POWER AMPLIFIERS WITH ADAPTIVE BIAS FOR ENVELOPE TRACKING APPLICATIONS

BACKGROUND

Field

[0001] Embodiments of the invention relate to electronic systems, and in particular, to power amplifiers for use in radio frequency (RF) electronics.

Description of the Related Technology

[0002] Power amplifiers are used in radio frequency (RF) communication systems to amplify RF signals for transmission via antennas. It is important to manage the power of RF signal transmissions to prolong battery life and/or provide a suitable transmit power level.

[0003] Examples of RF communication systems with one or more power amplifiers include, but are not limited to, mobile phones, tablets, base stations, network access points, customer-premises equipment (CPE), laptops, and wearable electronics. For example, in wireless devices that communicate using a cellular standard, a wireless local area network (WLAN) standard, and/or any other suitable communication standard, a power amplifier can be used for RF signal amplification. An RF signal can have a frequency in the range of about 30 kHz to 300 GHz, for instance, in the range of about 410 MHz to about 7.125 GHz for Fifth Generation (5G) cellular communications in Frequency Range 1 (FR1) or in the range of about 24.250 GHz to about 52.600 GHz for Frequency Range 2 (FR2) of the 5G communication standard.

SUMMARY

[0004] In one aspect, the present disclosure relates to a mobile device. The mobile device includes a transceiver configured to generate a radio frequency signal, a power management system including an envelope tracker configured to generate a power amplifier supply voltage that changes in relation to an envelope of the radio frequency signal, and a front end system including a power amplifier configured to amplify the radio frequency signal and to receive power from the power amplifier supply voltage. The power amplifier includes a

current mirror having an input configured to receive a reference current and an output electrically connected to the power amplifier supply voltage, and a field-effect transistor configured to amplify the radio frequency signal and having a gate biased based on an internal voltage of the current mirror.

[0005] In various examples, the internal voltage of the current mirror increases in response to a decrease of the power amplifier supply voltage, and decreases in response to an increase of the power amplifier supply voltage.

[0006] In a number of examples, the field-effect transistor is a short channel metal oxide semiconductor transistor.

[0007] In several examples, the power amplifier further includes a choke inductor electrically connected between the power amplifier supply voltage and a drain of the field-effect transistor.

[0008] In some examples, the current mirror is a Wilson current mirror.

[0009] In various examples, the power amplifier further includes a buffer configured to buffer the internal voltage of the current mirror to generate a gate bias voltage of the field-effect transistor. According to a number of examples, the buffer includes a first depletion-mode transistor and a second depletion-mode transistor configured to provide buffering with a zero shift.

[0010] In several examples, the current mirror includes a first mirror transistor having a drain configured to output the internal voltage, a second mirror transistor, a third mirror transistor, and a fourth mirror transistor, the third mirror transistor and the first mirror transistor connected in series between the input of the current mirror and a ground voltage, and the fourth mirror transistor and the second mirror transistor connected in series between the output of the current mirror and the ground voltage. According to a number of examples, a gate of the first mirror transistor is connected to a gate of the second mirror transistor, and a gate of the third mirror transistor is connected to a gate of the fourth mirror transistor. In accordance with various examples, a drain of the second mirror transistor is connected to the gate of the second mirror transistor, and a drain of the third mirror transistor is connected to the gate of the third mirror transistor.

[0011] In several examples, the power amplifier further includes a current source configured to generate the reference current.

[0012] In some examples, the envelope tracker includes a DC-to-DC converter configured to output a plurality of regulated voltages, a modulator configured to generate a modulator output voltage at an output based on the plurality of regulated voltages and the envelope of the radio frequency signal, and a modulator output filter coupled between the output of the modulator and the power amplifier supply voltage.

[0013] In various examples, the envelope tracker includes a DC-to-DC converter and an error amplifier configured to operate in parallel with one another to generate the power amplifier supply voltage.

[0014] In another aspect, the present disclosure relates to an envelope tracking system. The envelope tracking system includes an envelope tracker configured to generate a power amplifier supply voltage that changes in relation to an envelope of a radio frequency signal, and a power amplifier configured to amplify the radio frequency signal and to receive power from the power amplifier supply voltage. The power amplifier includes a current mirror having an input configured to receive a reference current and an output electrically connected to the power amplifier supply voltage, and a field-effect transistor configured to amplify the radio frequency signal and having a gate biased based on an internal voltage of the current mirror.

[0015] In various examples, the internal voltage of the current mirror increases in response to a decrease of the power amplifier supply voltage, and decreases in response to an increase of the power amplifier supply voltage.

[0016] In several examples, the field-effect transistor is a short channel metal oxide semiconductor transistor.

[0017] In some examples, the power amplifier further includes a choke inductor electrically connected between the power amplifier supply voltage and a drain of the field-effect transistor.

[0018] In various examples, the current mirror is a Wilson current mirror.

[0019] In several examples, the power amplifier further includes a buffer configured to buffer the internal voltage of the current mirror to generate a gate bias voltage of the field-effect transistor. According to a number of examples, the buffer includes a first depletion-mode transistor and a second depletion-mode transistor configured to provide buffering with a zero shift.

[0020] In some examples, the current mirror includes a first mirror transistor having a drain configured to output the internal voltage, a second mirror transistor, a third mirror transistor, and a fourth mirror transistor, the third mirror transistor and the first mirror transistor connected in series between the input of the current mirror and a ground voltage, and the fourth mirror transistor and the second mirror transistor connected in series between the output of the current mirror and the ground voltage. According to a number of examples, a gate of the first mirror transistor is connected to a gate of the second mirror transistor, and a gate of the third mirror transistor is connected to a gate of the fourth mirror transistor. In various examples, a drain of the second mirror transistor is connected to the gate of the second mirror transistor, and a drain of the third mirror transistor is connected to the gate of the third mirror transistor.

[0021] In several examples, the power amplifier further includes a current source configured to generate the reference current.

[0022] In some examples, the envelope tracker includes a DC-to-DC converter configured to output a plurality of regulated voltages, a modulator configured to generate a modulator output voltage at an output based on the plurality of regulated voltages and the envelope of the radio frequency signal, and a modulator output filter coupled between the output of the modulator and the power amplifier supply voltage.

[0023] In several examples, the envelope tracker includes a DC-to-DC converter and an error amplifier configured to operate in parallel with one another to generate the power amplifier supply voltage.

[0024] In another aspect, the present disclosure relates to a method of radio frequency signal amplification in a mobile device. The method includes generating a power amplifier supply voltage that changes in relation to an envelope of a radio frequency signal using an envelope tracker, powering a power amplifier using the power amplifier supply voltage, amplifying the radio frequency signal using a field-effect transistor of the power amplifier, and generating a gate bias voltage of the field-effect transistor using an internal voltage of a current mirror of the power amplifier, including providing a reference current to an input of the current mirror and providing the power amplifier supply voltage to an output of the current mirror.

[0025] In various examples, the method includes increasing the internal voltage of the current mirror in response to a decrease of the power amplifier supply voltage, and decreasing the internal voltage of the current mirror in response to an increase of the power amplifier supply voltage.

[0026] In several examples, the field-effect transistor is a short channel metal oxide semiconductor transistor.

[0027] In a number of examples, the method further includes providing the power amplifier supply voltage to a drain of the field-effect transistor using a choke inductor.

[0028] In some examples, the current mirror is a Wilson current mirror.

[0029] In various examples, the method further incudes buffering the internal voltage of the current mirror to generate the gate bias voltage of the field-effect transistor.

[0030] In a number of examples, the method further includes generating the reference current using a current source.

[0031] In several examples, generating the power amplifier supply voltage includes outputting a plurality of regulated voltages from a DC-to-DC converter, generating a modulator output voltage based on the plurality of regulated voltages and the envelope of the radio frequency signal using a modulator, and filtering the modulator output voltage to generate the power amplifier supply voltage using a modulator output filter.

[0032] In some examples, generating the power amplifier supply voltage includes tracking the envelope using a DC-to-DC converter and an error amplifier operating in parallel.

BRIEF DESCRIPTION OF THE DRAWINGS

[0033] Figure 1 is a schematic diagram of one embodiment of a mobile device.

[0034] Figure 2 is a schematic diagram of one embodiment of a transmit system for transmitting radio frequency (RF) signals from a mobile device.

[0035] Figure 3 is a schematic diagram of a power amplifier according to one embodiment.

[0036] Figure 4A is a graph of one example of power gain versus output power for a power amplifier without adaptive bias.

[0052] Figure 11A is a schematic diagram of one embodiment of a packaged module.

[0053] Figure 11B is a schematic diagram of a cross-section of the packaged module of Figure 11A taken along the lines 11B–11B.

[0054] Figure 12 is a schematic diagram of one embodiment of a phone board.

DETAILED DESCRIPTION OF EMBODIMENTS

[0055] The following detailed description of certain embodiments presents various descriptions of specific embodiments. However, the innovations described herein can be embodied in a multitude of different ways, for example, as defined and covered by the claims. In this description, reference is made to the drawings where like reference numerals can indicate identical or functionally similar elements. It will be understood that elements illustrated in the figures are not necessarily drawn to scale. Moreover, it will be understood that certain embodiments can include more elements than illustrated in a drawing and/or a subset of the elements illustrated in a drawing. Further, some embodiments can incorporate any suitable combination of features from two or more drawings.

[0056] Figure 1 is a schematic diagram of one example of a mobile device 100. The mobile device 100 includes a baseband system 1, a transceiver 2, a front end system 3, antennas 4, a power management system 5, a memory 6, a user interface 7, and a battery 8.

[0057] The mobile device 100 can be used communicate using a wide variety of communications technologies, including, but not limited to, 2G, 3G, 4G (including LTE, LTE-Advanced, and LTE-Advanced Pro), 5G, WLAN (for instance, Wi-Fi), WPAN (for instance, Bluetooth and ZigBee), WMAN (for instance, WiMax), and/or GPS technologies.

[0058] The transceiver 2 generates RF signals for transmission and processes incoming RF signals received from the antennas 4. It will be understood that various functionalities associated with the transmission and receiving of RF signals can be achieved by one or more components that are collectively represented in Figure 1 as the transceiver 2. In one example, separate components (for instance, separate circuits or dies) can be provided for handling certain types of RF signals.

[0059] The front end system 3 aids in conditioning signals transmitted to and/or received from the antennas 4. In the illustrated embodiment, the front end system 3 includes

the antennas 4. For example, in the context of signal transmission, the phases of the transmit signals provided to the antennas 4 are controlled such that radiated signals from the antennas 4 combine using constructive and destructive interference to generate an aggregate transmit signal exhibiting beam-like qualities with more signal strength propagating in a given direction. In the context of signal reception, the phases are controlled such that more signal energy is received when the signal is arriving to the antennas 4 from a particular direction. In certain implementations, the antennas 4 include one or more arrays of antenna elements to enhance beamforming.

[0065] The baseband system 1 is coupled to the user interface 7 to facilitate processing of various user input and output (I/O), such as voice and data. The baseband system 1 provides the transceiver 2 with digital representations of transmit signals, which the transceiver 2 processes to generate RF signals for transmission. The baseband system 1 also processes digital representations of received signals provided by the transceiver 2. As shown in Figure 1, the baseband system 1 is coupled to the memory 6 of facilitate operation of the mobile device 100.

[0066] The memory 6 can be used for a wide variety of purposes, such as storing data and/or instructions to facilitate the operation of the mobile device 100 and/or to provide storage of user information.

[0067] The power management system 5 provides a number of power management functions of the mobile device 100. The power management system 5 of Figure 1 includes an envelope tracker 60. As shown in Figure 1, the power management system 5 receives a battery voltage from the battery 8. The battery 8 can be any suitable battery for use in the mobile device 100, including, for example, a lithium-ion battery.

[0068] The mobile device 100 of Figure 1 illustrates one example of an RF communication system that can include power amplifier(s) implemented in accordance with one or more features of the present disclosure. However, the teachings herein are applicable to RF communication systems implemented in a wide variety of ways.

[0069] Figure 2 is a schematic diagram of one embodiment of a transmit system 130 for transmitting RF signals from a mobile device. The transmit system 130 includes a battery 101, an envelope tracker 102, a power amplifier 103, a directional coupler 104, a duplexing and switching circuit 105, an antenna 106, a baseband processor 107, a signal delay

[0139] Figure 11A is a schematic diagram of one embodiment of a packaged module 800. Figure 11B is a schematic diagram of a cross-section of the packaged module 800 of Figure 11A taken along the lines 11B–11B.

[0140] The packaged module 800 includes an IC or die 801, surface mount components 803, wirebonds 808, a package substrate 820, and encapsulation structure 840. The package substrate 820 includes pads 806 formed from conductors disposed therein. Additionally, the die 801 includes pads 804, and the wirebonds 808 have been used to electrically connect the pads 804 of the die 801 to the pads 806 of the package substrate 820.

[0141] The die 801 includes a power amplifier 846, which can be implemented in accordance with any of the embodiments herein.

[0142] The package substrate 820 can be configured to receive a plurality of components such as the die 801 and the surface mount components 803, which can include, for example, surface mount capacitors and/or inductors.

[0143] As shown in Figure 11B, the packaged module 800 is shown to include a plurality of contact pads 832 disposed on the side of the packaged module 800 opposite the side used to mount the die 801. Configuring the packaged module 800 in this manner can aid in connecting the packaged module 800 to a circuit board such as a phone board of a wireless device. The example contact pads 832 can be configured to provide RF signals, bias signals, power low voltage(s) and/or power high voltage(s) to the die 801 and/or the surface mount components 803. As shown in Figure 11B, the electrically connections between the contact pads 832 and the die 801 can be facilitated by connections 833 through the package substrate 820. The connections 833 can represent electrical paths formed through the package substrate 820, such as connections associated with vias and conductors of a multilayer laminated package substrate.

[0144] In some embodiments, the packaged module 800 can also include one or more packaging structures to, for example, provide protection and/or facilitate handling of the packaged module 800. Such a packaging structure can include overmold or encapsulation structure 840 formed over the package substrate 820 and the components and die(s) disposed thereon.

[0145] It will be understood that although the packaged module 800 is described in the context of electrical connections based on wirebonds, one or more features of the present

disclosure can also be implemented in other packaging configurations, including, for example, flip-chip configurations.

[0146] Figure 12 is a schematic diagram of one embodiment of a phone board 900. The phone board 900 includes the module 800 shown in Figures 11A-11B attached thereto. Although not illustrated in Figure 12 for clarity, the phone board 900 can include additional components and structures.

Applications

[0147] Some of the embodiments described above have provided examples in connection with wireless devices or mobile phones. However, the principles and advantages of the embodiments can be used for any other systems or apparatus that have needs for power amplifiers.

[0148] Such envelope trackers can be implemented in various electronic devices. Examples of the electronic devices can include, but are not limited to, consumer electronic products, parts of the consumer electronic products, electronic test equipment, etc. Examples of the electronic devices can also include, but are not limited to, memory chips, memory modules, circuits of optical networks or other communication networks, and disk driver circuits. The consumer electronic products can include, but are not limited to, a mobile phone, a telephone, a television, a computer monitor, a computer, a hand-held computer, a personal digital assistant (PDA), a microwave, a refrigerator, an automobile, a stereo system, a cassette recorder or player, a DVD player, a CD player, a VCR, an MP3 player, a radio, a camcorder, a camera, a digital camera, a portable memory chip, a washer, a dryer, a washer/dryer, a copier, a facsimile machine, a scanner, a multi-functional peripheral device, a wrist watch, a clock, etc. Further, the electronic devices can include unfinished products.

Conclusion

[0149] Unless the context clearly requires otherwise, throughout the description and the claims, the words "comprise," "comprising," and the like are to be construed in an inclusive sense, as opposed to an exclusive or exhaustive sense; that is to say, in the sense of "including, but not limited to." The word "coupled", as generally used herein, refers to two or more elements that may be either directly connected, or connected by way of one or more

WHAT IS CLAIMED IS:

1. A mobile device comprising:

a transceiver configured to generate a radio frequency signal;

a power management system including an envelope tracker configured to generate a power amplifier supply voltage that changes in relation to an envelope of the radio frequency signal; and

a front end system including a power amplifier configured to amplify the radio frequency signal and to receive power from the power amplifier supply voltage, the power amplifier including a current mirror having an input configured to receive a reference current and an output electrically connected to the power amplifier supply voltage, and a field-effect transistor configured to amplify the radio frequency signal and having a gate biased based on an internal voltage of the current mirror.

2. The mobile device of claim 1 wherein the internal voltage of the current mirror increases in response to a decrease of the power amplifier supply voltage, and decreases in response to an increase of the power amplifier supply voltage.

3. The mobile device of claim 1 wherein the field-effect transistor is a short channel metal oxide semiconductor transistor.

4. The mobile device of claim 1 wherein the power amplifier further includes a choke inductor electrically connected between the power amplifier supply voltage and a drain of the field-effect transistor.

5. The mobile device of claim 1 wherein the current mirror is a Wilson current mirror.

6. The mobile device of claim 1 wherein the power amplifier further includes a buffer configured to buffer the internal voltage of the current mirror to generate a gate bias voltage of the field-effect transistor.

7. The mobile device of claim 6 wherein the buffer includes a first depletion-mode transistor and a second depletion-mode transistor configured to provide buffering with a zero shift.

8. The mobile device of claim 1 wherein the current mirror includes a first mirror transistor having a drain configured to output the internal voltage, a second mirror transistor, a third mirror transistor, and a fourth mirror transistor, the third mirror transistor and the first mirror transistor connected in series between the input of the current mirror and a ground voltage, and the fourth mirror transistor and the second mirror transistor connected in series between the output of the current mirror and the ground voltage.

9. The mobile device of claim 8 wherein a gate of the first mirror transistor is connected to a gate of the second mirror transistor, and a gate of the third mirror transistor is connected to a gate of the fourth mirror transistor.

10. The mobile device of claim 9 wherein a drain of the second mirror transistor is connected to the gate of the second mirror transistor, and a drain of the third mirror transistor is connected to the gate of the third mirror transistor.

11. The mobile device of claim 1 wherein the power amplifier further includes a current source configured to generate the reference current.

12. An envelope tracking system comprising:

an envelope tracker configured to generate a power amplifier supply voltage that changes in relation to an envelope of a radio frequency signal; and

a power amplifier configured to amplify the radio frequency signal and to receive power from the power amplifier supply voltage, the power amplifier including a current mirror having an input configured to receive a reference current and an output electrically connected to the power amplifier supply voltage, and a field-effect transistor configured to amplify the radio frequency signal and having a gate biased based on an internal voltage of the current mirror.

13. The envelope tracking system of claim 12 wherein the internal voltage of the current mirror increases in response to a decrease of the power amplifier supply voltage, and decreases in response to an increase of the power amplifier supply voltage.

14. The envelope tracking system of claim 12 wherein the field-effect transistor is a short channel metal oxide semiconductor transistor.

15. The envelope tracking system of claim 12 wherein the current mirror is a Wilson current mirror.

16. The envelope tracking system of claim 12 wherein the power amplifier further includes a buffer configured to buffer the internal voltage of the current mirror to generate a gate bias voltage of the field-effect transistor.

17. The envelope tracking system of claim 12 wherein the current mirror includes a first mirror transistor having a drain configured to output the internal voltage, a second mirror transistor, a third mirror transistor, and a fourth mirror transistor, the third mirror transistor and the first mirror transistor connected in series between the input of the current mirror and a ground voltage, and the fourth mirror transistor and the second mirror transistor connected in series between the output of the current mirror and the ground voltage.

18. A method of radio frequency signal amplification in a mobile device, the method comprising:

generating a power amplifier supply voltage that changes in relation to an envelope of a radio frequency signal using an envelope tracker;

powering a power amplifier using the power amplifier supply voltage;

amplifying the radio frequency signal using a field-effect transistor of the power amplifier; and

generating a gate bias voltage of the field-effect transistor using an internal voltage of a current mirror of the power amplifier, including providing a reference current to an input of the current mirror and providing the power amplifier supply voltage to an output of the current mirror.

19. The method of claim 18 further comprising increasing the internal voltage of the current mirror in response to a decrease of the power amplifier supply voltage, and decreasing the internal voltage of the current mirror in response to an increase of the power amplifier supply voltage.

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20. The method of claim 18 further comprising buffering the internal voltage of the current mirror to generate the gate bias voltage of the field-effect transistor.