Green Wireless Communications: A Power Amplifier Perspective

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***Abstract*—In this paper, we survey two essential and practical characteristics of radio-frequency power amplifier (PA), namely, *linearity* and *efficiency*. Nonlinear amplification yields significant distortion of the transmit signals and strong interference for cochannel users. Imperfect efficiency of the PA causes an overhead of the systems resulting in energy efficiency (EE) degradation. Therefore, the linearity and efficiency of the PA should be precisely characterized in the system design.**

We first survey the linearity and efficiency models of PA, and then introduce commonly used technologies for improving the EE according to three approaches: i) transmitter architecture, ii) signal processing, and iii) network protocols.

We then introduce our recent work on a multiple PA switching (PAS) architecture, in which one or more PAs are switched on at any time to maximize the EE while satisfying the required spectral efficiency (SE). We consider the case where either *full* or *partial* channel state information is available at the transmitter (CSIT). Since the transmitter selects the most efficient PA that satisfies a target rate with the least power consumption, EE is improved, and a Pareto-optimal SE-EE tradeoff region can be enlarged as verified in the numerical results with real-life device parameters. For example, we observe around 323% and 50% EE improvements for a single antenna system with a full CSIT and for a transmit antenna selection and maximum ration combining system with a partial CSIT, respectively; as a result, we can surmise that the PAS is one promising technology for green, i.e., energy efficient, wireless communication systems.

I. INTRODUCTION

Recently, green technologies that can reduce energy consumption and carbon-dioxide emission and reuse/recycle the resources have been attracting academia/industry/government. Especially, green information communication technology (ICT) has been studied widely to achieve high energy efficiency (EE), and to resolve the conflict between high demands of quality-of-service (QoS) and energy saving, e.g., [1]–[5]. It is reported in [1] that the ICT is the fifth largest industry in power consumption; ICT infrastructure consumes 3% of the world-wide energy consumption; and ICT emits around 2% of the world-wide carbon-dioxide. To overcome severe fading and interferences, significant amount of energy is consumed in *wireless* access networks, particularly at the transmitter, compared to fixed line networks in which the communicating nodes are connected through physical wires [3], [4]. More specifically, power amplifier (PA) is a major power consumer in the wireless networks. In cellular networks, for example, energy is consumed mostly at a base station (BS) [4], of which 50%–80% of power consumption is consumed at the PAs [6], [7]. Consequently, it is essential to consider precisely the PA effects for designing the green wireless communication systems.

In the paper, we briefly recapitulate two fundamental characteristics of a practical PA, namely, *linearity* and *efficiency*. A tradeoff between the nonlinearity and the efficiency has been observed in [8]. As the PA input signal increases, the PA become more nonlinear and distorting, while its efficiency increases. The nonlinear amplification causes significant degradation on performance, while the inefficient amplification causes severe reduction of system EE. We first survey the linearity and efficiency models of PAs, and the existing technologies which resolve the issues arisen from the aforementioned PA characteristics according to three approaches: i) transmitter architecture, ii) signal processing, and iii) network protocols. Then, we introduce our recent work on PA switching/selection (PAS), in which one or multiple PAs are selected to improve system EE. To do this, a spectral efficiency (SE)/throughput and EE tradeoff is analyzed under the full/partial channel state information at the transmitter (CSIT). From numerical results, we verify that PAS with multiple PAs is one promising technology for green wireless communication systems.

II. FUNDAMENTAL CHARACTERISTICS OF PA

According to operation class (i.e., amplification method), different PA has its own characteristics, such as a power-output capability (or transistor utilization factor), a linearity, and an efficiency. For example [9], [10], class-A PA has high linearity, yet the efficiency η is lower than 50% with utilization factor $u = 0.125$, and is generally used for millimeter wave (20-100GHz), where u is defined as output power per transistor normalized for peak drain voltage and current of 1V and 1A, respectively; class-B PA has high linearity with $\eta \leq 78.5\%$ and $u = 0.125$ and is generally used for broadband at high frequency (HF) and very high frequency (VHF); class-C PA has moderate linearity with $\eta \leq 85\%$ and is used for high-power vacuum-tube transmitter; class-D has low linearity, yet very high efficiency with $u = 0.159$ and is used for $100\,\text{W}$ to $1\,\text{kW}$ transmitter at HF; class-E has low linearity, yet high efficiency at K-band ($19 - 26.5\,\text{GHz}$) with $u = 0.098$; and class-F has low linearity, yet high efficiency at UHF and microwave.

The transmitted signal distorted from the PA nonlinearity yields a co-channel interference (CCI) and causes a significant performance degradation of detection at the receiver. The inefficiency of the PA causes a network-level EE degradation. We introduce the linearity and efficiency models of the practical PAs.

A. Linearity Models

Though a transistor-level PA model is accurate, it is difficult to obtain, generalize or analyze. In contrast to a transistor-level PA model, a system-level PA model includes a few parameters which are obtained from measurements, and it is tractable and reasonably accurate; therefore, it has been widely used to model PAs. The system-level PA model is divided into two types, either with or without a memory effect.

1) Models with Memory Effect: Due to the capacitance and inductance in the circuits and the thermal fluctuation of the PAs, a frequency-domain fluctuation (i.e., an electrical and thermal memory effects, respectively) arises in the transfer function of the PA [11]. As reported in [12], the memory effects are negligible when the system bandwidth is between $1\,\mathrm{MHz}$ and $5\,\mathrm{MHz}$. However, the electrical memory effects are severe for the systems using wide-band signal higher than $5\,\mathrm{MHz}$ and the thermal memory effects are severe for the systems using narrow-band signal lower than $1\,\mathrm{MHz}$. A few commonly used PA models with memory effects are as follows: i) the Volterra series model that is a multivariate polynomial series expressed as a function of the PA input signal, the delay, and the delay time [13]; ii) the Wiener, Hammerstein, and Wiener-Hammerstein models consist of a filter part with memory and another with a memoryless PA part [14]; and iii) the memory polynomial that is a Volterra series model assuming phase independency [15].

2) Memoryless Models: Memoryless models basically assume that the previous PA output signal does not affect the current PA output signal. Amplitude-to-amplitude (AM-AM) distortion and amplitude-to-phase (AM-PM) distortion are used for the memoryless model. PM-AM and PM-PM distortions are typically ignored unless they are strong (e.g., a quadrature modulator with predistortion). The distortion components which are close to the carrier frequency are difficult to be filtered away, hence they are emphasized by using a passband model. However, to ease simulation and computation, a baseband PA model that represents the nonlinearity of complex baseband frequency approximation is more widely used than the passband model [16]. The straightforward way to model the baseband PA is to use a polynomial function, yet to model the nonlinearity its required order increases significantly. Hence, the following baseband model is commonly used for representing the nonlinearity, consisting of an amplitude-dependent gain function $\mathsf{L}_{\mathrm{PA}}(\cdot)$ and a phase shift function $\Phi_{\mathrm{PA}}(\cdot)$ as

$$v_{\mathrm{out}} = \mathsf{L}_{\mathrm{PA}}\left(|v_{\mathrm{in}}|\right) e^{2\pi j \Phi_{\mathrm{PA}}(|v_{\mathrm{in}}|)},$$

where v_{in} and v_{out} are PA input and output voltages, respectively. For the amplitude-dependant and phase shift functions, the following baseband PA models are commonly used.

- *Saleh model* for traveling wave tube amplifier [17]:

$$\mathsf{L}_{\mathrm{PA}}\left(|v_{\mathrm{in}}|\right) \triangleq \frac{a_1|v_{\mathrm{in}}|}{1+a_2|v_{\mathrm{in}}|^2}$$
$$\Phi_{\mathrm{PA}}(|v_{\mathrm{in}}|) \triangleq \frac{b_1|v_{\mathrm{in}}|^2}{1+b_2|v_{\mathrm{in}}|^2}.$$

  where a_i and b_i are the distortion coefficients[1].
- *Ghorbani model* for field-effect transistor (FET) amplifier and for low amplitude nonlinearity [18]:

$$\mathsf{L}_{\mathrm{PA}}\left(|v_{\mathrm{in}}|\right) \triangleq \frac{a_1|v_{\mathrm{in}}^{a_2}|}{1+a_3|v_{\mathrm{in}}^{a_2}|} + a_4|v_{\mathrm{in}}|$$
$$\Phi_{\mathrm{PA}}(|v_{\mathrm{in}}|) \triangleq \frac{b_1|v_{\mathrm{in}}^{b_2}|}{1+b_3|v_{\mathrm{in}}^{b_2}|} + b_4|v_{\mathrm{in}}|$$

  where a_i and b_i are the distortion coefficients[2].
- *Rapp model* for envelope characteristic of solid state power (especially, class-AB) amplifier with saturation amplitude v_{sat} and smoothness factor p [19]:

$$\mathsf{L}_{\mathrm{PA}}\left(|v_{\mathrm{in}}|\right) \triangleq |v_{\mathrm{in}}| \left(1 + \left(\frac{|v_{\mathrm{in}}|}{v_{\mathrm{sat}}}\right)^{2p}\right)^{-\frac{1}{2p}}$$

- *Soft limiter model* for analysis [20]:

$$\mathsf{L}_{\mathrm{PA}}\left(|v_{\mathrm{in}}|\right) \triangleq \begin{cases} |v_{\mathrm{in}}|, & \text{if } |v_{\mathrm{in}}| < v_{\mathrm{sat}} \\ v_{\mathrm{sat}}, & \text{otherwise,} \end{cases} \tag{1}$$

  where v_{sat} is a saturation output amplitude.

B. Efficiency Models

Since the PA is a major power consumer of the wireless communication systems, its efficiency should be precisely considered in the network power consumption model. Three commonly used efficiencies of PA are defined as follows [21]:

1) *Drain efficiency:* $\eta_{\mathrm{D}} \triangleq \frac{P_{\mathrm{out}}}{P_{\mathrm{DC}}}$
2) *Power-added efficiency (PAE):* $\eta_{\mathrm{PAE}} \triangleq \frac{P_{\mathrm{out}}-P_{\mathrm{in}}}{P_{\mathrm{DC}}}$
3) *Overall efficiency:* $\eta_{\mathrm{O}} \triangleq \frac{P_{\mathrm{out}}}{P_{\mathrm{DC}}+P_{\mathrm{in}}}$

where P_{out}, P_{DC}, and P_{in} are RF-output power, discrete current (DC)-input power, and RF-drive power, respectively. The drain efficiency is typically between 20% and 30% as surveyed in [22], [23]. PAE is a reasonable indicator of PA when PA gain g is high, while the overall efficiency is usable in all situation [10]. In wireless network power modeling, if not specifically mentioned, typically $\eta_{\mathrm{D}} \simeq \eta_{\mathrm{PAE}} \simeq \eta_{\mathrm{O}}$ because P_{in} is relatively small compared to P_{DC} and P_{out}. A typical PA only achieve its peak efficiency at the peak output power (PEP). The efficiency drops rapidly as the output power decreases [24].

Though the PA power consumption P_{PA} depends on many factors including the specific hardware implementation, DC bias condition, load characteristics, operating frequency and PA output power, the component that consumes majority of

[1]E.g., $a_1 = 2.1587$, $a_2 = 1.1517$, $b_1 = 4.033$, $b_2 = 9.104$ [17].

[2]E.g., $a_1 = 8.1081$, $a_2 = 1.5413$, $a_3 = 6.5202$, $a_4 = -0.0718$, $b_1 = 4.6645$, $b_2 = 2.0965$, $b_3 = 10.88$, $b_4 = -0.003$ [18].

the power is given by the DC power fed to the PA, i.e., P_{DC} [10]. Using the relation between $P_{\mathrm{out}}^{\max}$ and η_{D} in [25], [26], we can model P_{PA} as a function of P_{in} as follows:

$$\text{Class-A: } P_{\mathrm{PA}} = 2P_{\mathrm{out}}^{\max}$$

$$\text{Doherty: } P_{\mathrm{PA}} = \frac{4P_{\mathrm{out}}^{\max}}{\ell\pi} \times \begin{cases} \sqrt{\xi}, & 0 < \xi \le \frac{1}{\ell^2} \\ (\ell+1)\sqrt{\xi}-1, & \frac{1}{\ell^2} < \xi \le 1 \end{cases} \quad (2)$$

where $\xi = \frac{P_{\mathrm{in}}}{P_{\mathrm{in}}^{\max}}$ and ℓ is for ℓ-way Doherty PA, which includes the special case of the class-B with $\ell = 1$.

III. Technologies for Energy Efficiency

To compensate the losses from the nonlinearity and inefficiency of the PAs, various technologies have been studied. In this section, we survey the EE improvement technologies according to three approaches: i) transmitter architecture, ii) signal processing, and iii) network protocols.

A. Transmitter Architecture

Since a wideband and dynamic-power signal operation is desired for modern wireless communications, such as OFDM and OFDMA systems, high linearity and efficiency are required over wide frequency band and power level. The most direct approach to relieve the nonlinearity and inefficiency issues is to use special architectures for the amplification. Many architectures to improve linearity and/or efficiency are introduced in [10], [27] and they are summarized as follows:

1) Linear architecture: Multiple cascade PAs are in a amplifier chain, in which each amplification stage has around 6-$20\,\mathrm{dB}$ gain. Class-A and class-B are typically used.

2) Corporate architecture: Multiple parallel PAs and power combiner are used for reliable amplification [28]. Two isolated PAs in hybrid combiner compensate each other if the other fails. Quadrature combiner is used to achieve a constant input impedance, to reduce the effect of a load impedance, and to cancel odd harmonics and backward intermodulation distortion.

3) Stage bypassing and gate switching: To increase transmitter efficiency, switching between multiple PAs whose maximum output power levels are different is possible [29].

4) Kahn technique: To achieve high efficiency and linearity for a wide range of signals and power (backoff) levels, the phase and envelop of the signal are amplified separately and then combined, which is thus also called the envelope elimination and restoration (EER) technique [30]. A highly efficient nonlinear RF PA, such as class-C, class-D, class-E, or class-F, amplifies the constant-amplitude phase modulated signal with allowing nonlinearity, while a highly efficient envelope amplifier, such as class-S or class-G, amplifies the envelope of the input signal linearly, resulting in the average efficiencies three to five times those of linear amplifiers from HF to L-band.

5) Envelope tracking architecture: Similar to the conventional linear RF PA, the PA input signal contains both amplitude and phase information. However, in contrast to the conventional linear RF PA, the envelope tracking RF PA's supply voltage is controlled by the envelope of the RF-drive to conserve power, resulting in an efficiency between the linear RF PA and the PAs using the Kahn technique.

6) Outphasing: To achieve high linearity of amplitude-modulated signal, a linear amplification using nonlinear components (LINC) splits the variable-amplitude signal into two signals with constant-amplitude and time-varying phase that are amplified separately with nonlinear high efficiency amplifiers and then combined to regenerate the variable amplitude signal [31].

7) Doherty technique: Class-B (carrier PA or main PA) and class-C (peaking PA or auxiliary PA) PAs are combined to improve efficiency, in which the class-B PA is activated if the signal amplitude is half or less than the PEP, while both PAs are activated if the signal amplitude is larger than half of the PEP [32]. Due to the high efficiency and linearity over wide frequency band and power level, Doherty technique is widely used for the modern cellular communications [2], [33]–[35], along with Kahn-based, envelope tracking, and outphasing architectures.

B. Signal Processing

The first approach can improve the PA characteristics, yet it is still limited to the device-level. With further knowledge of the signal properties, the PA linearity can be further improved.

1) Input backoff (IBO): To avoid the cut-off nonlinearity, i.e., clipping effect, to conserve power consumption, and to mitigate the CCI using the same frequency band, input backoff (IBO) is implemented by reducing the transmit power to sufficiently below its peak output power. Especially, for broadband signal having a high peak-to-average power ratio (PAPR), high IBO is needed for the linear amplification. The PAPR of an orthogonal frequency division multiplex (OFDM) signal is 8 to $13\,\mathrm{dB}$ and that of orthogonal frequency division multiple access (OFDMA) signal in long-term evolution (LTE) systems is around $11\,\mathrm{dB}$ [36], which is significant, and hence a comparable IBO is also needed. Though IBO is a passive approach to avoid the clipping, it is effective and can be always employed to the communication systems.

2) PAPR reduction methods: Since high IBO reduces the PA efficiency, various PAPR reduction methods have been actively studied, such as deliberate clipping, coding, partial transmission sequence and selective mapping, nonlinear companding transform, and tone reservation and tone injection. For further details refer to the references in [37].

3) Linearization: The IBO and PAPR focus on the avoidance of significant distortion from the clipping in the high power regime. There is a nonlinear effect causing system performance degradation in the low power regime as well. To mitigate the nonlinearity of PAs, various linearization methods have also been rigorously studied. Three commonly used linearization methods are classified as feedforward, feedback, and predistortion [38], [39].

4) SE improvement methods: Enormous signal processing methods which can improve SE can also improve the system EE, for example, 3-D multiple-input multiple-output (MIMO) systems and active antenna systems. However, the tradeoff between SE and EE should carefully considered in the system design.

C. Network Protocols

Further processing taking into account the network protocol can be used to increase the EE. Since the PA efficiency is imperfect, actively reducing the PA activation time is a promising approach to increase the system EE. Therefore, recently, many energy efficient network protocols that reduce the PA activation time or that use a low power PA have been rigorously studied.

For example, in cellular networks, a heterogenous network (HetNet) using small cells can improve EE due to the high efficiency of small base stations (or any types of access point in different networks) [40], [41]. Also, various network protocols to control deactivation of the BSs have been proposed to reduce the network energy consumption. The user equipments (UEs) in a cell with the deactivated BS can be supported in alternative ways to sustain reliable communications in the networks. In the cell zooming protocol, the BS with a high loading factor is activated and supports its UEs and the UEs in the inactivated (sleeping) BSs [42]–[45]. Effectively, the activated cell coverage is enhanced, thus this protocol is called cell zooming. In a coordinated multipoint (CoMP) transmission protocol, the activated BSs cooperate to support the UEs in the cells with the deactivated BS [46], [47], where extra signal processing and backhaul traffic can be issues. LTE networks consider further practical and simple approaches such as discontinuous transmission (DTX) [48]. The DTX performs non-transmission to save energy without additional compensation procedure. Similarly, BS coordinated napping (CoNap) has been proposed in [49]. Since the performance degradation is marginal if the traffic load is low, the non-transmission protocols DTX and CoNap can achieve energy saving without significant performance degradation.

IV. PA Switching (PAS) Strategy

Many theoretical studies have been performed to achieve high EE or good QoS and the balance between them [41], [50], [51]. As a fundamental figure of merit of QoS, the SE is considered which is defined as the amount of bits decoded reliably per unit time and per unit bandwidth, i.e., $\mathrm{b/s/Hz}$. The EE represents a total SE over bandwidth per unit power, i.e., $\mathrm{b/s/W} = \mathrm{b/J}$. High SE is needed to support the growing demands of high data traffic, yet it is restricted if the high EE is desired, i.e., there is a tradeoff between SE and EE. In [40], [52], the fundamental SE-EE tradeoff has been shown as

$$\mathsf{SE} = \log_2(1 + P_{\mathrm{out}}/\sigma^2) \ \ \mathrm{b/s/Hz} \tag{3a}$$

$$\mathsf{EE} = \frac{T\Omega\,\mathsf{SE}}{TP_{\mathrm{c}}} = \frac{\Omega\,\mathsf{SE}}{P_{\mathrm{c}}} \ \ \mathrm{b/J} \tag{3b}$$

by using Gaussian signalling [53], which is optimal for the ideal power amplifier. Here, σ^2 is the noise power; Ω is the total bandwidth used; T is the total time used; and P_{c} is the total power consumption. From (3), we see that SE-EE tradeoff region is decreasing-convex.

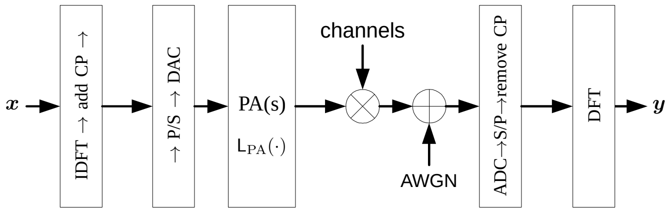

Fig. 1. An OFDM system with a non-linear memoryless PA represented by function $\mathsf{L}_{\mathrm{PA}}(\cdot)$, an inverse discrete Fourier transform (IDFT), a cyclic prefix (CP) insertion, a parallel-to-serial converter (P/S), a digital-to-analogue converter (DAC), and an analogue-to-digital converter (ADC).

For the SE and EE analysis with the practical PA impacts, namely *nonlinearity* and *inefficiency* introduced in Section II, the soft-limiter model in (1) is applicable because it is simple and yet capture the clipping effect. Note that almost linear AM-AM characteristics can be expected with the low power signals by applying linearization techniques introduced in Section III, yet the clipping effect still exists on the high power signals.

In the subsequent subsections, we briefly summarize our recent work on the PAS that is based on the *stage bypassing and gate switching* architecture introduced in Subsection III-A. The proposed PAS is applied to two systems with either full CSIT [22], [23] or partial CSIT [54].

A. PAS with Full CSIT [22], [23]

We quantify the impact of PA on the degradation of both SE and EE for a *single* antenna OFDM system illustrated in Fig. 1, under the assumptions of *full* CSIT and of *identical* efficiencies of PAs. The SE is expressed as

$$\mathsf{SE}(\xi) = H(Y) - \log_2 \pi e \sigma_z^2 \tag{4}$$

where ξ is a power loading factor defined as $\xi \triangleq \frac{P_{\mathrm{in}}}{P_{\mathrm{in}}^{\mathrm{max}}}$, $\xi \geq 0$, which is related to the IBO as $\mathrm{IBO} \triangleq 10\log_{10}(\xi^{-1})\,\mathrm{dB}$; Y represents a random variable whose realization is a received signal y; and σ_z^2 is an additive white Gaussian noise (AWGN) at the receiver. In (4), the differential entropy of Y is given by [53]

$$H(Y) = -\int_y \sum_{i=0,1} f_Y(y, S=i) \log_2 f_Y(y) dy,$$

where $f_Y(y, S=0)$ is a probability density function (pdf) of y when there is no-clipping and $f_Y(y, S=1)$ is a pdf with a clipping. The joint pdfs have been derived as follows (for the proofs, refer to [23]):

$$f_Y(y, S\!=\!0) = \mathsf{N}_0(y)[1 - \mathsf{Q}_1(\sqrt{\mu}, \sqrt{\rho_{\max}})]$$

$$f_Y(y, S\!=\!1) = \mathsf{N}_1(y)\left[\Pr(S=1)\exp\left(\frac{-2b_{\max}y_{\mathrm{Re}}}{\sigma_z^2}\right)\mathsf{I}_0\left(\frac{2b_{\max}|y|}{\sigma_z^2}\right)\right]$$

where $b_{\max} \triangleq \sqrt{P_{\mathrm{out}}^{\max}}$ and $P_{\mathrm{out}}^{\max}$ is a maximum power output of PA; $\mathsf{N}_0(y)$ denotes the pdf of $\mathcal{CN}\left(0, gP_{\mathrm{in}} + \sigma_z^2\right)$ and g is a parameter interpreted as the desired linear gain of the

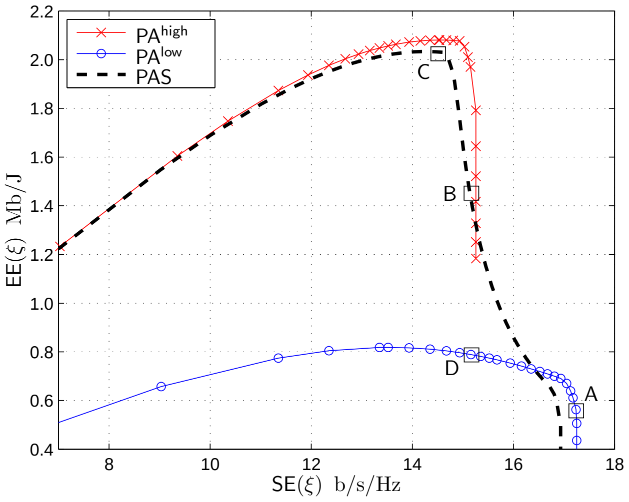

Fig. 2. A SE-EE tradeoff with switching $\mathsf{PA}^{\mathsf{low}}$ and $\mathsf{PA}^{\mathsf{high}}$.

PA, $\mathsf{Q}_1(\cdot,\cdot)$ is the Marcum-Q-function [55] with parameters $\rho_{\max} = \frac{2(gP_{\rm in}+\sigma_z^2)}{gP_{\rm in}}\sqrt{b_{\max}}$ and $\mu = \frac{8gP_{\rm in}(gP_{\rm in}+\sigma_z^2)}{\sigma_z^4}|y|^2$; $\mathsf{N}_1(y)$ is the pdf of $\mathcal{CN}\left(b_{\max},\sigma_z^2\right)$; $y_{\rm Re}$ is the real part of y; and $\mathsf{I}_0(\cdot)$ is the modified Bessel function of the first kind [55].

To provide tractable results, we establish a PA-dependent nonlinear power consumption model from recent studies on empirical power measurement and parameters for cellular and wireless local area networks [34], [35], [41], [56], [57]. We get a *PA-dependant nonlinear* power consumption model as

$$P_{\rm c}(\xi) = P_{\rm fix} + P_{\rm out}^{\max}\left(c_1 + c_2\sqrt{\xi}\right), \quad 0 < \xi \le 1, \tag{5}$$

where $P_{\rm fix}$ is a PA independent power consumption, and the parameters (c_1, c_2) are from (2): $\left(\frac{\pi}{2}c, 0\right)$ for class-A PA; $(0, c)$ for class-B PA; $\left(0, \frac{c}{\ell}\right)$ if $0 < \xi \le \frac{1}{\ell^2}$ or $\left(-\frac{c}{\ell}, \frac{(\ell+1)c}{\ell}\right)$ if $\frac{1}{\ell^2} < \xi \le 1$ for ℓ-way Doherty PA. Here, $P_{\rm fix}$ and c can be obtained from empirical results in [34], [41], [57].

Using the SE in (4) and total power consumption $P_{\rm c}(\xi)$ in (5), we can rewrite the EE in (3b) as a function of ξ as

$$\mathsf{EE}(\xi) = \Omega \mathsf{SE}(\xi) P_{\rm c}^{-1}(\xi).$$

From Fig. 2 (see details of numerical results in Section. IV-A1), we observe that the practical SE-EE tradeoff increases before a turning point and decreases rapidly after the turning point, i.e., the Pareto-optimal SE-EE tradeoff is narrow. To achieve a wide Pareto-optimal SE-EE tradeoff region, we propose a PAS technique. In the PAS transmitter, one or more PAs are switched on at any time to maximize the EE while satisfying the required SE. If the transmitter requires higher transmit power than its maximum output power of single PA to satisfy the target rate, multiple PAs are simultaneously activated at their maximum power and the amplified signals are combined to improve the SE [58]. The PAS technique may be implemented using the corporate architecture or a Kahn technique in Section III-A. As a result, the degree of freedom offered from the multiple PAs yields a high EE over a wide range of SE. We verify the theoretical results through simulations using real-life device parameters as follows.

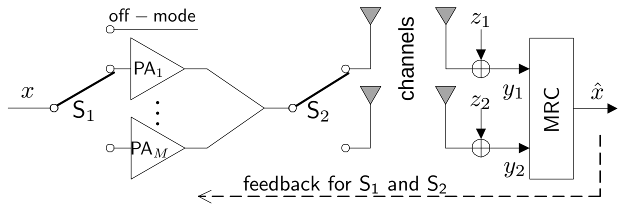

Fig. 3. A TAS-MRC system model with the proposed PA switching (PAS), in which switch S_1 selects a PA and switch S_2 selects a transmit antenna.

1) Numerical Results: We evaluate the PAS with the two PAs in [23]: a low power PA SM2122-44L (denoted by $\mathsf{PA}^{\mathsf{low}}$) with $P_{\rm out}^{\max} = 25\,\mathrm{W}$ and $g = 55\,\mathrm{dB}$ and a high power PA SM1720-50 (denoted by $\mathsf{PA}^{\mathsf{high}}$) with $P_{\rm out}^{\max} = 100\,\mathrm{W}$ and $g = 50\,\mathrm{dB}$. Both PAs operate in the $2\,\mathrm{GHz}$ band and can be used for LTE base stations. Bandwidth is set to be $10\,\mathrm{MHz}$. The channel attenuation is modeled as $A\,\mathrm{dB} = G - 128 + 10\log_{10}(d^{-\alpha})$ [59], 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 simulation, we set $G = 5\,\mathrm{dB}$, $\alpha = 3.76$, $d = 0.2\,\mathrm{km}$, $\sigma_z^2 = -174\,\mathrm{dBm}\,/\,\mathrm{Hz}$, $c = 4.7$, and $P_{\rm fix} = 130\,\mathrm{W}$ [34]. For simplicity, we assume the time fraction of any PA is switched on is a continuous value from 0 to 1.

Fig. 2 shows the SE-EE tradeoff with and without PAS. We assume that PA can be switched once every 20 frames, which is reasonable as one LTE frame consumes a time period of $10\,\mathrm{ms}$ [59], while the PA switching time is much less than $1\,\mathrm{ms}$ [23]. Each frame length is set to be $10\,\mathrm{ms}$. The switch insertion loss assumed by $1\,\mathrm{dB}$ causes EE and SE degradation, and the switching time consumption assumed by $10\,\mu\mathrm{s}$ causes further degradation. From the results, it is verified that the PAS can improve significantly the SE-EE tradeoff even with the switch insertion loss and the switching time. For example, the EE can be improved by around 210% (323%) if we reduce SE by 12% (15%) from A to B (C). In contrast, if a single PA $\mathsf{PA}^{\mathsf{high}}$ is used instead, the EE is improved by around 41% with a 12% reduction of SE from A to D.

B. PAS with Partial CSIT [54]

The PAS introduced in [22], [23] is extended to a transmit antenna selection and maximum ratio combining (TAS-MRC) systems illustrated in Fig. 3. For practical scenarios with M PAs, we employ only *partial* CSIT, specifically we only feed back information for PA selection, and consider a *power dependent* efficiency $\epsilon(\mu_m)$, where μ_m determines the maximum output power of PA m to be $\mu_m P_{\rm out}^{\max}$, $m \in \{1, \ldots, M\}$.

We assume without loss of generality that $0 < \mu_1 < \mu_2 < \cdots < \mu_M = 1$. Instead of a single PA with M power levels as in conventional power control systems, we propose the use of M PAs, in which each power level matches the maximum output power of the multiple PAs. Since each PA operates at

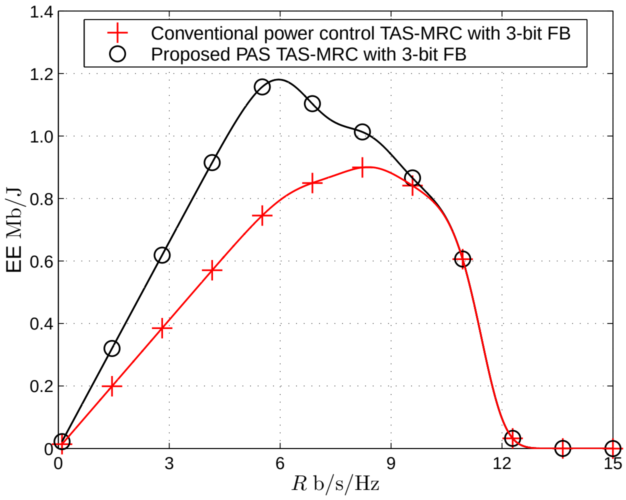

Fig. 4. EE comparison of TAS-MRC systems, in which 1-bit feedback (FB) is used for the TAS and 2-bit FB is used for power control/PAS.

its own maximum output power compared to the conventional power control systems, the average efficiency of PAs can be improved by selecting the most efficient PA that can support a target rate with the least power consumption.

For TAS-MRC systems, we derive a switching probability to PA m for given target rate $R\,\mathrm{b/s/Hz}$ as (proof is in [54])

$$f_m = (\Upsilon_{m-1} - \Upsilon_m)(\Upsilon_{m-1} + \Upsilon_m - 2) \quad (6)$$

by using order statistics [60], [61], where

$$\Upsilon_m \triangleq \left((2^R - 1)\,\sigma_m^2 + 1\right) e^{-(2^R-1)\sigma_m^2}$$

and $\sigma_m^2 \triangleq \frac{\sigma_z^2}{A\mu_m P_{\mathrm{out}}^{\max}}$. Using $\{f_m\}$ in (6), we obtain the EE of the proposed TAS-MRC systems for the given R as

$$\mathrm{EE}_{\mathrm{MRC}}^{\mathrm{TAS}} = \frac{\Omega R \Upsilon_1 (2 - \Upsilon_1)}{\sum_{m=1}^{M+1} P_{\mathrm{Tx},m}(\Upsilon_{m-1} - \Upsilon_m)(\Upsilon_{m-1} + \Upsilon_m - 2)},$$

where for consistency $\Upsilon_0 = 0$ and $\Upsilon_{M+1} = 1$, and $P_{\mathrm{Tx},m}$ is defined as

$$P_{\mathrm{Tx},m} \triangleq \begin{cases} \frac{100 c \mu_m P_{\mathrm{out}}^{\max}}{\epsilon(\mu_m)} + P_{\mathrm{fix}}, & \text{if } m = 1, \ldots, M, \\ P_{\mathrm{fix}}, & \text{if } m = M+1 \text{ (off-mode).} \end{cases}$$

The numerator of $\mathrm{EE}_{\mathrm{MRC}}^{\mathrm{TAS}}$ represents a total throughput over Ω bandwidth, and the denominator is a total power consumption when PA m is selected. The following numerical results verify the potential capability of PAS for EE improvement.

1) Numerical Results: To evaluate the performance of the proposed PAS, we employ three PAs, i.e., $M = 3$. Each PA operates at its optimal operating point with the highest PAE, i.e., assuming an $8\,\mathrm{dB}$ IBO, PA_1 [62], PA_2 [63], and PA_3 [64] are activated at their maximum output power $28\,\mathrm{dBm}$, $34\,\mathrm{dBm}$, and $40\,\mathrm{dBm}$, respectively, with efficiencies 55%, 43%, and 60%. Insertion loss of switch S_1 for the PAS is negligible since it is performed before the power amplifier; while the insertion loss of switch S_2 is assumed to be $1\,\mathrm{dB}$. We set $d = 0.6\,\mathrm{km}$ and $P_{\mathrm{fix}} = 40\,\mathrm{W}$. Other simulation parameters are the same as those in Subsection IV-A. All results are obtained by varying R from 0.1 to 15 bits in 0.1-bit steps.

In Fig. 4, the EE of the proposed PAS system is compared to that of the conventional systems which have a single PA PA_3 with four-level power control, i.e., $28\,\mathrm{dBm}$, $34\,\mathrm{dBm}$, and $40\,\mathrm{dBm}$, and off-mode. Note that the efficiency of PA_3 decreases as the output power decreases: 60% at $40\,\mathrm{dBm}$, 32% at $34\,\mathrm{dBm}$, and 9% at $28\,\mathrm{dBm}$. From the results, we see that the PAS with multiple PAs can improve the EE significantly. The significant EE improvement is observed especially when R is around $6\,\mathrm{b/s/Hz}$, because the low power PA, which yields high EE improvement, turns on with high probability.

V. Conclusion

In the paper, we survey linearity and efficiency models of practical power amplifiers (PAs) and introduce the technologies to improve the nonlinearity and/or to compensate the efficiency. For energy efficient wireless communications, multiple PAs are proposed to be switched with full or partial channel state information at the transmitter. Numerical results verify that the proposed PA switching (PAS) method can improve energy efficiency significantly. Furthermore, various existing technologies for the high linearity and efficiency of PA which are introduced in the paper can be incorporated in the PAS technology. Hence, the proposed PAS is one promising technology for energy efficient wireless communication systems. A few interesting issues and challenges to extend the PAS are as follows:

- Considering PA memory effects for wideband systems requiring high linearity and high output power.
- Reducing the manufacturing cost and form factor of the circuit with the multiple PAs.
- Applying the PAS to multi-band and to MIMO systems.

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References

[1] G. Fettweis and E. Zimmermann, "ICT Energy consumption? Trends and challenges," in *Proc. IEEE Wireless Personal Multimedia Communications (WPMC)*, Lapland, Finland, Sept. 8–11, 2008.
[2] L. M. Correia, D. Zeller, O. Blume, D. Ferling, Y. Jading, I. Gódor, G. Auer, and L. V. der Perre, "Challenges and enabling technologies for energy aware mobile radio networks," *IEEE Commun. Mag.*, vol. 48, pp.66–72, Nov. 2010.
[3] J. Baliga, R. Ayre, K. Hinton, and R. S. Tucker, "Energy consumption in wired and wireless access networks," *IEEE Commun. Mag.*, vol. 49, pp. 70–77, Jun. 2011.
[4] W. Vereecken, W. V. Heddeghem, M. Deruyck, B. Puype, B. Lannoo, W. Joseph, D. Colle, L. Martens, and P. Demeester, "Power consumption in telecommunication networks: Overview and reduction strategies," *IEEE Commun. Mag.*, vol. 49, pp. 62–69, Jun. 2011.
[5] J. Joung and S. Sun, "Power efficient resource allocation for downlink OFDMA relay cellular networks," *IEEE Trans. Sig. Processing*, vol. 60, pp. 2447–2459, May 2012.
[6] M. Gruber, O. Blume, D. Ferling, D. Zeller, M. A. Imran,"EARTH–Energy aware radio and network technologies," in *Proc. IEEE Personal, Indoor and Mobile Radio Commun. (PIMRC)*, Tokyo, Japan, Sep. 2009.
[7] H. Bogucka and A. Conti, "Degree of freedom for energy savings in practical adaptive wireless systems," *IEEE Commun. Mag.*, vol. 49, pp. 38–45, Jun. 2011.

[8] C.-P. Liang, J.-H. Jong, W. E. Stark, and J. R. East, "Nonlinear amplifier effects in communications systems," *IEEE Trans. Microwave Theory and Techniques*, vol. 47, pp. 1461–1466, Aug. 1999.

[9] F. H. Raab, P. Asbeck, S. Cripps, P. B. Kenington, Z. B. Popović, N. Pothecary, J. F. Sevic, and N. O. Sokal, "RF and microwave power amplifier and transmitter technologies–Part 2," *High Frequency Electronics*, pp. 22–36, May 2003.

[10] F. H. Raab, P. Asbeck, S. Cripps, P. B. Kenington, Z. B. Popović, N. Pothecary, J. F. Sevic, and N. O. Sokal, "Power amplifiers and transmitters for RF and microwave," *IEEE Trans. Microwave Theory and Techniques*, vol. 50, pp. 814–826, Mar. 2002.

[11] J. Vuolevi, T. Rahkonen, and J. Manninen, "Measurement technique for characterizing memory effects in RF power amplifiers," in *Proc. IEEE Radio and Wireless Conf. (RAWCON)*, Colorado, USA, Sep. 2000, pp. 195–198.

[12] S. Boumaiza and F. Ghannouchi, "Thermal memory effects modeling and compensation in RF power amplifiers and predistortion linearizers," *IEEE Trans. Microwave Theory and Techniques*, vol. 51, pp. 2427–2433, Dec. 2003.

[13] M. Gadringer, H. Arthaber, M. Mayer, and G. Magerl, "Modeling, analysis and classification of a PA based on identified Volterra kernels," in *Proc. Gallium Arsenide and Other Semiconductor Application Symposium (GAAS)*, Paris, France, Oct. 2005, pp. 405–408.

[14] D. R. Morgan, Z. Ma, J. Kim, M. G. Zierdt, and J. Pastalan, "A generalized memory polynomial model for digital predistortion of RF power amplifiers," *IEEE Trans. Sig. Processing*, vol. 54, pp. 3852–3860, Oct. 2006.

[15] J. Kim and K. Konstantinou, "Digital predistortion of wideband signals based on power amplifier model with memory," *Electronics Lett.*, vol. 27, pp. 1417–1418, Nov. 2001.

[16] M. C. Jeruchim, P. Balaban, and K. S. Shanmugan, *Simulation of Communication Systems: Modeling, Methodology, and Techiniques*, New York: Springer, 2000.

[17] A. A. M. Saleh, "Frequency-independent and frequency-dependent nonlinear models of TWT amplifiers," *IEEE Trans. Commun.*, vol. 29, pp. 1715–1720, Nov. 1981.

[18] A. Ghorbani and M. Sheikhan, "The effect of solid state power amplifiers (SSPAs) nonlinearities on MPSK and M-QAM signal transmission," in *Proc. Inter. Conf. Digital Processing of Signals in Communications*, Loughborough, UK, Sep. 1991, pp. 193–197.

[19] C. Rapp, "Effects of HPA-nonlinearity on a 4-DPSWOFDM signal for a digital sound broadcasting system," in *Proc. Second European Conference on Satellite Communications*, Lihge, Belgium, Oct. 1991, pp. 179–184.

[20] J. Tellado, L. M. C. Hoo, and J. M. Cioffi, "Maximum-likelihood detection of nonlinearly distorted multicarrier symbols by iterative decoding," *IEEE Trans. Communications*, vol. 51, pp. 218–228, Feb. 2003.

[21] M. K. Kazimierczuk, *RF Power Amplifiers*, UK: John Wiley & Sons, 2008.

[22] J. Joung, C. K. Ho, and S. Sun, "Tradeoff of spectral and energy efficiencies: Impact of power amplifier on OFDM systems," accepted *Proc. IEEE Global Telecommunications Conference (GLOBECOM)*, Anehighhm, USA, Dec. 2012.

[23] J. Joung, C. K. Ho, and S. Sun, "Spectral efficiency and energy efficiency of OFDM systems: Impact of power amplifiers and countermeasures," submitted to *IEEE J. Sel. Areas Commun.*, Apr. 2012.

[24] A. Shirvani, D. K. Su, and B. A. Wooley, "A CMOS RF power amplifier with parallel amplification for efficient power control," *IEEE J. Solid-State Circuits*, vol. 27, pp. 684–693, Jun. 2002.

[25] F. H. Raab, "Efficiency of Doherty RF power-amplifier systems," *IEEE Trans. Broadcast*., vol. BC-33, pp. 77–83, Sep. 1987.

[26] Y. Yang, J. Cha, B. Shin, and B. Kim, "A fully matched N-way Doherty amplifier with optimized linearity," *IEEE Trans. Microwave Theory And Techniques*, vol. 51, pp. 986–993, Mar. 2003.

[27] F. H. Raab, P. Asbeck, S. Cripps, P. B. Kenington, Z. B. Popović, N. Pothecary, J. F. Sevic, and N. O. Sokal, "RF and microwave power amplifier and transmitter technologies–Part 3," *High Frequency Electronics*, pp. 34–48, May 2003.

[28] S. C. Cripps, *RF Power Amplifiers for Wireless Communications*, Boston/London: ARTECH HOUSE, 2nd ed., 2006.

[29] J. Staudinger, "Applying switched gain stage concepts to improve efficiency and linearity for mobile CDMA power amplification," *Microwave Journal*, vol. 43, pp. 152–162, Sep. 2000.

[30] L. Kahn, "Single-sideband transmission by envelope elimination and restoration," *IEEE Proceedings of the Institute of Radio Engineers (IRE)*, vol. 40, pp. 803–806, Jul. 1952.

[31] D. Cox, "Linear amplification with nonlinear components," *IEEE Trans. Commun.*, vol. 22, pp. 1942–1945, Dec. 1974.

[32] W. H. Doherty, "A new high efficiency power amplifier for modulated waves," *IEEE Proceedings of the Institute of Radio Engineers (IRE)*, vol. 24, pp. 1163–1182, Sep. 1936.

[33] J. Cha, J. Kim, B. Kim, J. S. Lee, and S. H. Kim, "Highly efficient power amplifier for CDMA base stations using Doherty configuration," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Jun. 2004, pp. 553–556.

[34] G. Auer, V. Giannini, C. Desset, I. Godor, P. Skillermark, M. Olsson, M. A. Imran, D. Sabella, M. J. Gonzalez, O. Blume, and A. Fehske, "How much energy is needed to run a wireless network?" *IEEE Wireless Communications*, vol. 18, pp. 40–49, Oct. 2011.

[35] O. Arnold, F. Richter, G. Fettweis, and O. Blume, "Power consumption modeling of different base station types in heterogeneous cellular networks," in *Proc. IEEE Future Network and Mobile Summit 2010*, Florence, Italy, Jun, 2010.

[36] S. Kowlgi and C. Berland, "Linearity considerations for multi-standard cellular base station transmitters," in *Proc. IEEE Microwave Conf. (EuMC)*, Manchester, UK, Oct. 2011, pp. 226–229.

[37] T. Jiang and Y. Wu, "An overview: Peak-to-average power ratio reduction techniques for OFDM signals," *IEEE Trans. Broadcasting*, vol. 54, pp. 257–268, Jun. 2008.

[38] N. Pothecary, *Feedforward Linear Power Amplifiers*, Norwood, MA: Artech House, 1999.

[39] P. B. Kenington, *High Linearity RF Amplifier Design*, Norwood, MA: Artech House, 2000.

[40] Y. Chen, S. Zhang, S. Xu, and G. Y. Li, "Fundamental trade-offs on green wireless networks," *IEEE Commun. Mag.*, vol. 49, pp. 30–37, Jun. 2011.

[41] F. Richter, A. J. Fehske, and G. P. Fettweis, "Energy efficiency aspects of base station deployment strategies for cellular networks," in *Proc. IEEE Vehicular Technology Conference (VTC-Fall)*, Alaska, USA, Sep. 2009.

[42] Z. Niu, Y. Wu, J. Gong, and Z. Yang, "Cell zooming for cost-efficient green cellular networks," *IEEE Commun. Mag.*, vol. 48, pp.74–79, Nov. 2010.

[43] Koichi Adachi and Sumei Sun, "Power-Efficient Dynamic BS Muting in Clustered Cellular System," in *Proc. IEEE Personal, Indoor and Mobile Radio Communications (PIMRC)*, Sydney, Australia, Sep. 2012.

[44] K. Abdallah, I. Cerutti, and P. Castoldi, "Energy-efficient coordinated sleep of LTE cells," in *Proc. IEEE Inter. Conf. Commun. (ICC)*, Ottawa, Canada, Jun. 2012, pp. 6760–6764.

[45] A. Bousia, A. Antonopoulos, L. Alonso, and C. Verikoukis, "Green distance-aware base station sleeping algorithm in LTE-advanced," in *Proc. IEEE Inter. Conf. Commun. (ICC)*, Ottawa, Canada, Jun. 2012, pp. 1267–1371.

[46] R. Irmer, H. Droste, P. Marsch, M. Grieger, G. Fettweis, S. Brueck, H.-P. Mayer, L. Thiele, and V. Jungnickel, "Coordinated multipoint: Concepts, performance, and field trial results," *IEEE Commun. Mag.*, vol. 49, pp. 102–111, Feb. 2011.

[47] S. Han, C. Yang, G. Wang, and M. Lei, "On the energy efficiency of base station sleeping with multicell cooperative transmission," in *Proc. IEEE Personal Indoor and Mobile Radio Communications (PIMRC)*, Toronto, Canada, Sep. 2011, pp. 1536–1540.

[48] P. Frenger, P. Moberg, J. Malmodin, Y. Jading, and I. Godor, "Reducing energy consumption in LTE with cell DTX," in *Proc. IEEE Veh. Technol. Conf. (VTC)*, Budapest, Hungari, May 2011.

[49] K. Adachi, J. Joung, S. Sun, and P. H. Tan, "Energy-saving coordinated napping (CoNap) for wireless networks," accepted, *IEEE Workshop Global Telecommunications Conference (GLOBECOM)*, Anehighhm, USA, Dec. 2012.

[50] S. Tombaz, A. Västberg, and J. Zander, "Energy- and cost-efficient ultra-high-capacity wireless access," *IEEE Wireless Commun.*, vol. 18, pp. 18–24, Oct. 2011.

[51] Z. Hasan, H. Boostanimehr, V. K. Bhargava, "Green cellular networks: A survey, some research issues and challenges," *IEEE Communications Surveys & Tutorials*, vol. 13, pp. 524–540, Forth quarter 2011.

[52] S. Verdú, "Spectral efficiency in the wideband regime," *IEEE Trans. Inf. Theory*, vol. 48. no. 6, pp. 1319–1343, Jun. 2002.

[53] T. M. Cover and J. A. Thomas, *Elements of Information Theory*, 2nd ed., New Jersey, John Wiley & Sons, 2006.

[54] J. Joung, C. K. Ho, and S. Sun, “Power amplifier switching (PAS) for energy efficient systems,” accepted, *IEEE Wireless Communications Lett.*, Sep. 2012.
[55] A. Papoulis and S. Pillai, *Probability, Random Variables and Stochastic Processes*, 4th ed., McGraw-Hill, 2002.
[56] R. V. Raja Kumar and J. Gurugubelli, “How green the LTE technology can be?” in *Proc. IEEE Wireless Communication, Vehicular Technology, Information Theory and Aerospace & Electronic Systems Technology (Wireless VITAE)*, Chennai, India, Feb.–Mar., 2011.
[57] M. Deruyck, W. Vereecken, E. Tanghe, W. Joseph, M. Pickavet, L. Martens, and P. Demeester, “Comparison of power consumption of mobile WiMAX, HSPA and LTE access networks,” in *Proc. IEEE Telecommunications Internet and Media Techno Economics (CTTE)*, Gent, Belgium, Jun. 2010.
[58] I. Gutman, I. Iofedov, and D. Wulich, “Rate increase in digital communications by using master-slave power amplifiers,” in *Proc. IEEE Personal, Indoor and Mobile Radio Commun. (PIMRC)*, Sydney, Australia, Sep. 2012, pp. 2450–2455.
[59] LTE; E-UTRA; RF requirements for LTE Pico Node B (ETSI Tech Rep. 136 931 V9.0.0). [Online] Available: http://www.etsi.org/deliver/
[60] H. A. David, *Order Statistics*, New York: Wiley, 1970.
[61] J. G. Proakis and M. Salehi, *Digital Communications*. New York: McGraw-Hill, 5th ed., 2007
[62] Data sheet, “SKY65162-70LF: 400-2700 MHz linear power amplifier” SKYWORKS, [Online] Available: http://www.skyworksinc.com
[63] J. Kim, J. Cha, I. Kim, and B. Kim, “Optimum operation of asymmetrical-cells-based linear Doherty power amplifiers-uneven power drive and power matching,” *IEEE Trans. Microwave Theory and Techniques*, vol. 53, pp. 1802–1809, May 2005.
[64] V. Viswanathan, *Efficiency enhancement of base station power amplifiers using Doherty technique*, Thesis, Virginia Polytechnic Institute and State University, Feb. 2004.