

COMMUNICATION DEVICES AND METHODS FOR CONTROLLING A COMMUNICATION DEVICE

Cross-reference to Related Applications

[0001] The present application claims the benefit of the Singapore patent application No. 201203471-6 filed on 11 May 2012, the entire contents of which are incorporated herein by reference for all purposes.

Technical Field

[0002] Embodiments relate generally to communication devices and methods for controlling a communication device.

Background

[0003] Wireless access communication networks consume significant amount of energy to overcome fading and interference, compared to fixed line networks. In wireless networks, energy is mostly consumed at the transmitter, of which 50%-80% of power consumption is consumed at power amplifiers (PAs). However, the PA efficiency is typically between 20% and 30%, which confirms that the overhead incurred at PA is substantial. Thus, there may be a need for more efficient transmitters.

Summary

[0004] According to various embodiments, a communication device may be provided. The communication device may include: a plurality of power amplifiers in a radio frequency transmit chain; a power amplifier selection circuit configured to determine for every power amplifier in the radio frequency transmit chain, whether the power amplifier should be used; and a transmitter circuit configured to use the one or more determined power amplifiers for which it has been determined that they should be used for transmitting data.

[0005] According to various embodiments, a method for controlling a communication device may be provided. The method may include: determining for every power amplifier in a radio frequency transmit chain of the communication device, whether the power amplifier should be used; and using the one or more power amplifiers for which it has been determined that they should be used for transmitting data.

[0006] According to various embodiments, a selection criterion determination circuit may be provided. The selection criterion determination circuit may be configured to determine a criterion for which one or more power amplifiers of a plurality of power amplifiers in a radio frequency transmit chain in a communication device should be used.

Brief Description of the Drawings

[0007] In the drawings, like reference characters generally refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention. In the

following description, various embodiments are described with reference to the following drawings, in which:

FIG. 1 shows a communication system in accordance with an embodiment;

FIG. 2 shows a diagram illustrating a commonly used transmitter;

FIG. 3 shows a diagram illustrating a SE-EE tradeoff with an ideal power amplifier;

FIG. 4 shows a diagram illustrating a typical input-output model of a power amplifier;

FIG. 5 shows a diagram 500 illustrating a SE-EE tradeoff with a practical power amplifier;

FIG. 6A shows a communication device according to various embodiments;

FIG. 6B shows a communication device according to various embodiments;

FIG. 6C shows a flow diagram illustrating a method for controlling a communication device according to various embodiments;

FIG. 6D shows a selection criterion determination circuit according to various embodiments;

FIG. 7 shows a diagram illustrating an example of power amplifier switching with two power amplifiers according to various embodiments;

FIG. 8 shows a diagram illustrating SE-EE tradeoff with power amplifier switching;

FIG. 9 shows a diagram illustrating SE-EE tradeoff with power amplifier switching; and

FIG. 10 shows a block diagram showing a transmitter for the power amplifier switching technique, with two power amplifiers and one variable gain amplifier, according to various embodiments.

Description

[0008] Embodiments described below in context of the devices are analogously valid for the respective methods, and vice versa. Furthermore, it will be understood that the embodiments described below may be combined, for example, a part of one embodiment may be combined with a part of another embodiment.

[0009] In this context, the communication device as described in this description may include a memory which is for example used in the processing carried out in the communication device. In this context, the radio communication terminal as described in this description may include a memory which is for example used in the processing carried out in the radio communication terminal. In this context, the access point as described in this description may include a memory which is for example used in the processing carried out in the access point. A memory used in the embodiments may be a volatile memory, for example a DRAM (Dynamic Random Access Memory) or a non-volatile memory, for example a PROM (Programmable Read Only Memory), an EPROM (Erasable PROM), EEPROM (Electrically Erasable PROM), or a flash memory, e.g., a floating gate memory, a charge trapping memory, an MRAM (Magnetoresistive Random Access Memory) or a PCRAM (Phase Change Random Access Memory).

[0010] In an embodiment, a "circuit" may be understood as any kind of a logic implementing entity, which may be special purpose circuitry or a processor executing

software stored in a memory, firmware, or any combination thereof. Thus, in an embodiment, a "circuit" may be a hard-wired logic circuit or a programmable logic circuit such as a programmable processor, e.g. a microprocessor (e.g. a Complex Instruction Set Computer (CISC) processor or a Reduced Instruction Set Computer (RISC) processor). A "circuit" may also be a processor executing software, e.g. any kind of computer program, e.g. a computer program using a virtual machine code such as e.g. Java. Any other kind of implementation of the respective functions which will be described in more detail below may also be understood as a "circuit" in accordance with an alternative embodiment.

[0011] FIG. 1 shows a communication system 100, for example a wireless access communication network, according to various embodiments. A mobile radio base station 102 may communicate with a communication device 104, for example a mobile radio communication device, for example a mobile phone, like indicated by arrow 106.

[0012] FIG. 2 shows a diagram 200 illustrating a commonly used transmitter (which may be a communication device, for example a radio communication device, for example a mobile phone) of wireless communication systems. The transmitter may include a base band (BB) module 202, and a RF module 204. The transmitter may further include an antenna 226. Block 206 shows transceiver antennas and a channel 228, for example a wireless communication channel. An antenna 230 at the receiver may receive the data and may provide them to the receiver (for example another communication device, for example a base station). 226 may indicate a transmitter feeder loss that may be an attenuation between actual transmit antenna feeder and transmitter, i.e., 204. 230 may be a receiver feeder loss that is an attenuation between actual receive antenna and a receiver,

i.e., 208. The feeder loss may depend mainly on length and dimension of feeder, and also may depends on frequency. The BB module 202 may include a circuit 210 (for example an ASIC (application-specific integrated circuit), an FPGA (field-programmable gate array), or a DSP (digital signal processor)) configured to perform one or more of the following: digital up-converting, digital pre-distorting, scrambling, CRC (cyclic redundancy check), convolution encoding, interleaving, modulation, IFFT (inverse fast Fourier transformation), add CP (cyclic prefix), and/ or perform P-to-S (parallel to serial) translation. A DAC (digital analogue converter) 212 may provide input from the BB module 202 to a filter 214, which may be connected to a mixer 216. Further, a synthesizer 218 may be connected to the mixer 216. An output of the mixer 216 may be provided to a further filter 220, and further to a VGA 222 (variable gain amplifier) and a PA 224.

[0013] Wireless access communication networks consume significant amount of energy to overcome fading and interference, compared to fixed line networks. In wireless networks, energy is mostly consumed at the transmitter, of which 50%-80% of power consumption is consumed at power amplifiers (PAs). However, the PA efficiency is typically between 20% and 30%, which confirms that the overhead incurred at PA is substantial. To ensure high energy efficiency (EE) in the communication systems, the PA characteristics have to be carefully considered in the transmitter designs.

[0014] On the other hand, high spectral efficiency (SE) may be desired to support the growing demands of high data traffic. To support high SE in wireless fading channels, orthogonal frequency division multiplex (OFDM) and orthogonal frequency division multiple access (OFDMA) systems remain as popular choices. However, OFDM and

OFDMA modulated signals exhibit high peak-to-average power ratio (PAPR), resulting in severe nonlinear effects and SE degradation. To circumvent the resulting performance degradation, input backoff (IBO) may be implemented by reducing the input power. In order to retain high SE, the technique of IBO in turn results in a reduction of EE, because PA operates at high efficiency when it is near its power saturation point. Hence, a SE-EE tradeoff exists when the optimization is performed with respect to the PA. It may thus be desired to jointly study the role that a PA plays in both SE and EE of wireless communication systems. To quantify the impact of PA on the degradation of both SE and EE, the PA is modelled accurately and tractably on PA's (i) nonlinearity behaviour, and PA's (ii) imperfect efficiency to specify the relationship of PA power consumption P_{PA} and the transmission power P_{out} . For the nonlinearity, the PA is modelled by a soft limiter, i.e., the output is clipped to a constant if the input signal exceeds a threshold value, and experiences a linear scaling of its input otherwise. For the efficiency model of PA, PA-dependent (Class A, Class B, and Doherty types) nonlinear power consumption models are established. As a consequence, practical SE, EE, and their tradeoff have been observed.

[0015] From the analysis and numerical evaluation, it may be observed that the practical PA supports a narrow SE-EE tradeoff with only a limited range of SE. A wide range of SE-EE tradeoff may be desired because the required data rates (equivalent to SE) vary dynamically and, yet high EE is required always. In other words, the commonly used transmitter structure where only a single PA is activated always regardless of the required SE is inefficient in terms of the EE. According to the dynamic request of SE and the dynamic characteristics of the wireless channels, the desired SE is also dynamically

varying. When the required SE is low, a better PA may exist which can improve the EE while achieving the desired SE. Various devices and methods may be provided to use multiple PAs and to use a PA switching technique according to various embodiments. Throughout the PA switching technique according to various embodiments, one or more PAs may be switched on at any time between frames (or slots). As a result, the degree of freedom offered from the multiple PAs yields a high EE over a wide range of SE. Numerical results show that the SE-EE tradeoff improvement is significant even with the practical losses such as switch insertion loss and switching time overhead.

[0016] In wireless communications between one transmitter and one receiver, if the PA at the transmitter is ideal, the SE and EE may be defined as follows

$$\begin{aligned} \text{SE}(\xi) &= \log_2(1 + \gamma\xi) \\ \text{EE}(\xi) &= \frac{T\Omega \text{SE}(\xi)}{TP_c} = \frac{\Omega \text{SE}(\xi)}{P_c} \end{aligned}$$

where

- SE represents an achievable sum rate, i.e., the amount of bits that are reliably decoded per channel use, in b/s/Hz
- T is the total time used
- Ω is the total bandwidth used
- P_c is the total power consumption including the PA power consumption P_{PA}
- EE represents the total amount of reliably decoded bits normalized by the energy in b/J
- ξ is power ratio defined as $P_{\text{in}}/P_{\text{in}}^{\text{max}}$ where P_{in} is PA input power and $P_{\text{in}}^{\text{max}}$ is maximum allowable PA input power corresponding to the maximum PA output power $P_{\text{out}}^{\text{max}}$
- γ is a maximum power output normalized by the noise variance σ_z^2 , i.e., $P_{\text{out}}^{\text{max}}/\sigma_z^2$
- $\gamma\xi = \frac{uP_c}{\sigma_z^2}$

[0017] In this case, the SE-EE tradeoff may be as shown in FIG.3.

[0018] FIG. 3 shows a diagram 300 illustrating a SE-EE tradeoff with an ideal PA. SE may be indicated by a horizontal axis 302, and EE may be indicated by a vertical axis 304. The relation between SE and EE is shown in curve 306. A maximum value 308 of EE may be $1/(\sigma^2 \ln 2)$. Like indicated by dashed arrow 310, there may be a wide tradeoff range.

[0019] The ideal SE-EE tradeoff in FIG. 3 may be wide enough to accommodate the dynamic SE. However, the practical SE-EE tradeoff may have a different shape from that in FIG. 3 because a PA may not be ideal in practice. The practical PA may be modelled as a soft limiter as follows:

$$L_{PA}(a_t) = \begin{cases} \sqrt{g}a_t, & \text{if } a_t < \sqrt{P_{in}^{max}} : \text{no clipping} \\ \sqrt{P_{out}^{max}}, & \text{if } a_t \geq \sqrt{P_{in}^{max}} : \text{clipping} \end{cases}$$

where a positive real value g is a parameter interpreted as the desired linear gain. The soft limiter model is illustrated in FIG. 4.

[0020] FIG. 4 shows a diagram 400 illustrating a typical input-output model of a power amplifier. Output power P_{out} (shown on a vertical axis 404) may be plotted in a curve 406 over input power P_{in} (shown on a horizontal axis 402).

[0021] Using the soft limiter model of PA, the practical SE and EE may be derived as follows:

$$SE(\xi) = H(Y) - \log_2 \pi e \sigma_z^2 \quad (1)$$

where the entropy of the received time-domain signal y is

$$H(Y) = - \int_y f_Y(y) \log_2 f_Y(y) dy \quad (2)$$

and $f_Y(y)$ may be a probability density function (pdf) of y . Using a binary random variable $S=\{0,1\}$ denoting whether clipping happens or not, i.e., $S=1$ if there is clipping and $S=0$ otherwise, the pdf of y can be rewritten as

$$f_Y(y) = f_Y(y, S=0) + f_Y(y, S=1) \quad (3)$$

and the joint pdfs may be derived as follows:

$$f_Y(y, S=0) = N_0(y)[1 - Q_1(\sqrt{\mu}, \sqrt{\rho_{\max}})] \quad (4)$$

$$f_Y(y, S=1) = N_1(y) \left[\Pr(S=1) \exp\left(\frac{-2b_{\max} y_{\text{Re}}}{\sigma_z^2}\right) I_0\left(\frac{2b_{\max} |y|}{\sigma_z^2}\right) \right] \quad (5)$$

where

- $N_0(y)$ denotes the pdf of $\mathcal{CN}(0, gP_m + \sigma_z^2)$
- $b_{\max} = \sqrt{P_{\text{out}}^{\max}}$
- $Q_1(\cdot, \cdot)$ is the Marcum-Q-function with parameters $\rho_{\max} \triangleq \frac{2(gP_m + \sigma_z^2)}{gP_m} \sqrt{b_{\max}}$ and $\mu(y) \triangleq \frac{8gP_m(gP_m + \sigma_z^2)}{\sigma_z^4} |y|^2$
- $N_1(y)$ is the pdf of $\mathcal{CN}(b_{\max}, \sigma_z^2)$
- y_{Re} is the real part of y
- $I_0(\cdot)$ is the modified Bessel function of first kind

[0022] On the other hand, the practical EE may be derived as

$$EE(\xi) = \frac{\Omega SE(\xi)}{P_c(\xi)} \quad (6)$$

where

$$P_c(\xi) = P_{\text{fix}} + c_0 \left(c_1 + c_2 \sqrt{\xi} \right) P_{\text{out}}^{\max} \quad (7)$$

[0023] Here, P_{fix} may be a fixed power consumption including power supply (PS) loss, cooling and battery (CB) backup loss, base band (BB) power consumption and radio frequency (RF) power consumption and it may be modelled as

$$P_{\text{fix}} = (1 + C_{\text{PS}})(1 + C_{\text{CB}})(P_{\text{BB}} + P_{\text{RF}}). \quad (8)$$

[0024] The fixed power in equation (8) may be measured empirically. The coefficient c_0 may be depending on the communication coverage, i.e., PA max power, and c_1 and c_2 may be depending on the PA types. For l -way Doherty PA, they may be modelled as follows:

$$(c_1, c_2) = \frac{4}{\ell\pi} \times \begin{cases} (0, 1), & 0 < \xi \leq \frac{1}{\ell^2}, \\ (-1, \ell + 1), & \frac{1}{\ell^2} < \xi \leq 1. \end{cases} \quad (9)$$

where l may be a positive integer, and $l=1$ if the PA is Class B type.

[0025] From the practical SE-EE tradeoff, the practical EE may increase before a turning point and may decrease rapidly after the turning point as shown in FIG. 5.

[0026] FIG. 5 shows a diagram 500 illustrating a SE-EE tradeoff with a practical PA. SE may be indicated by a horizontal axis 502, and EE may be indicated by a vertical axis 504. The relation between SE and EE is shown in curve 506. Like indicated by arrow 508, there may only be a narrow tradeoff range.

[0027] The single PA may support a narrow SE-EE tradeoff in practice with only a limited range of SE. For example, the EE improvement may be marginal when the SE is decreased. This problem may be resolved by switching the PA according to various embodiments, which may be called a PA switching.

[0028] According to various embodiments, a power amplifier switching technique for energy efficient transmission may be provided.

[0029] FIG. 6A shows a communication device 600 according to various embodiments. The communication device 600 may include a plurality of power amplifiers 602 in a radio frequency (RF) transmit chain. The communication device 600

may further include a power amplifier selection circuit 604 configured to determine for every power amplifier in the radio frequency transmit chain, whether the power amplifier should be used. The communication device 600 may further include a transmitter circuit 606 configured to use the one or more power amplifiers for which it has been determined that they should be used for transmitting data. The plurality of power amplifiers 602, the power amplifier selection circuit 604, and the transmitter circuit 606 may be coupled with each other, for example via a connection 608, for example an optical connection or an electrical connection, such as for example a cable or a computer bus or via any other suitable electrical connection to exchange electrical signals.

[0030] According to various embodiments, the communication device may have a plurality of RF transmit chains, and the determination may be performed (for example separately) for each of the RF transmit chains.

[0031] The communication device 600 may for example be a mobile radio communication device, for example a mobile phone.

[0032] According to various embodiments, the communication device 600 may further include a single common variable gain amplifier (not shown) in the RF transmit chain configured to be used with each of the plurality of power amplifiers 602.

[0033] According to various embodiments, the communication device 600 may further include a plurality of variable gain amplifiers (not shown) for multiple RF transmit chains, wherein each variable gain amplifier of the plurality of variable gain amplifiers is configured to be used with one of the plurality of power amplifiers 602 per a RF transmit chain.

[0034] FIG. 6B shows a communication device 610 according to various embodiments. The communication device 610 may, similar to the communication device 600 of FIG. 6A, include a plurality of power amplifiers 602. The communication device 610 may, similar to the communication device 600 of FIG. 6A, further include a power amplifier selection circuit 604 configured to determine for every power amplifier in the radio frequency transmit chain, whether the power amplifier should be used. The communication device 600 may, similar to the communication device 600 of FIG. 6A, further include a transmitter circuit 606 configured to use the one or more power amplifiers for transmitting data. The communication device 610 may further include a selection criterion determination circuit 612, like will be described in more detail below. The communication device 610 may further include a switch 614, like will be described in more detail below. The plurality of power amplifiers 602, the power amplifier selection circuit 604, the transmitter circuit 606, the selection criterion determination circuit 612, and the switch 614 may be coupled with each other, for example via a connection 616, for example an optical connection or an electrical connection, such as for example a cable or a computer bus or via any other suitable electrical connection to exchange electrical signals.

[0035] According to various embodiments, the selection criterion determination circuit 612 may be configured to determine a criterion for which one or more power amplifiers of the plurality of power amplifiers 602 in the RF transmit chain should be used.

[0036] According to various embodiments, the power amplifier selection circuit 604 may further be configured to determine which one or more power amplifiers of the

plurality of power amplifiers 602 in the RF transmit chain should be used based on the determined criterion.

[0037] According to various embodiments, the criterion may include or may be an indicator. The indicator may include or may be at least one of a signal to noise ratio of a communication of the communication device; a sharing factor indicating which of the plurality of power amplifiers 602 should be used in the RF transmit chain for which fraction of time; or power amplifiers' indices.

[0038] According to various embodiments, the switch 614 may be configured to selectively connect the determined one or more power amplifiers in a transmission path of the communication device 610.

[0039] According to various embodiments, at any time, one or more power amplifiers of the communication device 610 may be used.

[0040] FIG. 6C shows a flow diagram 618 illustrating a method for controlling a communication device according to various embodiments. In 620, it may be determined for every power amplifier in a radio frequency transmit chain of the communication device, whether the power amplifier should be used. In 622, the one or more power amplifiers for which it has been determined that they should be used may be used for transmitting data.

[0041] A single common variable gain amplifier may be used with at least one of the plurality of power amplifiers in the RF transmit chain.

[0042] According to various embodiments, the method may further include determining a criterion for which one or more power amplifiers of the plurality of power amplifiers should be used in the RF transmit chain.

[0043] According to various embodiments, the method may further include determining which one or more power amplifiers of the plurality of power amplifiers in the RF transmit chain should be used based on the determined criterion.

[0044] According to various embodiments, the criterion may include or may be an indicator. The indicator may include or may be at least one of a signal to noise ratio of a communication of the communication device; a sharing factor indicating which of the plurality of power amplifiers in the RF transmit chain should be used for which fraction of time; or power amplifiers' indices.

[0045] According to various embodiments, the method may further include selectively connecting the determined one or more power amplifiers in a transmission path of the communication device.

[0046] According to various embodiments, at any time, one or more power amplifiers of the communication device may be used.

[0047] FIG. 6D shows a selection criterion determination circuit 624 according to various embodiments. The selection criterion determination circuit 624 may be configured to determine a criterion for which one or more power amplifiers of a plurality of power amplifiers in a RF transmit chain in a communication device should be used.

[0048] The criterion may include or may be an indicator. The indicator may include or may be at least one of a signal to noise ratio of a communication of the communication device; a sharing factor indicating which of the plurality of amplifiers per RF transmit chain should be used for which fraction of time; or power amplifiers' indices.

[0049] According to various embodiments, the selection criterion determination circuit 624 may be configured to be provided in the communication device.

[0050] According to various embodiments, the selection criterion determination circuit 624 may be configured to be provided in a further communication device in communication with the communication device.

[0051] According to various embodiments, a power amplifier (PA) switching technique may be provided, in which one or more PAs may be switched on intermittently to maximize the energy efficiency (EE) and yet deliver the overall required spectral efficiency (SE). For the selection of which PA to switch on, the received signal-to-noise ratio (SNR) information or PA time sharing factor may be fed back to the transmitter from the receiver. Based on the feedback information, the transmitter may switch on/off the PAs in a PA bank. From the numerical evaluation, it may be verified that the better SE-EE tradeoff may be achieved by the PA switching technique according to various embodiments, even by taking into account the practical losses such as the switch insertion loss and switching time overhead. For example, if SE is reduced by 15% with a single PA (100W maximum output power), the EE may be improved by 69% in the commonly used systems. In contrast, if the PA switching technique according to various embodiments is used, with one additional PA (25W maximum output power), EE may be improved by 323% with the same SE reduction.

[0052] For example, an arbitrary number of PAs may be activated according to the objective of the communications. For example, high and reliable communications, multiple PAs may be activated. For high energy efficiency, a single proper PA may be activated.

[0053] According to various embodiments, a power amplifier switching technique may be provided like will be described in more detail below.

[0054] For simplicity of description, two PAs, (for example a first PA, which may be referred to as PA-1, and a second PA, which may be referred to as PA-2) may be considered (in other words: description may be provided for the case of two PAs only). However, it will be understood that what is described for two PAs may be applied to any number of PAs, for example to multiple PAs.

[0055] FIG. 7 shows a diagram 700 illustrating an example of PA switching with two PA (a first PA (PA-1) and a second PA (PA-2) according to various embodiments. Time may be understood to run from left to right, like indicated by arrow 714.

[0056] FIG. 7 illustrates the PA switching between two PAs. For example, K frames may be considered, each frame with length of T. It may be assumed that the first PA (PA-1) is used for the first k frames (illustrated by dots 702, frame (k-1) 704 and frame (k) 706), then the first PA (PA-1) may be switched to the second PA (PA-2) (indicated by switching overhead ϵ 708, and finally the second PA (PA-2) may be used for the remaining (K-k) frames (indicated by frame (k+1) 710 and dots 712). Two practical factors which decrease the SE and EE may be considered in the implementation of the PA switching technique:

- Switch insertion loss: L_s (dB), which may be the attenuation between input and output ports of the switch. It may be inevitable loss when a switch is used for PA; and
- Switching time overhead: ϵ (sec)

[0057] It is to be noted that the switch circuit itself always may incur the insertion loss, while the switching time effect may be ignored when there is enough number of frames. For example, for frequency division duplex (FDD) systems, the switching time

effect with more than 20 FDD frames may be ignored. For example for time division duplex (TDD) systems, in which the downlink (DL) and uplink (UL) frames may be transmitted alternately from base station (BS) to the communication devices (for example to the user equipment (UE)) and from UE to BS, the switching time may be ignored because the PA may be switched between two consecutive DL frames. It is to be noted that the typical frame length is 10 to 20ms, while typically only a few micro seconds (μ s) is required for the switching.

[0058] A time sharing factor may be defined as

$$\eta \triangleq \frac{k}{K}, 0 \leq \eta \leq 1$$

[0059] The achievable SE and EE from PA switching may be derived as follows:

$$\begin{aligned} SE_s(\xi, \eta) &= \frac{kTSE_1(\xi) + (K - k)TSE_2(\xi)}{KT + \epsilon} \\ &= \frac{KT}{KT + \epsilon} (\eta SE_1(\xi) + (1 - \eta)SE_2(\xi)) \end{aligned} \quad (10)$$

and

$$\begin{aligned} EE_s(\xi, \eta) &= \frac{KT\Omega SE_s(\xi, \eta)}{kTP_c^1(\xi) + (K - k)TP_c^2(\xi)} \\ &= \frac{KT}{KT + \epsilon} \left(\frac{EE_1(\xi)EE_2(\xi) (\eta SE_1(\xi) + (1 - \eta)SE_2(\xi))}{\eta SE_1(\xi)EE_2(\xi) + (1 - \eta)SE_2(\xi)EE_1(\xi)} \right) \end{aligned} \quad (11)$$

where the $SE_1(\xi)$ and $SE_2(\xi)$ may be SE with the PA insertion loss L_s dB and the $EE_1(\xi)$ and $EE_2(\xi)$ are the corresponding EEs. The $SE_1(\xi)$ and $SE_2(\xi)$ may be obtained from (1)-(5). The $EE_1(\xi)$ and $EE_2(\xi)$ in (11) may be obtained from (6)-(9). Here, $\epsilon=0$ if $\eta=0$ or $\eta=1$ (i.e., there is no switching), and $\epsilon>0$ otherwise. Specifically, only the first PA (PA-1) may be turned on if $\eta=1$, and PA-2 if $\eta=0$. Although the PA switching may incur a switch insertion loss and an overhead of switching time, a better tradeoff of SE-EE may be

achieved due to the increased degree of freedom of choosing different PAs as verified in the computer simulation.

[0060] In the following, numerical results for a simulation with two PAs will be described.

[0061] The simulation environments may be summarized as follows:

- PA-1: Low power PA PA^{low} with $P_{out}^{max} = 25W$ and $g = 55dB$;
- PA-2: Highpower PA PA^{high} with $P_{out}^{max} = 100W$ and $g = 50dB$;
- Bandwidth: 10 MHz;
- The channel attenuation is modeled: $G - 128 + 10\log_{10}(d^{-\alpha})dB$;
 - $G = 5dB$ includes the transceiver feeder loss and antenna gains;
 - $d = 200m$ is the distance in kilometres between a transmitter and a receiver;
 - $\alpha = 3.76$ is a path loss exponent;
- Noise variance: $\sigma_z^2 = -174dBm / Hz$;
- Power consumption model: $c_0 = 4.7$ and $P_{fix} = 130W$;
- PA switching frequency: once in 20 frames;
- Frame length: 10 ms.

It will be understood that the simulation parameters for PA-1 and PA-2 may be determined to be any suitable value. For example, P_{out}^{max} and g may be set up with arbitrary values.

[0062] FIG. 8 shows a diagram 800 illustrating SE-EE tradeoff with switching PA^{low} and PA^{high} frame length is 10ms, and 20 frames are transmitted. SE may be indicated by a horizontal axis 802, and EE may be indicated by a vertical axis 804.

[0063] FIG. 8 shows the SE-EE tradeoff in various cases. As described above, the switch insertion loss, 1dB, may cause non-negligible EE and SE degradation, however, the switching time overhead may yield negligible degradation. This may be because the frame length in time is typically larger than the switching time. For example, the considered frame length in the simulation may follow the long 3GPP-LTE (Third Generation Project Partnership – Long Term Evolution) specification, which may be 10ms.

[0064] From top to bottom of legend of Fig. 8, let us call system 1 to 8. System 1 uses only a low power PA. System 2 uses only a low power PA with a switch. System 3 uses only a high power PA. System 4 uses only a high power PA with a switch. The numerical results of Systems 2 and 4 are included to see the effect of the 'switch insertion loss' that is assumed to be 1dB. System 5 uses both high and low power PAs with switch yet without switch insertion loss and switching time overhead, which is the reason why System 5 is ideal. Systems 6, 7, and 8 use both high and low power PAs with insertion loss 1 dB and with various switching time overhead, i.e., 0 usec, 10 usec, and 1ms. For comparison, ideal switching with $L_s=0\text{dB}$ and $\epsilon=0$ may be evaluated. From the results, it may be verified that the PA switching may improve the SE-EE tradeoff significantly even with the switch insertion loss and the switching time overhead that is 10% of the frame size. For simplicity, the fraction of time when any PA is switched on may be a continuous value from 0 to 1. As a result, the EE improvement may be as follows: For example,

- PA switching technique according to various embodiments with two PAs, i.e., PA^{low} and PA^{high}
 - A→B: EE improvement **210%**, SE reduction 12%

- $A \rightarrow C$: EE improvement 323%, SE reduction 15%
- Commonly used method with a single PA, i.e., PA^{high}
 - $A \rightarrow D$: EE improvement 41%, SE reduction 12%
 - $A \rightarrow E$: EE improvement 69%, SE reduction 15%

[0065] In the following, a PA switching strategy according to various embodiments will be described.

[0066] For comparison, the block diagram of commonly used communication systems with a single PA as illustrated in FIG. 2 and described above may be used. Regardless of the target SE and signal-to-noise ratio (SNR), according to FIG. 2, the same PA may always be activated. The PA input signal may be controlled by the VGA (variable gain amplifier) to be operated in the PA's linear region. It is to be noted that the commonly used mechanism for VGA may be based on the power of input signal x .

[0067] FIG. 9 shows a diagram 900 illustrating a SE-EE tradeoff with switching PA^{low} and PA^{high} , wherein frame length is 10ms, and 20 frames are transmitted. SE may be indicated by a horizontal axis 902, and EE may be indicated by a vertical axis 904. The relation between SE and EE is shown in curve 906.

[0068] To describe the PA switching strategy according to various embodiments, two critical points A (SE_H, EE_H) and B (SE_L, EE_L) may be defined as shown in FIG. 9. These points may be determined off-line for given PAs' characteristics. Any points on the solid line 906 in FIG. 9 may be achievable by the PA switching technique according to various embodiments. The point S(SE_S, EE_S) may represent one example SE point obtained using PA switching.

[0069] According to various embodiments, a strategy may be provided for implementing the PA switching technique according to various embodiments. It will be understood that although only a few examples of the applications of the technique according to various embodiments are described herein, the technique according to various embodiments may be applied to a variety of application.

[0070] FIG. 10 shows a block diagram 1000 showing a transmitter (which may be a communication device, for example a mobile radio communication device, for example a mobile phone) for the PA switching technique, e.g., with two PAs (a first PA 1032 and a second PA 1034) and one VGA 1028, according to various embodiments.

[0071] The TSFC module 1002 may include a circuit 1008 (for example an ASIC (application-specific integrated circuit), an FPGA (field-programmable gate array), or a DSP (digital signal processor)) configured to perform one or more of the following: digital up-converting, digital pre-distorting, scrambling, CRC (cyclic redundancy check), convolution encoding, interleaving, modulation, IFFT (inverse fast Fourier transformation), add CP (cyclic prefix), and/ or perform P-to-S (parallel to serial) translation. A DAC (digital analogue converter) 1018 may provide input from the TSFC module 1002 to a filter 1020, which may be connected to a mixer 1022. Further, a local oscillator 1024 may be connected to the mixer 1022. An output of the mixer 1022 may be provided to a further filter 1026.

[0072] The TSFC module 1002 may provide VGA control 1012 and a circuit 1010 configured to determine a PA sharing factor η .

[0073] FIG. 10 illustrates the block diagram 1000 of the PA switching systems according to various embodiments with two PAs 1032, 1034 and one VGA 1028

(variable gain amplifier). Various applications may be possible with three fundamental modules: i) a Feedback (FB) Module 1006, ii) a Time Sharing Factor Computing (TSFC) Module 1002, and iii) a PA (VGA) Bank & Switch (PABS) Module 1004. The operation of each module for the given {target SE SE_T , SE_L of PA^{low} , SE_H of PA^{high} } may be as follows:

[0074] The feedback (FB) module 1006 may be located at the receiver (which may be a communication device, for example a radio communication device, for example a mobile radio communication device, for example a mobile phone), which in addition to parts 1048 of a commonly used receiver may include the FB module 1006. The receiver may measure the received SNR by using a training signal. The FB module 1006 may provide SNR feedback or η feedback (like indicated in block 1004), and may feed back [the SNR information to the TSFC module 1002 in the transmitter like indicated by arrow 1046, so that the TSFC module 1002 may find the time sharing factor η ; or the FB module 1006 directly may feed back η to the transmitter, if the TSFC module 1002 is deployed in the FB module 1006 at the receiver.

[0075] When communications between transmitter 104 and receiver 102 are considered, there may be a reciprocal transmission time or frequency. In time division duplex (TDD) systems, 104 and 102 may transmit alternately in different time. In frequency division duplex (FDD) systems, 104 and 102 may transmit at the same time, yet using different frequency bands. The feedback information, i.e., indicator 1044, such as SNR, PA time sharing factor, PAs' indices, or etc, may be transmitted when 102 may transmit to 104. In summary, feedback information may be delivered when 102 transmits to 104.

[0076] The transmitter may further include an antenna 103, which, for example via a wireless communication channel 1040, may transmit data to an antenna 1042 at the receiver (for example another communication device, for example a base station).

[0077] In an exemplary embodiments, the time sharing factor computing (TSFC) module 1002 may be located at the BB module in the transmitter or at the FB module in the receiver. The TSFC module 1002 may determine the required SE, SE_R , and the required PA input power, based on the given SNR for the target SE, SE_T . The TSFC 1002 may provide power control according to the PA input signal if the distortion from the DAC 1018 is negligible. The TSFC module 1002 may determine the PA time sharing factor η , for example as follows:

- i. If $SE_R > SE_H$, set $\eta=0$.
- ii. If $SE_R < SE_L$, set $\eta=1$.
- iii. If $SE_L \leq SE_R \leq SE_H$, set $SE_S=SE_R$, $SE_1=SE_L$, and $SE_2=SE_H$ in (10), and find η that satisfies the equality (10).

[0078] It will be understood that the criterion as described above is just an example and many other criteria can be applied. For example, the receiver or the transmitter may adapt various criteria.

[0079] In another example: The receiver may know a maximum available power of each power amplifier. The receiver may estimate a channel gain using a training signal which is transmitted by a Reference Power Amplifier. The reference power amplifier may be any one of plurality of power amplifiers. Then, the receiver may estimate expected spectral efficiency of the case when any combination of power amplifiers are activated. According to the expected SE, the receiver may choose power amplifier(s)

which are activated and involved in data transmission. Similarly, the receiver may estimate energy efficiency of the network and choose the proper power amplifier(s) according to the target energy efficiency.

[0080] Based on the η , the TSFC module 1002 may determine the turn on/off time of each PA (and VGA DC control signal once requested). The TSFC module 1002 may send the signal to switch on/off PAs (and control VGA once requested). This control signal may be called a PA switching signal.

[0081] The power amplifier bank and switch (PABS) module 1004 may be located at the RF module in the transmitter. According to the PA switching signal, switches (for example a first switch 1030 and a second switch 1036) may operate to turn on the selected PAs 1032, 1034. Each switch 1030, 1036 may be connected just before and after the PAs 1032, 1034 and may be synchronized to turn on one of the multiple PAs 1030, 1032 in a PA bank. The second switch 1036 after the PA 1032, 1034 may be removed if each PA 1032, 1034 has isolated and individual transmit antenna. The VGA 1028 may control the PA input power in order to operate the PA 1032, 1034 in its linear region according to a VGA control signal 1016 once present. Generally, any number of and any types of PA may compose the PA bank for the switching technique.

[0082] According to various embodiments, a power amplifier (PA) switching technique may be provided. According to various embodiments, a feedback (FB) module may be provided. According to various embodiments, a power amplifier bank and switch (PABS) module may be provided. According to various embodiments, a time sharing factor computing (TSFC) module may be provided. According to various embodiments, a power amplifier bank which may include a plurality of PAs may be provided at the PABS

module. According to various embodiments, one or multiple synchronized pairs of switches may be provided at the PABS module. According to various embodiments, a feedback device at the receiver may be provided for the PA switching at the transmitter. According to various embodiments, a computing device for PA time sharing factor η may be provided at the SFC module. According to various embodiments, a loop for a PA switching signalling may be provided from BB module. According to various embodiments, a single VGA controlled by TSFC module may be provided. According to various embodiments, a single VGA may control input signals of multiple PAs. According to various embodiments, a loop for a VGA controlling signal may be provided from BB module. According to various embodiments, a feedback loop for time sharing factor may be provided from the FB module. According to various embodiments, any combinations including SFC, PABS, and FB modules may be provided. According to various embodiments, any metric for PA switching including the ways that the TSFC determines the PA time sharing factor like described above may be provided. According to various embodiments, PA input power control at the BB module may be provided.

[0083] For example, the invention can be applied to a transmitter with multiple transmit antennas, i.e., with multiple RF transmit chains from DAC to transmit antenna in Fig. 10. In this case, each RF transmit chain has an individual variable gain amplifier. Thus, multiple VGAs are used at the transmitter.

[0084] While the invention has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is

thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

Claims

What is claimed is:

1. A communication device comprising:
a plurality of power amplifiers in a radio frequency transmit chain;
a selection criterion determination circuit configured to determine a criterion for which one or more power amplifiers of the plurality of power amplifiers in the radio frequency transmit chain should be used;
a power amplifier selection circuit configured to determine which one or more power amplifiers of the plurality of power amplifiers in the radio frequency transmit chain should be used based on the determined criterion; and
a transmitter configured to use the one or more power amplifiers for which it has been determined that they should be used for transmitting data,
wherein the criterion comprises an indicator comprising at least a sharing factor indicating which of the plurality of power amplifiers in the radio frequency transmit chain should be used for which fraction of time.
2. The communication device of claim 1, further comprising:
a single common variable gain amplifier configured to be used with each of the plurality of power amplifiers in the radio frequency transmit chain.
3. The communication device of claim 1 or 2,

wherein the indicator further comprises at least one of a signal to noise ratio of a communication of the communication device, and a power amplifier index.

4. The communication device of any one of claims 1 to 3, further comprising:
a switch configured to selectively connect the determined one or more power amplifiers in a transmission path of the communication device.
5. The communication device of any one of claims 1 to 4,
wherein at any time, one or more power amplifiers of the communication device are used.
6. A method for controlling a communication device, the method comprising:
determining a criterion for which one or more power amplifiers of a plurality of power amplifiers in a radio frequency transmit chain of the communication device should be used;
determining which one or more power amplifier of the plurality of power amplifiers in the radio frequency transmit chain should be used based on the determined criterion;
and
using the one or more power amplifiers for which it has been determined that they should be used for transmitting data,

wherein the criterion comprises an indicator comprising at least a sharing factor indicating which of the plurality of power amplifiers in the radio frequency transmit chain should be used for which fraction of time.

7. The method of claim 6,
wherein a single common variable gain amplifier configured to be used with each of the plurality of power amplifiers in the radio frequency transmit chain.
8. The method of claim 6 or 7,
wherein the indicator further comprises at least one of a signal to noise ratio of a communication of the communication device, and a power amplifier index.
9. The method of any one of claims 6 to 8, further comprising:
selectively connecting the determined one or more power amplifiers in a transmission path of the communication device.
10. A selection criterion determination circuit configured to determine a criterion for which one or more power amplifiers of a plurality of power amplifiers in a radio frequency transmit chain in a communication device should be used,
wherein the criterion comprises an indicator comprising at least a sharing factor indicating which of the plurality of amplifiers in the radio frequency transmit chain should be used for which fraction of time.

11. The selection criterion determination circuit of claim 10,
wherein the indicator further comprises at least one of a signal to noise ratio of a communication of the communication device, and a power amplifier index.
12. The selection criterion determination circuit of claim 10 or 11,
wherein the selection criterion determination circuit is configured to be provided in the communication device.
13. The selection criterion determination circuit of claim 10 or 11,
wherein the selection criterion determination circuit is configured to be provided in a further communication device in communication with the communication device.