conventional power controlled MIMO transmitter disappears. However, the EE improvement compared to a MIMO transmitter without power control turns to increase at around $R = 13 \text{ bits/sec/Hz}$ and keeps increasing because the high target rate cannot be supported even with the two high-MaxOut PAs, resulting in zero throughput. From the result, we see that turning off a transmitter (i.e., PA) can improve significantly EE if the transmitter cannot support too high target rate.

VI. CONCLUSION

Since conventional MIMO systems use identical high maximum-output (MaxOut) power amplifiers (PAs), the system energy efficiency (EE) may decrease when low power transmission occurs a lot. In the paper, we propose a PA switching (PAS) method using auxiliary low-MaxOut PAs to improve system EE fulfilling the target rate. Numerical results verify the EE merit of the proposed PAS. Further extension of the PAS technology to various transmit-receive methods is an interesting direction to pursue, while reducing the form factor of the proposed PAS architecture remains as further work.

REFERENCES


