MULTI-LEVEL ENVELOPE TRACKING SYSTEMS WITH SEPARATE DC AND AC PATHS

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 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 in frequency range 1 (FR1).

SUMMARY

[0003a] In an aspect, the present disclosure refers to an envelope tracking system comprising: a power amplifier configured to amplify a radio frequency signal and to receive power from a power amplifier supply voltage; and an envelope tracker configured to generate the power amplifier supply voltage based on an envelope signal corresponding to an envelope of the radio frequency signal, the envelope tracker including a DC-to-DC converter configured to output a plurality of regulated voltages, a modulator configured to generate a modulator output voltage based on the plurality of regulated voltages and the envelope signal, a first filter coupled between the modulator output voltage and the power amplifier supply voltage, and a

second filter coupled between a DC voltage and the power amplifier supply voltage.

[0003b] In another aspect, the present disclosure refers to a mobile device comprising: a transceiver configured to generate a radio frequency transmit signal; a front end circuit including a power amplifier configured to amplify the radio frequency transmit signal and to receive power from a power amplifier supply voltage; and a power management circuit including an envelope tracker configured to generate the power amplifier supply voltage based on an envelope signal corresponding to an envelope of the radio frequency transmit signal, the envelope tracker including a DC-to-DC converter configured to output a plurality of regulated voltages, a modulator configured to generate a modulator output voltage based on the plurality of regulated voltages and the envelope signal, a first filter coupled between the modulator output voltage and the power amplifier supply voltage, and a second filter coupled between a DC voltage and the power amplifier supply voltage.

[0003c] In another aspect, the present disclosure refers to a method of envelope tracking, the method comprising: amplifying a radio frequency signal using a power amplifier; supplying power to the power amplifier using a power amplifier supply voltage; 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 an envelope signal using a modulator, the envelope signal corresponding to an envelope of the radio frequency signal; controlling the power amplifier supply voltage using a first filter that is between the modulator output voltage and the power amplifier supply voltage; and controlling the power amplifier supply voltage using a second filter that is between a DC voltage and the power amplifier supply voltage.

[0004] In certain ~~embodiments~~examples, the present disclosure relates to an envelope tracking system including a power amplifier configured to amplify a radio frequency signal and to receive power from a power amplifier supply voltage, and an envelope tracker configured to generate the power amplifier supply voltage based on an envelope signal corresponding to an envelope of the radio frequency signal. 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 based on the plurality of regulated voltages and the envelope signal, a first filter coupled between the modulator output voltage and the power amplifier supply voltage, and a second filter coupled between a DC voltage and the power amplifier supply voltage.

[0005] In various examples~~embodiments~~, the DC-to-DC converter is further configured to generate the DC voltage. According to a number of examples~~embodiments~~, the DC-to-DC

converter is configured to generate the DC voltage with a different pulse-width modulator sequence relative to each of the plurality of regulated voltages.

[0006] In several examples~~embodiments~~, the DC-to-DC converter is configured to receive a battery voltage, and to generate the plurality of regulated voltages and the DC voltage based on providing DC-to-DC conversion of the battery voltage.

[0007] In some examples~~embodiments~~, each of the plurality of regulated voltages has a different voltage level.

[0008] In various examples~~embodiments~~, the envelope tracker further includes a plurality of decoupling capacitors each coupled between ground and a corresponding one of the plurality of regulated voltages.

[0009] In several examples~~embodiments~~, the modulator includes a plurality of switches each coupled between the modulator output voltage and a corresponding one of the plurality of regulated voltages.

[0010] In some examples~~embodiments~~, the first filter includes at least one series inductor and at least one shunt capacitor. According to a number of examples~~embodiments~~, the first filter further includes a DC blocking capacitor in series between the modulator output voltage and the power amplifier supply voltage.

[0011] In various examples~~embodiments~~, the second filter includes at least one series inductor and at least one shunt capacitor.

[0012] In several examples~~embodiments~~, the envelope tracker further includes a controllable delay circuit configured to control a relative delay between an AC path through the first filter and a DC path through the second filter. According to a number of examples~~embodiments~~, the controllable delay circuit includes a plurality of controllable delay buffers each configured to control a delay of a respective one of the plurality of regulated voltages.

[0013] In various examples~~embodiments~~, a DC path through the second filter carries at least seventy five percent of the energy provided from the envelope tracker to the power amplifier.

[0014] In certain examples~~embodiments~~, the present disclosure relates to an envelope tracker. The envelope tracker includes a power amplifier supply voltage terminal configured to output a power amplifier supply voltage, a DC-to-DC converter configured to output a plurality of regulated voltages based on regulating a battery voltage, a modulator configured to generate a modulator output voltage based on the plurality of regulated

voltages and an envelope signal, an AC path filter coupled between the modulator output voltage and the power amplifier supply voltage, and a DC path filter coupled between a DC voltage and the power amplifier supply voltage.

[0015] In several examples~~embodiments~~, the DC-to-DC converter is further configured to generate the DC voltage. According to a number of examples~~embodiments~~, the DC-to-DC converter is configured to generate the DC voltage with a different pulse-width modulator sequence relative to each of the plurality of regulated voltages.

[0016] In some examples~~embodiments~~, the DC-to-DC converter is configured to receive a battery voltage, and to generate the plurality of regulated voltages and the DC voltage based on providing DC-to-DC conversion of the battery voltage.

[0017] In various examples~~embodiments~~, each of the plurality of regulated voltages has a different voltage level.

[0018] In several examples~~embodiments~~, the envelope tracker further includes a plurality of decoupling capacitors each coupled between ground and a corresponding one of the plurality of regulated voltages.

[0019] In some examples~~embodiments~~, the modulator includes a plurality of switches each coupled between the modulator output voltage and a corresponding one of the plurality of regulated voltages.

[0020] In various examples~~embodiments~~, the AC path filter includes at least one series inductor and at least one shunt capacitor. According to a number of examples~~embodiments~~, the AC path filter further includes a DC blocking capacitor in series between the modulator output voltage and the power amplifier supply voltage.

[0021] In several examples~~embodiments~~, the DC path filter includes at least one series inductor and at least one shunt capacitor.

[0022] In various examples~~embodiments~~, the envelope tracker further includes a controllable delay circuit configured to control a relative delay between an AC path through the first filter and a DC path through the second filter. According to a number of examples~~embodiments~~, the controllable delay circuit includes a plurality of controllable delay buffers each configured to control a delay of a respective one of the plurality of regulated voltages.

[0023] In some examples~~embodiments~~, the DC path filter carries at least seventy five percent of the energy provided from the envelope tracker to the power amplifier supply voltage terminal.

[0024] In certain examples~~embodiments~~, the present disclosure relates to a mobile device. The mobile device includes a transceiver configured to generate a radio frequency transmit signal, a front end circuit including a power amplifier configured to amplify the radio frequency transmit signal and to receive power from a power amplifier supply voltage, and a power management circuit including an envelope tracker configured to generate the power amplifier supply voltage based on an envelope signal corresponding to an envelope of the radio frequency transmit signal. 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 based on the plurality of regulated voltages and the envelope signal, a first filter coupled between the modulator output voltage and the power amplifier supply voltage, and a second filter coupled between a DC voltage and the power amplifier supply voltage.

[0025] In some examples~~embodiments~~, the DC-to-DC converter is further configured to generate the DC voltage. According to a number of examples~~embodiments~~, the DC-to-DC converter is configured to generate the DC voltage with a different pulse-width modulator sequence relative to each of the plurality of regulated voltages.

[0026] In several examples~~embodiments~~, the mobile device further includes a battery that provides a battery voltage, and the DC-to-DC converter is configured to generate the plurality of regulated voltages and the DC voltage based on providing DC-to-DC conversion of the battery voltage.

[0027] In some examples~~embodiments~~, each of the plurality of regulated voltages has a different voltage level.

[0028] In various examples~~embodiments~~, the envelope tracker further includes a plurality of decoupling capacitors each coupled between ground and a corresponding one of the plurality of regulated voltages.

[0029] In several examples~~embodiments~~, the modulator includes a plurality of switches each coupled between the modulator output voltage and a corresponding one of the plurality of regulated voltages.

[0030] In some examples~~embodiments~~, the first filter includes at least one series inductor and at least one shunt capacitor. According to a number of examples~~embodiments~~, the first filter further includes a DC blocking capacitor in series between the modulator output voltage and the power amplifier supply voltage.

[0031] In several examples~~embodiments~~, the second filter includes at least one series inductor and at least one shunt capacitor.

[0032] In various examples~~embodiments~~, the envelope tracker further includes a controllable delay circuit configured to control a relative delay between an AC path through the first filter and a DC path through the second filter. According to a number of examples~~embodiments~~, the controllable delay circuit includes a plurality of controllable delay buffers each configured to control a delay of a respective one of the plurality of regulated voltages.

[0033] In some examples~~embodiments~~, a DC path through the second filter carries at least seventy five percent of the energy provided from the envelope tracker to the power amplifier.

[0034] In certain examples~~embodiments~~, the present disclosure relates to a method of envelope tracking. The method includes amplifying a radio frequency signal using a power amplifier, supplying power to the power amplifier using a power amplifier supply voltage, outputting a plurality of regulated voltages from a DC-to-DC converter, and generating a modulator output voltage based on the plurality of regulated voltages and an envelope signal using a modulator, the envelope signal corresponding to an envelope of the radio frequency signal. The method further includes controlling the power amplifier supply voltage using a first filter that is between the modulator output voltage and the power amplifier supply voltage, and controlling the power amplifier supply voltage using a second filter that is between a DC voltage and the power amplifier supply voltage.

[0035] In several examples~~embodiments~~, the method further includes generating the DC voltage using the DC-to-DC converter. According to a number of examples~~embodiments~~, the method further includes generating the DC voltage with a different pulse-width modulator sequence relative to each of the plurality of regulated voltages.

[0036] In various examples~~embodiments~~, the method further includes generating the plurality of regulated voltages and the DC voltage based on providing DC-to-DC conversion of a battery voltage.

[0037] In some examples~~embodiments~~, each of the plurality of regulated voltages has a different voltage level.

[0038] In several examples~~embodiments~~, the method further includes providing DC blocking using a series DC blocking capacitor of the first filter.

[0039] In various examples~~embodiments~~, the method further includes controlling a relative delay between an AC path through the first filter and a DC path through the second filter using a controllable delay circuit.

BRIEF DESCRIPTION OF THE DRAWINGS

[0040] Figure 1 is a schematic diagram of a mobile device according to one embodiment.

[0041] Figure 2 is a schematic diagram of one embodiment of an envelope tracking system for a power amplifier.

[0042] Figure 3A is a schematic diagram of another embodiment of an envelope tracking system for a power amplifier.

[0043] Figure 3B is a schematic diagram of another embodiment of an envelope tracking system for a power amplifier.

[0044] Figure 3C is a schematic diagram of another embodiment of an envelope tracking system for a power amplifier.

[0045] Figure 3D is a schematic diagram of another embodiment of an envelope tracking system for a power amplifier.

[0046] Figure 4 is a graph of efficiency versus output power.

[0047] Figure 5 is a schematic diagram of another embodiment of an envelope tracking system for a power amplifier.

[0048] Figure 6 is a schematic diagram of another embodiment of an envelope tracking system for a power amplifier.

[0049] Figure 7 is a schematic diagram of a mobile device according to another embodiment.

[0050] Figure 8 is a schematic diagram of one embodiment of a communication system for transmitting radio frequency (RF) signals.

[0051] Figure 9 is a schematic diagram of a multi-level supply (MLS) modulation system according to one embodiment.

[0052] Figure 10 is a schematic diagram of an MLS DC-to-DC converter according to one embodiment.

[0053] Figure 11 is a schematic diagram of one example of timing for MLS DC-to-DC conversion.