POWER AMPLIFIER MODULES WITH CONTROLLABLE ENVELOPE TRACKING NOISE FILTERS

BACKGROUND

Field

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

Description of the Related Technology

[0002] Power amplifiers are used in 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 to 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, such as in the range of about 410 MHz to about 7.125 GHz for fifth generation (5G) communications using Frequency Range 1 (FR1) or in the range of about 24.25 GHz to 52.6 GHz for 5G communications using Frequency Range 2 (FR2).

SUMMARY

[0004] In certain examples, 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 module including a power amplifier configured to amplify the radio frequency signal and to receive power from the power amplifier supply voltage, the power amplifier module further including a controllable filter configured to filter the power amplifier supply voltage to provide envelope tracking noise filtering. In an aspect, there is provided 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 is relation to an envelope of the radio frequency signal; and a power amplifier module including a power amplifier configured to amplify the radio frequency signal and to receive power from the power amplifier supply voltage, the power amplifier module further including a controllable filter configured to filter the power amplifier supply voltage, wherein the controllable filter includes a plurality of circuit branches that are selectable, and the plurality of circuit branches includes a plurality of series inductor-capacitor networks. In an aspect, there is provided an envelope tracking system comprising an envelope tracker configured to generate a power amplifier supply voltage that changes is relation to an envelope of a radio frequency signal; and a power amplifier module including a power amplifier configured to amplify the radio frequency signal and to receive power from the power amplifier supply voltage, the power amplifier module further including a controllable filter configured to filter the power amplifier supply voltage to provide envelope tracking noise filtering, wherein the controllable filter includes a plurality of circuit branches that are selectable, and the plurality of circuit branches includes a plurality of series inductor-capacitor networks. In an aspect, there is provided a method of envelope tracking in a mobile device, the method comprising: generating a power amplifier supply voltage that changes is relation to an envelope of a radio frequency signal using an envelope tracker; amplifying the radio frequency signal using a power amplifier of a power amplifier module; powering the power amplifier using the power amplifier supply voltage; and filtering the power amplifier supply voltage using a controllable filter of the power amplifier module, wherein filtering the power amplifier supply voltage using the controllable filter includes selecting one or more circuit branches of a plurality of circuit branches, and the plurality of circuit branches includes a plurality of series inductor-capacitor networks.

[0005] In various examples, the controllable filter includes a plurality of circuit branches that are selectable. According to a number of examples, each of the circuit branches includes a switch for selecting the circuit branch. In accordance with several examples, the plurality of circuit branches includes a plurality of series inductor-capacitor networks. According to some examples, the plurality of circuit branches includes a plurality of series resistor-inductor-capacitor networks. In accordance with a number of examples, the plurality of circuit branches includes a plurality of series resistor-capacitor networks.

[0006] In several examples, an amount of filtering provided by the controllable filter changes based on a signal characteristic of the radio frequency signal. According to certain examples, the signal characteristic is bandwidth. In accordance with a number of examples, the signal characteristic is a waveform type.

[0007] In some examples, an amount of filtering provided by the controllable filter changes based on a number of resource blocks allocated to the radio frequency signal.

[0008] In various examples, the power amplifier module is configured to receive data over an interface for programming a setting of the controllable filter.

[0009] In several 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. According to a number of examples, a filtering characteristic of the modulator output filter is controllable. In accordance with various examples, each of the plurality of switches is connected between the output of the modulator and a corresponding one of the plurality of regulated voltages.

[0010] In some 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. According to various examples, the error amplifier is included on the power amplifier module, and the DC-to-DC converter is external to the power amplifier module.

[0011] In certain examples, the present disclosure relates to a method of envelope tracking 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, amplifying the radio frequency signal using a power amplifier of a power amplifier module, powering the power amplifier using the power amplifier supply voltage, and filtering the power amplifier supply voltage using a controllable filter of the power amplifier module.

[0012] In various examples, the method further includes providing an adjustable amount of envelope tracking noise filtering using the controllable filter.

[0013] In several examples, filtering the power amplifier supply voltage using the controllable filter includes selecting one or more circuit branches of a plurality of circuit branches. According to a number of examples, each of the circuit branches includes a switch for selecting the circuit branch. In accordance with some examples, the plurality of circuit branches includes a plurality of series inductor-capacitor networks. According to various examples, the plurality of circuit branches includes a plurality of series resistor-inductor-capacitor networks. In accordance with a number of examples, the plurality of circuit branches includes a plurality of series resistor-capacitor networks.

[0014] In some examples, the method further includes changing an amount of filtering provided by the controllable filter based on a signal characteristic of the radio frequency signal. According to a number of examples, the signal characteristic is bandwidth. In accordance with various examples, the signal characteristic is a waveform type.

[0015] In several examples, an amount of filtering provided by the controllable filter changes based on a number of resource blocks allocated to the radio frequency signal.

[0016] In various examples, the method further includes programming a setting of the controllable filter using an interface of the power amplifier module.

[0017] In some 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. According to a number of examples, the method further includes controlling a filtering characteristic of the modulator output filter to provide multiple layers of controllable filtering for the power amplifier supply voltage.

[0018] In several examples, generating the power amplifier supply voltage includes tracking the envelope using a DC-to-DC converter and an error amplifier operating in parallel.

[0019] In certain examples, 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 power amplifier module including a power amplifier configured to amplify the radio frequency signal and to receive power from the power amplifier supply voltage. The power amplifier module further includes a controllable filter configured to filter the power amplifier supply voltage.

[0020] In various examples, the controllable filter is operable to provide an adjustable amount of envelope tracking noise filtering.

[0021] In several examples, the controllable filter includes a plurality of circuit branches that are selectable. According to a number of examples, each of the circuit branches includes a switch for selecting the circuit branch. In accordance with some examples, the plurality of circuit branches includes a plurality of series inductor-capacitor networks. According to various examples, the plurality of circuit branches includes a plurality of series resistor-inductor-capacitor networks. In accordance with a number of examples, the plurality of circuit branches includes a plurality of series resistor-capacitor networks.

[0022] In some examples, an amount of filtering provided by the controllable filter changes based on a signal characteristic of the radio frequency signal. According to various examples, the signal characteristic is bandwidth. In accordance with a number of examples, the signal characteristic is a waveform type.

[0023] In several examples, an amount of filtering provided by the controllable filter changes based on a number of resource blocks allocated to the radio frequency signal.

[0024] In various examples, the power amplifier module is configured to receive data over an interface for programming a setting of the controllable filter.

[0025] 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. According to a number of examples, a filtering characteristic of the modulator output filter is controllable. In accordance with several examples, each of the plurality of switches is connected between the output of the modulator and a corresponding one of the plurality of regulated voltages.

[0026] 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. According to a number of examples, the error amplifier is included on the power amplifier module, and the DC-to-DC converter is external to the power amplifier module.

BRIEF DESCRIPTION OF THE DRAWINGS

[0027] Figure 1 is a schematic diagram of a mobile device according to one embodiment.

[0028] Figure 2A is a schematic diagram of an envelope tracking system according to one embodiment.

[0029] Figure 2B is a schematic diagram of an envelope tracking system according to another embodiment.

[0030] Figure 3 is a schematic diagram of an envelope tracking system according to another embodiment.

[0031] Figure 4 is a graph of one example of third-order intermodulation distortion (IM3) versus filter inductance.

[0032] Figure 5A is a schematic diagram of a power amplifier module according to another embodiment.

[0033] Figure 5B is a schematic diagram of a power amplifier module according to another embodiment.

[0034] Figure 5C is a schematic diagram of a power amplifier module according to another embodiment.

[0035] Figure 6A is a schematic diagram of one embodiment of a packaged module.

regulated MLS voltages of different voltage levels. However, the MLS switching circuitry 121 can be implemented to output more or fewer regulated voltages.

[0077] As shown in Figure 2B, the MLS switching circuitry 121 is controlled by the digital control circuit 122. The digital control circuit 122 can provide programmability to the MLS switching circuitry 121 including, but not limited to, control over voltage levels of one or more regulated voltages outputted by the MLS switching circuitry 121. As shown in Figure 2B, the digital control circuit 122 is coupled to the SPI bus. In certain implementations, the digital control circuit 122 controls the MLS switching circuitry 121 based on data received over the SPI bus and/or other chip interface.

[0078] The baseband MLS modulator 123 includes an output coupled to the power amplifier supply voltage V_{PA} through the modulator output filter 104. The output of the baseband MLS modulator 123 provides an output voltage V_{OUT}. In certain implementations, the baseband MLS modulator 123 includes switches coupled between each of the regulated MLS voltages and the modulator output filter 104. Additionally, the modulator's switches are selectively opened or closed by the modulator control circuit 124 based on the envelope signal.

[0079] In certain implementations, the modulator control circuit 124 includes a differential envelope amplifier for converting the differential analog envelope signal into a single-ended envelope signal, and two or more comparators that compare the single-ended analog envelope signal to different signal thresholds. Additionally, the modulator control circuit 124 controls the activation of the switches of the MLS modulator 123 based on the results of the comparisons.

[0080] In the illustrated embodiment, the modulator output filter 104 includes a first series inductor 131, a second series inductor 132, a first shunt capacitor 135, and a second shunt capacitor 136. In this example, the first shunt capacitor 135 and the second shunt capacitor 136 are controllable. Although two examples of controllable filter components are shown, other filter components of an envelope tracker can additionally or alternatively be implemented to be controllable.

[0081] As shown in Figure 2B, the power amplifier module 101 includes a power amplifier 137 and a controllable filter 138. The power amplifier 137 amplifies an RF input signal RF_{IN} to generate an RF output signal RF_{OUT}. Additionally, the controllable filter 138 inductors L1, L2, … Ln, capacitors C1, C2, … Cn, and switches S1, S2, … Sn implemented

[0093] In the illustrated embodiment, the controllable filter 301 includes inductors L1, L2, … Ln, capacitors C1, C2, … Cn, and switches S1, S2, … Sn implemented as selectable branches of LC networks. For example, the interface can receive digital data indicating which of the switches S1, S2, … Sn are opened and which are closed.

[0094] Figure 5B is a schematic diagram of a power amplifier module 320 according to another embodiment. The power amplifier module 320 includes a power amplifier 81 and a controllable filter 311 controlled by an interface.

[0095] The power amplifier module 320 of Figure 5B is similar to the power amplifier module 310 of Figure 5A, except that the power amplifier module 320 includes a different implementation of a controllable filter. In particular, the controllable filter 311 of Figure 5B includes resistors R1, R2, … Rn, capacitors C1, C2, … Cn, and switches S1, S2, … Sn implemented as selectable branches of RC networks.

[0096] Figure 5C is a schematic diagram of a power amplifier module 330 according to another embodiment. The power amplifier module 330 includes a power amplifier 81 and a controllable filter 321 controlled by an interface.

[0097] The power amplifier module 330 of Figure 5C is similar to the power amplifier module 310 of Figure 5A, except that the power amplifier module 330 includes a different implementation of the controllable filter. In particular, the controllable filter 321 of Figure 5C includes resistors R1, R2, … Rn, inductors L1, L2, … Ln, capacitors C1, C2, … Cn, and switches S1, S2, … Sn implemented as selectable branches of RLC networks.

[0098] Figure 6A is a schematic diagram of one embodiment of a packaged module 600. Figure 6B is a schematic diagram of a cross-section of the packaged module 600 of Figure 6A taken along the lines 6B–6B.

[0099] The packaged module 600 includes radio frequency components 601, a semiconductor die 602, surface mount devices 603, wirebonds 608, a package substrate 620, and an encapsulation structure 640. The package substrate 620 includes pads 606 formed from conductors disposed therein. Additionally, the semiconductor die 602 includes pins or pads 604, and the wirebonds 608 have been used to connect the pads 604 of the die 602 to the pads 606 of the package substrate 620.

[0100] The semiconductor die 602 includes a power amplifier 645 and a controllable filter 646, which can be implemented in accordance with any of the embodiments

[0105] Figure 7 is a schematic diagram of a mobile device 800 according to another embodiment. The mobile device 800 includes a baseband system 801, a transceiver 802, a front end system 803, antennas 804, a power management system 805, a memory 806, a user interface 807, and a battery 808.

[0106] The mobile device 800 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.

[0107] The transceiver 802 generates RF signals for transmission and processes incoming RF signals received from the antennas 804. 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 7 as the transceiver 802. In one example, separate components (for instance, separate circuits or dies) can be provided for handling certain types of RF signals.

[0108] The front end system 803 aids in conditioning signals transmitted to and/or received from the antennas 804. In the illustrated embodiment, the front end system 803 includes power amplifiers (PAs) 811, low noise amplifiers (LNAs) 812, filters 813, switches 814, and duplexers 815. However, other implementations are possible.

[0109] For example, the front end system 803 can provide a number of functionalizes, including, but not limited to, amplifying signals for transmission, amplifying received signals, filtering signals, switching between different bands, switching between different power modes, switching between transmission and receiving modes, duplexing of signals, multiplexing of signals (for instance, diplexing or triplexing), or some combination thereof.

[0110] The mobile device 800 can be implemented in accordance with any of the embodiments herein. In certain implementations, the filters 813 include at least one controllable envelope tracking noise filter for filtering the supply voltage of at least one of the power amplifiers 811.

[0111] In certain implementations, the mobile device 800 supports carrier aggregation, thereby providing flexibility to increase peak data rates. Carrier aggregation can be used for both Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD),

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 power amplifier module including a power amplifier configured to amplify the radio frequency signal and to receive power from the power amplifier supply voltage, the power amplifier module further including a controllable filter configured to filter the power amplifier supply voltage, wherein the controllable filter includes a plurality of circuit branches that are selectable, and the plurality of circuit branches includes a plurality of series inductor-capacitor networks.

2. The mobile device of claim 1 wherein the controllable filter is operable to provide an adjustable amount of envelope tracking noise filtering.

3. The mobile device of claim 1 wherein each of the circuit branches includes a switch for selecting the circuit branch.

4. The mobile device of claim 1 wherein the plurality of circuit branches includes a plurality of series resistor-inductor-capacitor networks.

5. The mobile device of claim 1 wherein the plurality of circuit branches includes a plurality of series resistor-capacitor networks.

6. The mobile device of claim 1 wherein 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.

7. The mobile device of claim 6 wherein a filtering characteristic of the modulator output filter is controllable.

8. The mobile device of claim 1 wherein 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.

9. The mobile device of claim 8 wherein the error amplifier is included on the power amplifier module, and the DC-to-DC converter is external to the power amplifier module.

10. 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 module including a power amplifier configured to amplify the radio frequency signal and to receive power from the power amplifier supply voltage, the power amplifier module further including a controllable filter configured to filter the power amplifier supply voltage to provide envelope tracking noise filtering, wherein the controllable filter includes a plurality of circuit branches that are selectable, and the plurality of circuit branches includes a plurality of series inductor-capacitor networks.

11. The envelope tracking system of claim 10 wherein the power amplifier module is configured to receive data over an interface for programming a setting of the controllable filter.

12. A method of envelope tracking 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;

amplifying the radio frequency signal using a power amplifier of a power amplifier module;

powering the power amplifier using the power amplifier supply voltage; and

filtering the power amplifier supply voltage using a controllable filter of the power amplifier module, wherein filtering the power amplifier supply voltage using the controllable filter includes selecting one or more circuit branches of a plurality of circuit branches, and the plurality of circuit branches includes a plurality of series inductor-capacitor networks.

13. The method of claim 12 further comprising providing an adjustable amount of envelope tracking noise filtering using the controllable filter.

14. The method of claim 12 further comprising changing an amount of filtering provided by the controllable filter based on a signal characteristic of the radio frequency signal.

15. The method of claim 14 wherein the signal characteristic is bandwidth.

16. The method of claim 14 wherein the signal characteristic is a waveform type.