MULTI-LEVEL ENVELOPE TRACKING WITH ANALOG INTERFACE

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) cellular communications in Frequency Range 1 (FR1).

SUMMARY

[0004] In ~~certain embodiments~~a first aspect, the present disclosure relates to an envelope tracking system. The envelope tracking system includes 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 analog 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 at an output based on the plurality of regulated voltages and the analog envelope signal, and a modulator output filter coupled between the output of the modulator and the power amplifier supply voltage, the modulator configured to generate the modulator output voltage based on comparing the analog envelope signal to a plurality of signal thresholds.

[0005] In some ~~embodiment~~examples, the modulator includes a plurality of switches selectively activated based on comparing the analog envelope signal to the plurality of signal thresholds. According to a number of ~~embodiment~~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.

[0006] In various ~~embodiment~~examples, the envelope tracker further includes a plurality of modulators including the modulator and a plurality of modulator output filters including the modulator output filter, each of the plurality of modulators coupled to the power amplifier supply voltage by way of a corresponding one of the plurality of modulator output filters. According to a number of ~~embodiment~~examples, an active number of the plurality of modulators is selected based on comparing the analog envelope signal to the plurality of signal thresholds.

[0007] In several ~~embodiment~~examples, the modulator is configured to receive the analog envelope signal over a Mobile Industry Peripheral Interface Analog Reference Interface for Envelope Tracking.

[0008] In some ~~embodiment~~examples, the analog envelope signal is a differential envelope signal. According to a number of ~~embodiment~~examples, the modulator includes a differential envelope amplifier configured to amplify the differential envelope signal to generate a single-ended envelope signal. In accordance with various ~~embodiment~~examples, the modulator further includes a plurality of comparators each configured to compare the single-ended envelope signal to a corresponding one of the plurality of signal thresholds. According to several ~~embodiment~~examples, the differential envelope amplifier includes an amplification circuit configured to amplify the differential envelope signal, and a common mode feedback circuit operable to compensate the amplification circuit for a common mode error arising from a common mode voltage of the differential envelope signal. In accordance with a number of ~~embodiment~~examples, the amplification circuit includes a first differential input configured to receive the differential envelope signal and a second differential input configured to receive a differential compensation signal from the common mode feedback circuit. According to various ~~embodiment~~examples, the common mode feedback circuit is configured to provide feedback from an output of the amplification circuit to the second differential input of the amplification circuit. In accordance with several

~~embodiment~~examples, the differential envelope amplifier further includes a differential input filter

configured to filter the differential envelope signal prior to amplification by the amplification circuit.

[0009] In some ~~embodiment~~examples, each of the plurality of signal thresholds is controllable.

[0010] In various ~~embodiment~~examples, the envelope tracker further includes a DC path filter coupled between a DC voltage and the power amplifier supply voltage. According to a number of ~~embodiment~~examples, the DC-to-DC converter is further configured to generate the DC voltage. In accordance with several ~~embodiment~~examples, 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. According to a number of ~~embodiment~~examples, the DC path filter includes at least one series inductor and at least one shunt capacitor. In accordance with some ~~embodiment~~examples, a DC path through the DC path filter carries at least seventy five percent of the energy provided from the envelope tracker to the power amplifier.

[0011] In several ~~embodiment~~examples, each of the plurality of regulated voltages has a different voltage level.

[0012] In some ~~embodiment~~examples, the envelope tracker further includes a plurality of decoupling capacitors each coupled between ground and a corresponding one of the plurality of regulated voltages.

[0013] In various ~~embodiment~~examples, the modulator output filter includes at least one series inductor and at least one shunt capacitor. According to a number of ~~embodiment~~examples, the modulator output filter further includes a DC blocking capacitor in series between the modulator output voltage and the power amplifier supply voltage.

[0014] In ~~certain embodiments~~a second aspect, 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 for a power amplifier, a DC-to-DC converter configured to output a plurality of regulated voltages based on regulating a battery voltage, a modulator output filter, and a modulator including an output coupled to the power amplifier supply voltage terminal through the modulator output filter. The modulator is configured to generate a modulator output voltage at the output based on the plurality of

regulated voltages and an analog envelope signal, and to generate the modulator output voltage based on comparing the analog envelope signal to a plurality of signal thresholds.

[0015] In some ~~embodiment~~examples, the modulator includes a plurality of switches selectively activated based on comparing the analog envelope signal to the plurality of signal thresholds. According to various ~~embodiment~~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. In accordance with a number of ~~embodiment~~examples, the envelope tracker further includes a plurality of modulators including the modulator and a plurality of modulator output filters including the modulator output filter, each of the plurality of modulators coupled to the power amplifier supply voltage terminal by way of a corresponding one of the plurality of modulator output filters. According to several ~~embodiment~~examples, an active number of the plurality of modulators is selected based on comparing the analog envelope signal to the plurality of signal thresholds.

[0016] In various ~~embodiment~~examples, the modulator is configured to receive the analog envelope signal over a Mobile Industry Peripheral Interface Analog Reference Interface for Envelope Tracking.

[0017] In some ~~embodiment~~examples, the analog envelope signal is a differential envelope signal. According to several ~~embodiment~~examples, the modulator includes a differential envelope amplifier configured to amplify the differential envelope signal to generate a single-ended envelope signal. In a number of ~~embodiment~~examples, the modulator further includes a plurality of comparators each configured to compare the single-ended envelope signal to a corresponding one of the plurality of signal thresholds. According to various ~~embodiment~~examples, the differential envelope amplifier includes an amplification circuit configured to amplify the differential envelope signal, and a common mode feedback circuit operable to compensate the amplification circuit for a common mode error arising from a common mode voltage of the differential envelope signal. In accordance with several ~~embodiment~~examples, the amplification circuit includes a first differential input configured to receive the differential envelope signal and a second differential input configured to receive a differential compensation signal from the common mode feedback circuit. According to a number of ~~embodiment~~examples, the common mode feedback circuit is configured to provide feedback from an output of the amplification circuit to the second differential input of the amplification circuit. In accordance with various ~~embodiment~~examples, the differential envelope

amplifier further includes a differential input filter configured to filter the differential envelope signal prior to amplification by the amplification circuit.

[0018] In several ~~embodiment~~examples, each of the plurality of signal thresholds is controllable.

[0019] In some ~~embodiment~~examples, the envelope tracker further includes a DC path filter coupled between a DC voltage and the power amplifier supply voltage terminal. According to a number of ~~embodiment~~examples, the DC-to-DC converter is further configured to generate the DC voltage. In accordance with various ~~embodiment~~examples, 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. According to several ~~embodiment~~examples, the DC path filter includes at least one series inductor and at least one shunt capacitor. In accordance with a number of ~~embodiment~~examples, a DC path through the DC path filter carries at least seventy five percent of the energy provided to the power amplifier supply voltage terminal.

[0020] In various ~~embodiment~~examples, each of the plurality of regulated voltages has a different voltage level.

[0021] In several ~~embodiment~~examples, the envelope tracker further includes a plurality of decoupling capacitors each coupled between ground and a corresponding one of the plurality of regulated voltages.

[0022] In some ~~embodiment~~examples, the modulator output filter includes at least one series inductor and at least one shunt capacitor. According to a number of ~~embodiment~~examples the modulator output filter further includes a DC blocking capacitor in series between the output of the modulator and the power amplifier supply voltage terminal.

[0023] In ~~certain embodiments~~a third aspect, 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 analog 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 at an output based on the plurality of regulated voltages and the analog envelope signal,

and a modulator output filter coupled between the output of the modulator and the power amplifier supply voltage. The

modulator is configured to generate the modulator output voltage based on comparing the analog envelope signal to a plurality of signal thresholds.

[0024] In various ~~embodiment~~examples, the modulator includes a plurality of switches selectively activated based on comparing the analog envelope signal to the plurality of signal thresholds. According to a number of ~~embodiment~~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.

[0025] In several ~~embodiment~~examples, the envelope tracker further includes a plurality of modulators including the modulator and a plurality of modulator output filters including the modulator output filter, each of the plurality of modulators coupled to the power amplifier supply voltage by way of a corresponding one of the plurality of modulator output filters. According to a number of ~~embodiment~~examples, an active number of the plurality of modulators is selected based on comparing the analog envelope signal to the plurality of signal thresholds.

[0026] In various ~~embodiment~~examples, the modulator is configured to receive the analog envelope signal over a Mobile Industry Peripheral Interface Analog Reference Interface for Envelope Tracking.

[0027] In some ~~embodiment~~examples, the analog envelope signal is a differential envelope signal. According to a number of ~~embodiment~~examples, the modulator includes a differential envelope amplifier configured to amplify the differential envelope signal to generate a single-ended envelope signal. In accordance with several ~~embodiment~~examples, the modulator further includes a plurality of comparators each configured to compare the single-ended envelope signal to a corresponding one of the plurality of signal thresholds. According to various ~~embodiment~~examples, the differential envelope amplifier includes an amplification circuit configured to amplify the differential envelope signal, and a common mode feedback circuit operable to compensate the amplification circuit for a common mode error arising from a common mode voltage of the differential envelope signal. In accordance with a number of ~~embodiment~~examples, the amplification circuit includes a first differential input configured to receive the differential envelope signal and a second differential input configured to receive a differential compensation signal from the common mode feedback circuit. According to various ~~embodiment~~examples, the common mode feedback circuit is

configured to provide feedback from an output of the amplification circuit to the second differential input of the amplification circuit. In accordance with several

~~embodiment~~examples, the differential envelope amplifier further includes a differential input filter configured to filter the differential envelope signal prior to amplification by the amplification circuit.

[0028] In various ~~embodiment~~examples, each of the plurality of signal thresholds is controllable.

[0029] In several ~~embodiment~~examples, the envelope tracker further includes a DC path filter coupled between a DC voltage and the power amplifier supply voltage. According to a number of ~~embodiment~~examples, the DC-to-DC converter is further configured to generate the DC voltage. In accordance with some ~~embodiment~~examples, the mobile device further includes a battery that outputs a battery voltage, the DC-to-DC converter configured to generate the plurality of regulated voltages and the DC voltage based on providing DC-to-DC conversion of the battery voltage. According to various ~~embodiment~~examples, the DC path filter includes at least one series inductor and at least one shunt capacitor. In accordance with a number of ~~embodiment~~examples, a DC path through the DC path filter carries at least seventy five percent of the energy provided from the envelope tracker to the power amplifier.

[0030] In various ~~embodiment~~examples, each of the plurality of regulated voltages has a different voltage level.

[0031] In some ~~embodiment~~examples, the envelope tracker further includes a plurality of decoupling capacitors each coupled between ground and a corresponding one of the plurality of regulated voltages.

[0032] In several ~~embodiment~~examples, the modulator output filter includes at least one series inductor and at least one shunt capacitor. According to a number of ~~embodiment~~examples, the modulator output filter further includes a DC blocking capacitor in series between the modulator output voltage and the power amplifier supply voltage.

BRIEF DESCRIPTION OF THE DRAWINGS

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

[0034] Figure 2 is a schematic diagram of one embodiment of an envelope tracking system for a power amplifier.

[0035] Figure 3A is a schematic diagram of another embodiment of an envelope tracking system for a power amplifier.