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(54) **TUNABLE NOTCH FILTER USING FEEDBACK THROUGH AN EXISTING FEEDBACK RECEIVER**

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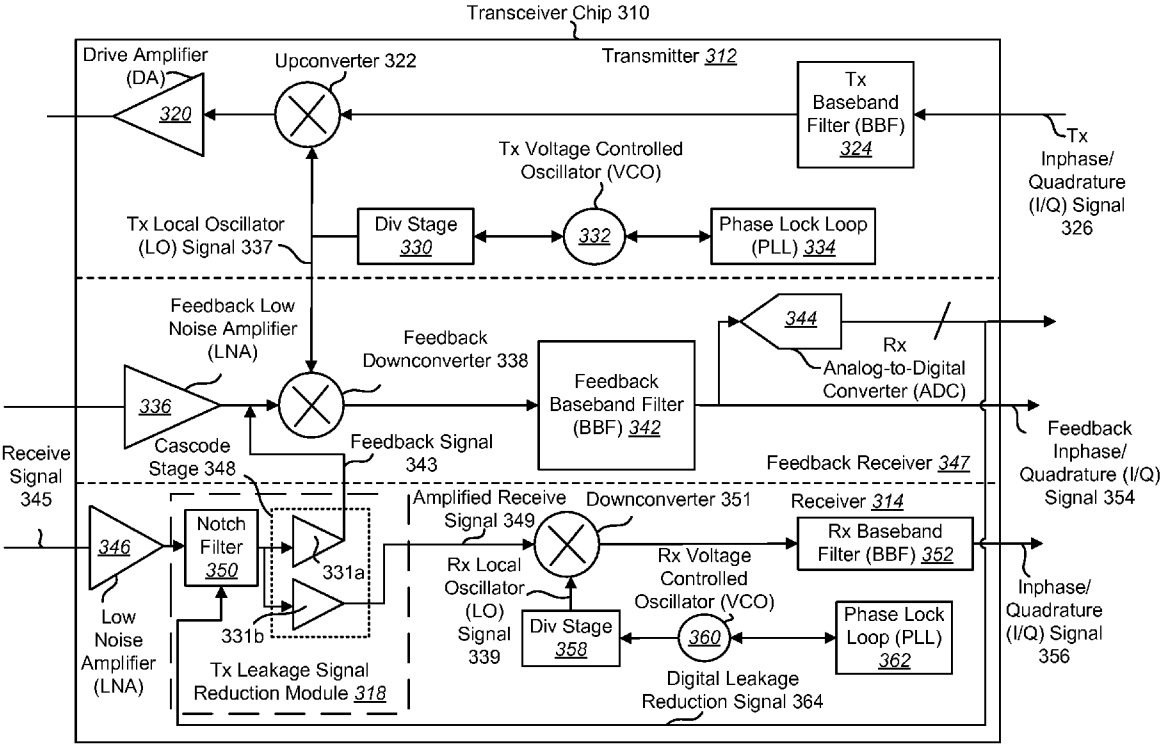
USPC **375/219**; 455/79

(57) **ABSTRACT**

A wireless communication device configured for reducing Tx leakage in a receive signal is described. The wireless communication device includes a transceiver chip. The transceiver chip includes a receiver, a feedback receiver and a transmitter. The wireless communication device also includes a Tx leakage signal reduction module. The Tx leakage signal reduction module reuses the feedback receiver.



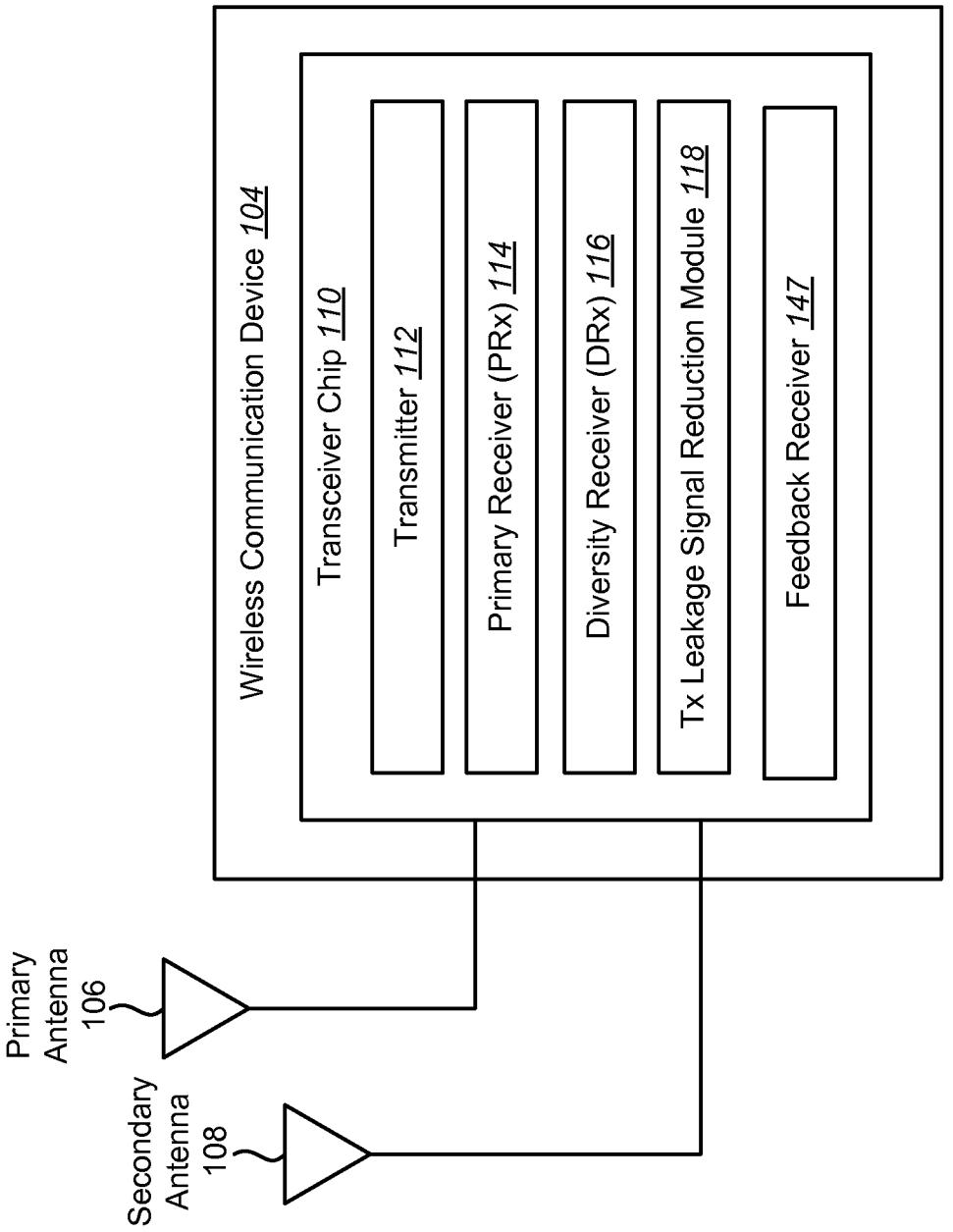

Wireless Communication Device 104
Transceiver Chip 110
Transmitter 112
Primary Receiver (PRx) 114
Diversity Receiver (DRx) 116
Tx Leakage Signal Reduction Module 118
Feedback Receiver 147
Primary Antenna 106
Secondary Antenna 108

FIG. 1

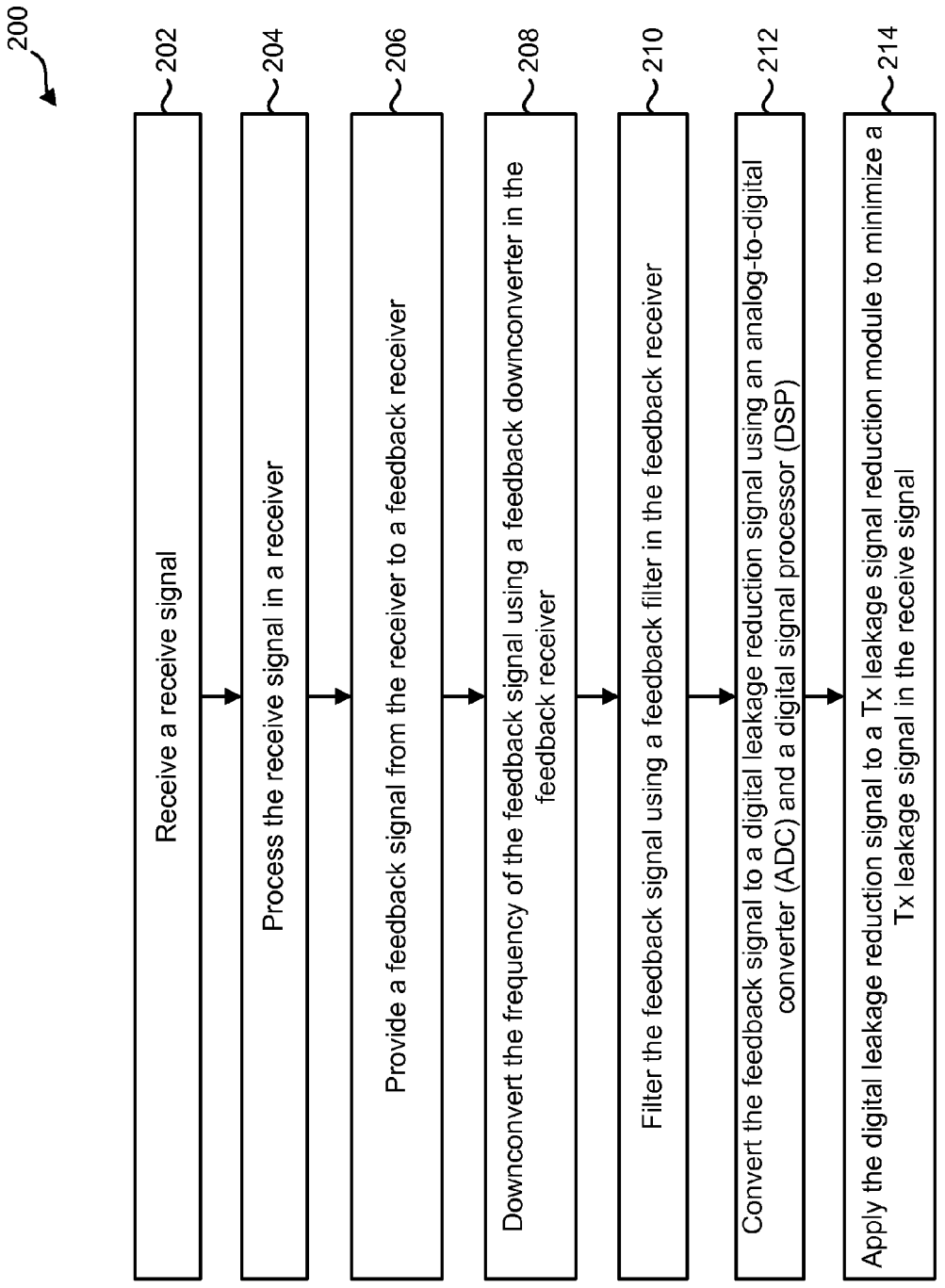

200
202
Receive a receive signal
204
Process the receive signal in a receiver
206
Provide a feedback signal from the receiver to a feedback receiver
208
Downconvert the frequency of the feedback signal using a feedback downconverter in the feedback receiver
210
Filter the feedback signal using a feedback filter in the feedback receiver
212
Convert the feedback signal to a digital leakage reduction signal using an analog-to-digital converter (ADC) and a digital signal processor (DSP)
214
Apply the digital leakage reduction signal to a Tx leakage signal reduction module to minimize a Tx leakage signal in the receive signal

FIG. 2

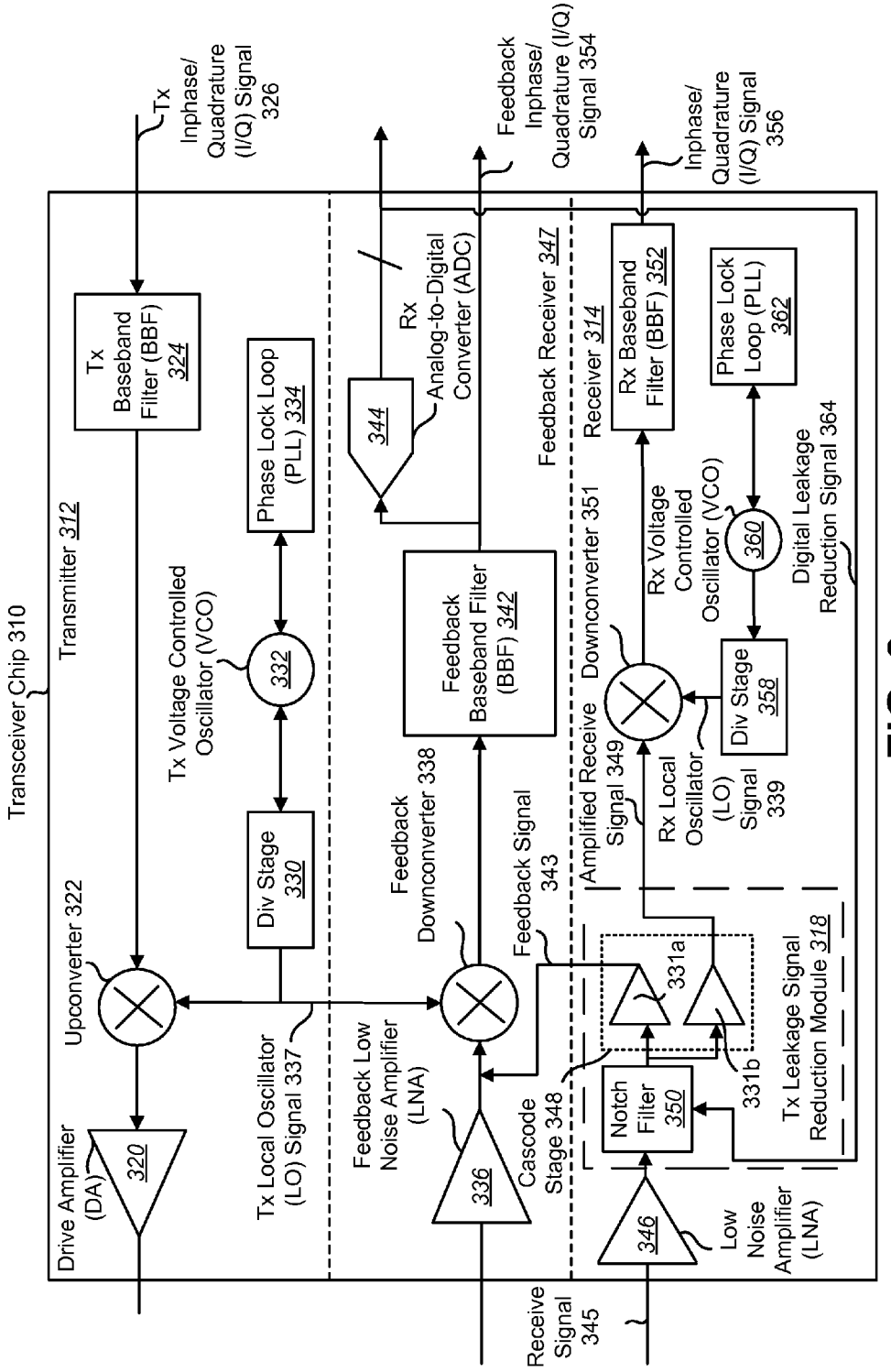

Transceiver Chip 310
Transmitter 312
Tx Inphase/ Quadrature (I/Q) Signal 326
Tx Baseband Filter (BBF) 324
Upconverter 322
Drive Amplifier (DA) 320
Tx Voltage Controlled Oscillator (VCO) 332
Phase Lock Loop (PLL) 334
Div Stage 330
Tx Local Oscillator (LO) Signal 337
Feedback Low Noise Amplifier (LNA) 336
Feedback Downconverter 338
Feedback Baseband Filter (BBF) 342
344
Rx Analog-to-Digital Converter (ADC)
Feedback Inphase/ Quadrature (I/Q) Signal 354
Feedback Receiver 347
Feedback Signal 343
Receive Signal 345
Low Noise Amplifier (LNA) 346
Cascode Stage 348
Notch Filter 350
331a
331b
Tx Leakage Signal Reduction Module 318
Receiver 314
Amplified Receive Signal 349
Downconverter 351
Rx Local Oscillator (LO) Signal 339
Rx Voltage Controlled Oscillator (VCO) 360
Div Stage 358
Rx Baseband Filter (BBF) 352
Phase Lock Loop (PLL) 362
Inphase/ Quadrature (I/Q) Signal 356
Digital Leakage Reduction Signal 364

FIG. 3

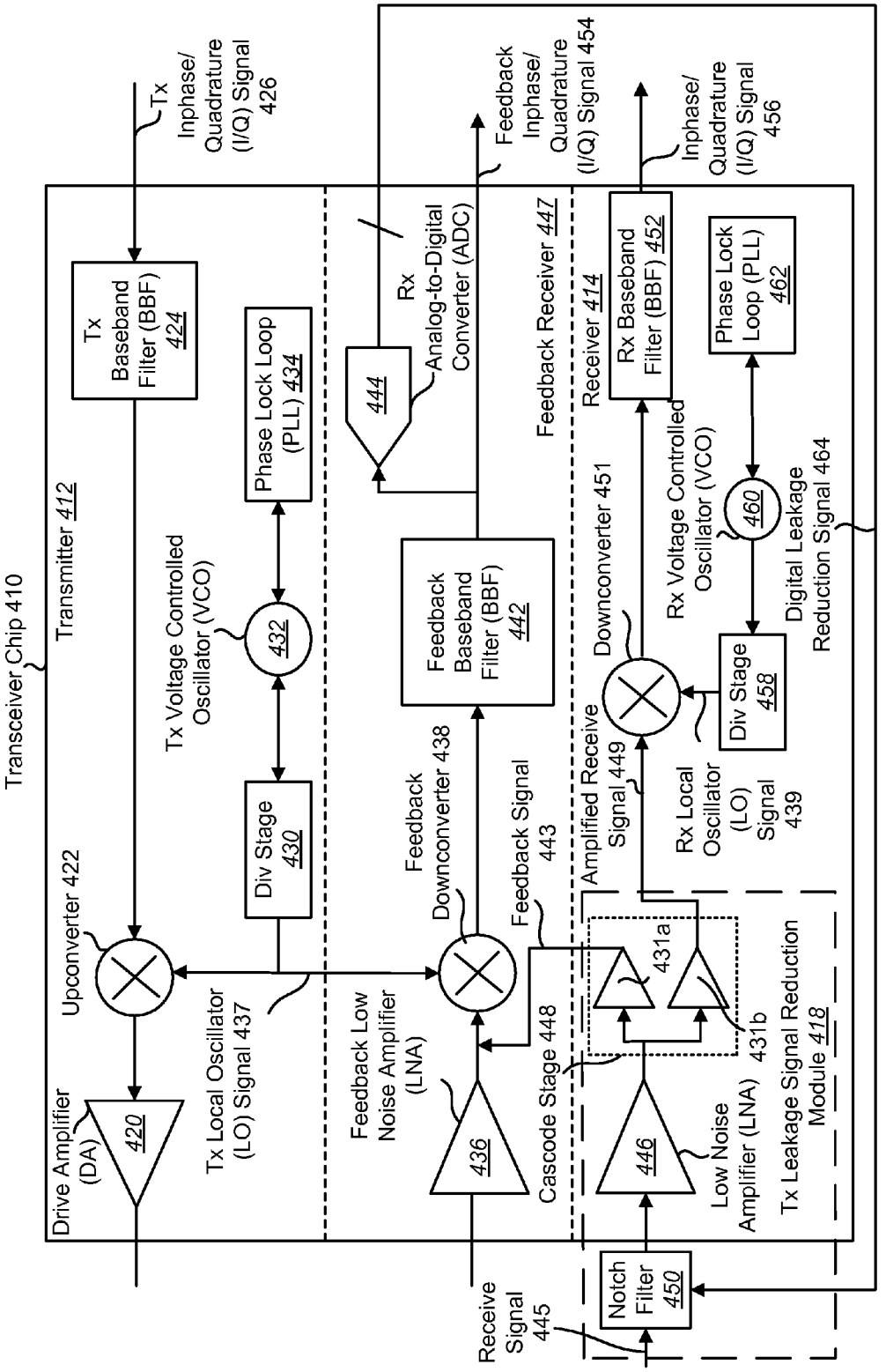

Transceiver Chip 410
Transmitter 412
Receiver 414
Tx Inphase/ Quadrature (I/Q) Signal 426
Tx Baseband Filter (BBF) 424
Phase Lock Loop (PLL) 434
Tx Voltage Controlled Oscillator (VCO)
432
Div Stage 430
Upconverter 422
Drive Amplifier (DA)
420
Tx Local Oscillator (LO) Signal 437
Feedback Low Noise Amplifier (LNA)
436
Feedback Downconverter 438
Feedback Baseband Filter (BBF) 442
444
Rx Analog-to-Digital Converter (ADC)
Feedback Inphase/ Quadrature (I/Q) Signal 454
Feedback Receiver 447
Feedback Signal 443
Cascode Stage 448
Amplified Receive Signal 449
Downconverter 451
Rx Voltage Controlled Oscillator (VCO)
460
Rx Baseband Filter (BBF) 452
Phase Lock Loop (PLL) 462
Inphase/ Quadrature (I/Q) Signal 456
Div Stage 458
Digital Leakage Reduction Signal 464
Rx Local Oscillator (LO) Signal 439
431a
431b
Low Noise Amplifier (LNA)
446
Tx Leakage Signal Reduction Module 418
Notch Filter 450
Receive Signal 445

FIG. 4

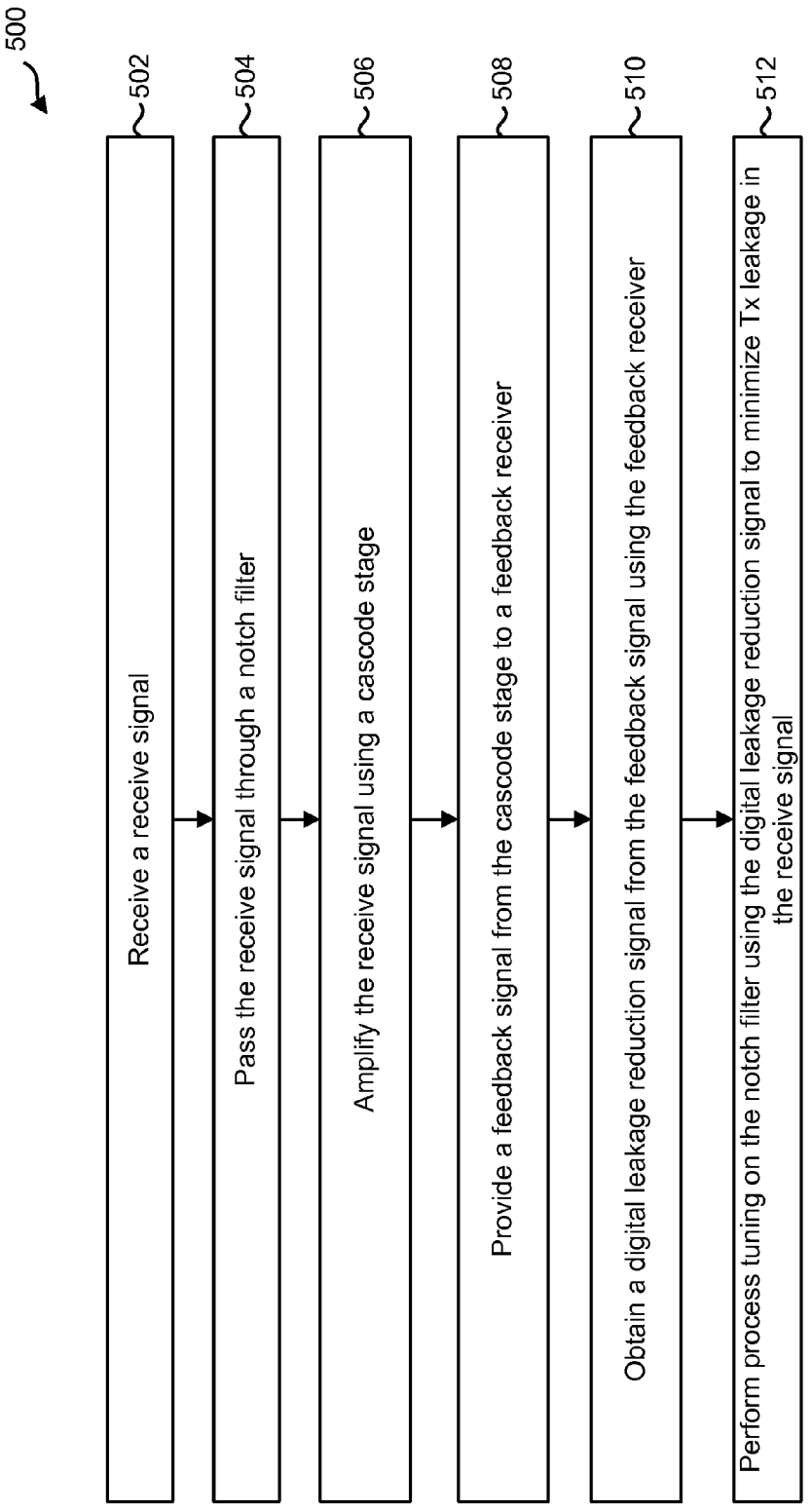

500
502
Receive a receive signal
504
Pass the receive signal through a notch filter
506
Amplify the receive signal using a cascode stage
508
Provide a feedback signal from the cascode stage to a feedback receiver
510
Obtain a digital leakage reduction signal from the feedback signal using the feedback receiver
512
Perform process tuning on the notch filter using the digital leakage reduction signal to minimize Tx leakage in the receive signal

FIG. 5

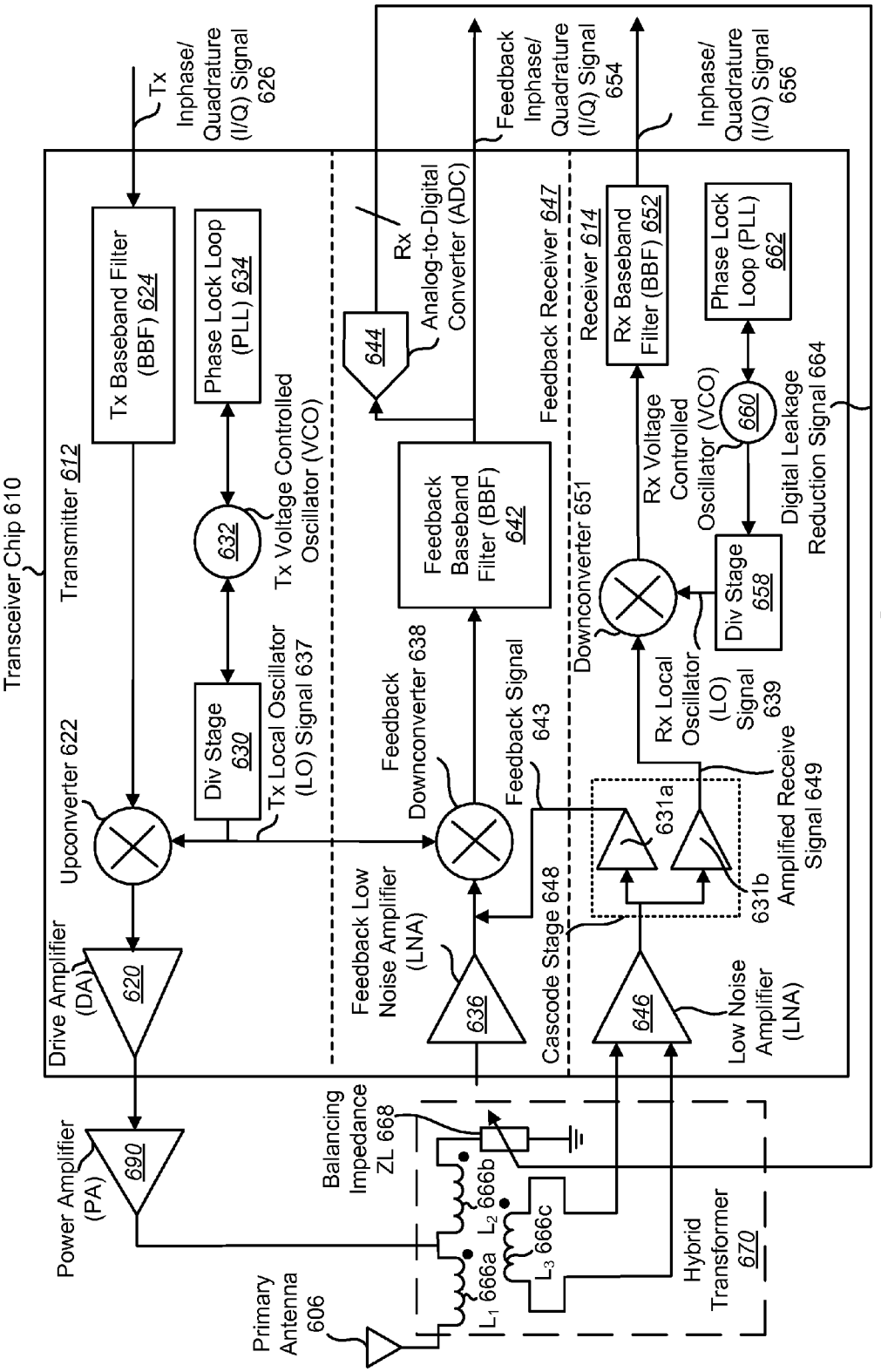

Transceiver Chip 610
Transmitter 612
Tx Inphase/ Quadrature (I/Q) Signal 626
Tx Baseband Filter (BBF) 624
Phase Lock Loop (PLL) 634
632
Tx Voltage Controlled Oscillator (VCO)
Div Stage 630
Tx Local Oscillator (LO) Signal 637
Upconverter 622
Drive Amplifier (DA) 620
Power Amplifier (PA) 690
Primary Antenna 606
Balancing Impedance ZL 668
L1 666a
L2 666b
L3 666c
Hybrid Transformer 670
Feedback Low Noise Amplifier (LNA) 636
Feedback Downconverter 638
Feedback Signal 643
Feedback Baseband Filter (BBF) 642
644
Rx Analog-to-Digital Converter (ADC)
Feedback Inphase/ Quadrature (I/Q) Signal 654
Feedback Receiver 647
Receiver 614
Rx Baseband Filter (BBF) 652
Phase Lock Loop (PLL) 662
Inphase/ Quadrature (I/Q) Signal 656
Rx Voltage Controlled Oscillator (VCO) 660
Digital Leakage Reduction Signal 664
Div Stage 658
Downconverter 651
Rx Local Oscillator (LO) Signal 639
Cascode Stage 648
631a
631b
Amplified Receive Signal 649
Low Noise Amplifier (LNA) 646

FIG. 6

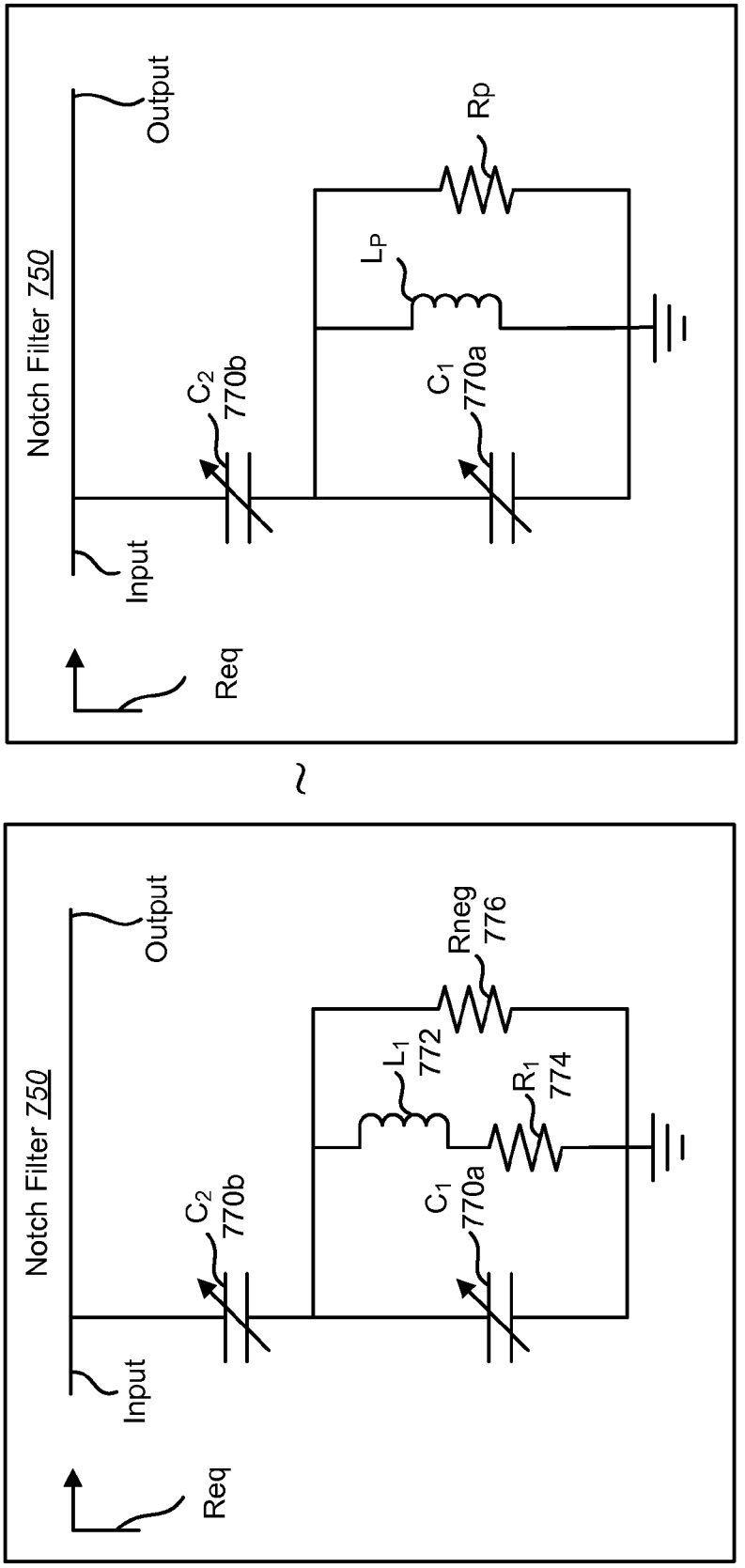

Notch Filter 750
Output
Input
Req
C_2 770b
C_1 770a
L_P
Rp
L_1 772
R_1 774
Rneg 776

FIG. 7

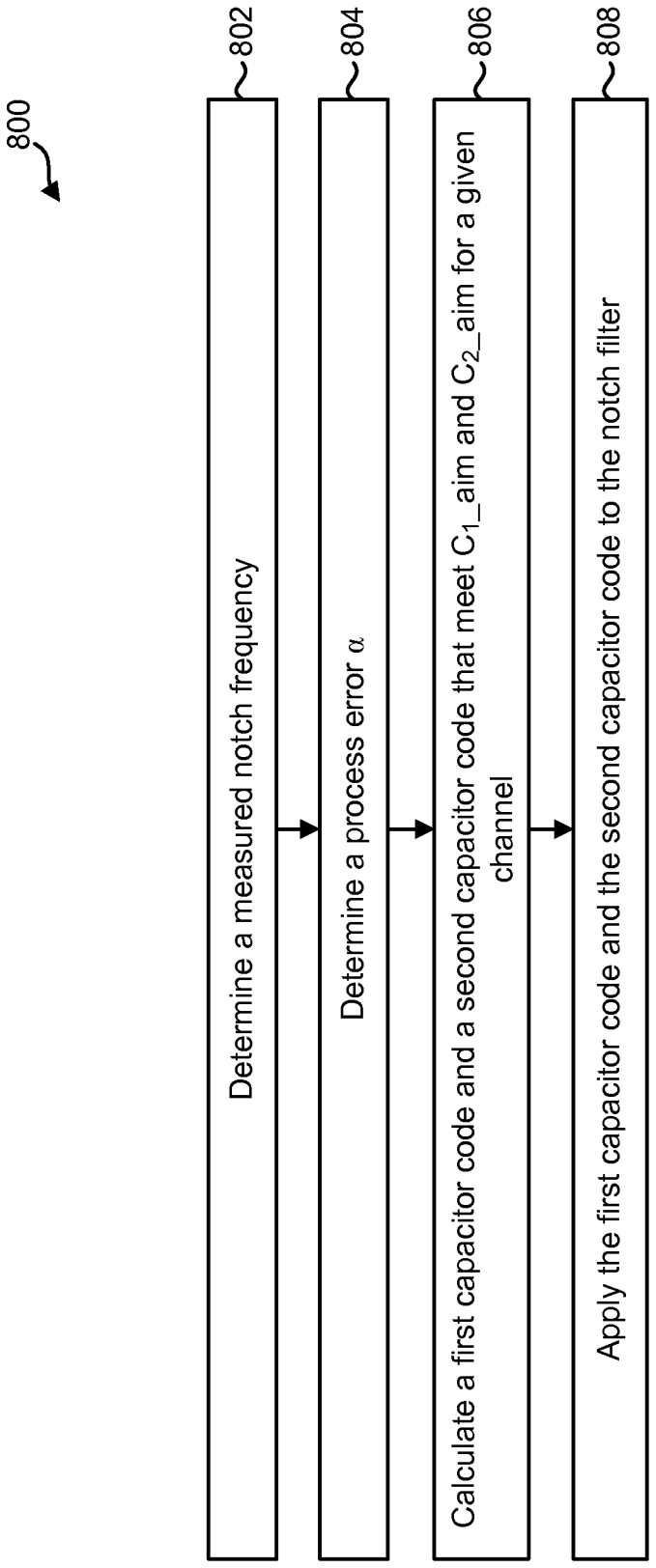

800
802
Determine a measured notch frequency
804
Determine a process error α
806
Calculate a first capacitor code and a second capacitor code that meet C_1_aim and C_2_aim for a given channel
808
Apply the first capacitor code and the second capacitor code to the notch filter

FIG. 8

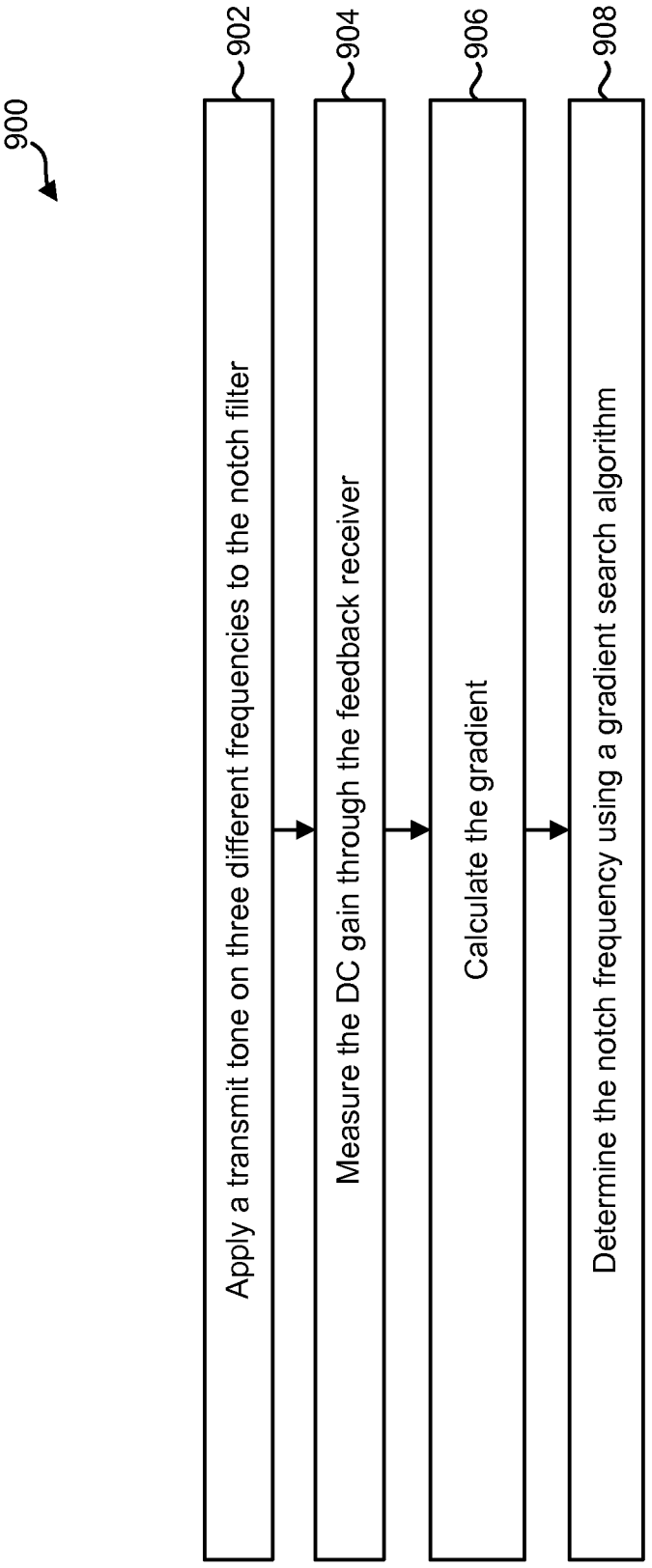

900
902
Apply a transmit tone on three different frequencies to the notch filter
904
Measure the DC gain through the feedback receiver
906
Calculate the gradient
908
Determine the notch frequency using a gradient search algorithm

FIG. 9

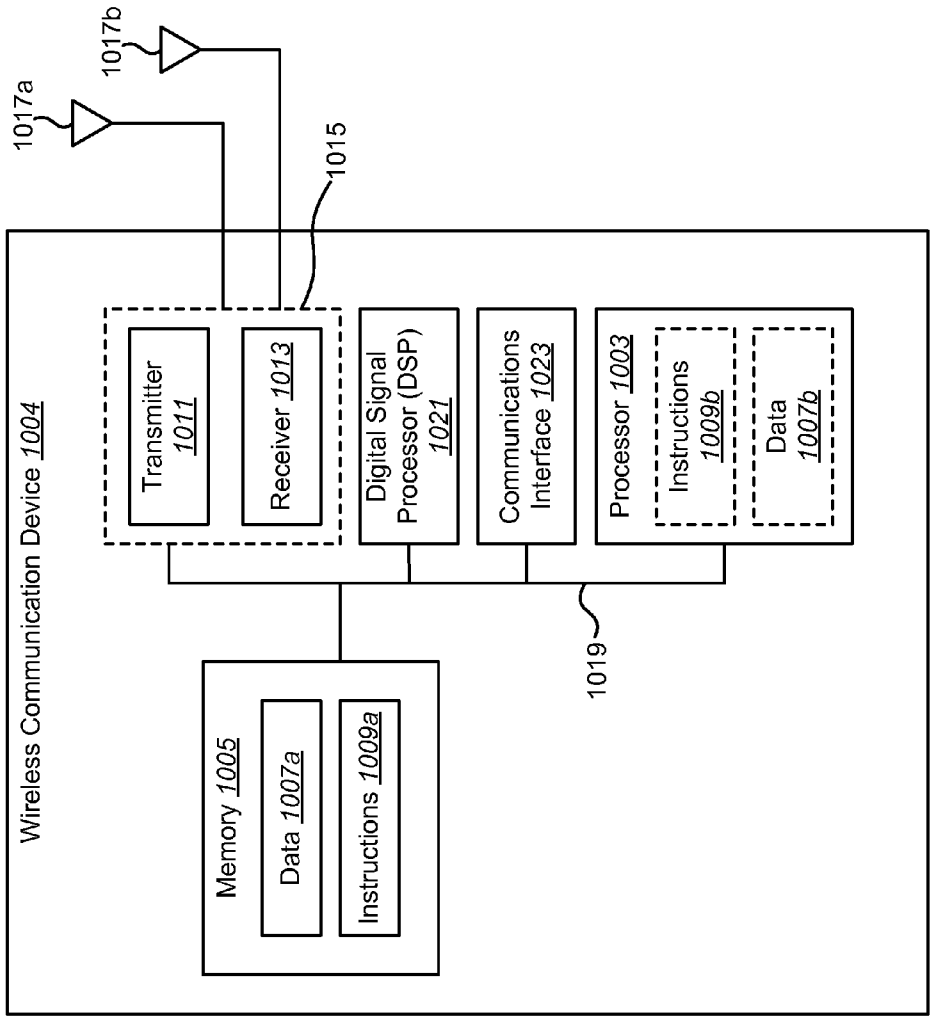

1017b
1017a
1015
Wireless Communication Device 1004
Transmitter 1011
Receiver 1013
Digital Signal Processor (DSP) 1021
Communications Interface 1023
Processor 1003
Instructions 1009b
Data 1007b
Memory 1005
Data 1007a
Instructions 1009a
1019

FIG. 10

TUNABLE NOTCH FILTER USING FEEDBACK THROUGH AN EXISTING FEEDBACK RECEIVER

CLAIM OF PRIORITY UNDER 35 U.S.C. X119

[0001] The present Application for Patent claims priority to Provisional Application No. 61/618,483, entitled "Tunable notch filter using feedback through an existing envelope tracking (ET) receiver" filed Mar. 30, 2012, and assigned to the assignee hereof and hereby expressly incorporated by reference herein.

TECHNICAL FIELD

[0002] The present disclosure relates generally to wireless devices for communication systems. More specifically, the present disclosure relates to systems and methods for a tunable notch filter using feedback through an existing feedback receiver.

BACKGROUND

[0003] Electronic devices (cellular telephones, wireless modems, computers, digital music players, Global Positioning System units, Personal Digital Assistants, gaming devices, etc.) have become a part of everyday life. Small computing devices are now placed in everything from automobiles to housing locks. The complexity of electronic devices has increased dramatically in the last few years. For example, many electronic devices have one or more processors that help control the device, as well as a number of digital circuits to support the processor and other parts of the device.

[0004] Electronic devices may transmit and receive wireless signals simultaneously. Because of the distance between an electronic device and a base station, wireless signals received by the electronic device may have considerably less amplitude than wireless signals transmitted by the electronic device. As such, portions of the transmit signal may leak onto the received signals, reducing the signal quality of the received signals. These leaked transmit signals may be filtered out. However, non-adaptive filters are limited in both the amount of signal removed and the frequency band of the signal removed. Benefits may be realized by using adaptive filters that adapt to the leakage signal that appears on the received signal.

SUMMARY

[0005] A wireless communication device configured for reducing Tx leakage in a receive signal is described. The wireless device includes a transceiver chip. The transceiver chip includes a receiver, a feedback receiver and a transmitter. The transceiver chip also includes a Tx leakage signal reduction module. The Tx leakage signal reduction module reuses the feedback receiver.

[0006] The Tx leakage signal reduction module may include a notch filter that reduces Tx leakage in the receive signal. The notch filter may be located on the transceiver chip. The notch filter may be coupled to an output of a low noise amplifier that receives the receive signal. The notch filter may instead be located off the transceiver chip. The notch filter may receive the receive signal. An output of the notch filter may be coupled to an input of a low noise amplifier on the transceiver chip.

[0007] The receiver may provide a feedback signal to the feedback receiver. The feedback receiver may provide a digital leakage reduction signal to the Tx leakage signal reduction module. The digital leakage reduction signal may tune a notch filter in the Tx leakage signal reduction module to minimize Tx leakage in the receive signal. The notch filter may include a first variable capacitor, a second variable capacitor, a first resistor, a second resistor and an inductor. The notch filter may be tuned to provide reliable rejection of Tx leakage across process, voltage and temperature. The digital leakage reduction signal may tune a balancing impedance in a hybrid transformer on the wireless communication device.

[0008] The hybrid transformer may include a first inductor, a second inductor and a third inductor. The balancing impedance may be coupled between the second inductor and ground. The feedback signal may be provided to a feedback downconverter in the feedback receiver by a first amplifier in a cascode stage in the receiver. An output of the feedback downconverter may be coupled to an analog-to-digital converter via a feedback baseband filter. An output of the analog-to-digital converter may be converted to the digital leakage reduction signal by a digital signal processor.

[0009] A method for reducing Tx leakage in a receive signal is also described. The receive signal is received. The receive signal is processed in a receiver. A feedback signal is provided from the receiver to a feedback downconverter. The feedback signal is converted to a digital leakage reduction signal using an analog-to-digital converter and a digital signal processor. The digital leakage reduction signal is used to reduce Tx leakage in the receive signal.

[0010] The feedback signal may be downconverted using the feedback downconverter. The downconverted feedback signal may be filtered using a feedback baseband filter. Processing the receive signal in the receiver may include passing the receive signal through a notch filter.

[0011] A measured notch frequency of the notch filter may be determined A process error may also be determined A first capacitor code and a second capacitor code may be calculated that meet requirements for a channel. The first capacitor code may be applied to the first variable capacitor and the second capacitor code may be applied to the second variable capacitor.

[0012] Determining a measured notch frequency of the notch filter may include applying a transmit tone on three different frequencies to the notch filter, measuring a DC gain through the feedback receiver, calculating a gradient and determining the measured notch frequency using a gradient search algorithm.

[0013] An apparatus for reducing Tx leakage in a receive signal is described. The apparatus includes means for receiving the receive signal. The apparatus also includes means for processing the receive signal in a receiver. The apparatus further includes means for providing a feedback signal from the receiver to a feedback downconverter. The apparatus also includes means for converting the feedback signal to a digital leakage reduction signal. The apparatus further includes means for using the digital leakage reduction signal to reduce Tx leakage in the receive signal.

[0014] A computer-program product for reducing Tx leakage in a receive signal is also described. The computer-program product includes a non-transitory computer-readable medium having instructions thereon. The instructions include code for causing a wireless communication device to receive the receive signal. The instructions also include code for causing the wireless communication device to process the

receive signal in a receiver. The instructions further include code for causing the wireless communication device to provide a feedback signal from the receiver to a feedback down-converter. The instructions also include code for causing the wireless communication device to convert the feedback signal to a digital leakage reduction signal using an analog-to-digital converter and a digital signal processor. The instructions further include code for causing the wireless communication device to use the digital leakage reduction signal to reduce Tx leakage in the receive signal.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] FIG. **1** shows a wireless communication device for use in the present systems and methods;

[0016] FIG. **2** is a flow diagram of a method for minimizing a Tx leakage signal in a primary receive signal;

[0017] FIG. **3** is a block diagram illustrating a transceiver chip that includes a Tx leakage signal reduction module;

[0018] FIG. **4** is a block diagram illustrating another transceiver chip that includes a Tx leakage signal reduction module;

[0019] FIG. **5** is a flow diagram of another method for minimizing a Tx leakage signal in a primary receive signal;

[0020] FIG. **6** is a block diagram illustrating Tx leakage signal reduction using an integrated duplexer;

[0021] FIG. **7** is a circuit diagram illustrating a notch filter;

[0022] FIG. **8** is a flow diagram of a method for process tuning a notch filter;

[0023] FIG. **9** is a flow diagram of a method for finding the measured notch frequency of a notch filter; and

[0024] FIG. **10** illustrates certain components that may be included within a wireless communication device.

DETAILED DESCRIPTION

[0025] The 3rd Generation Partnership Project (3GPP) is a collaboration between groups of telecommunications associations that aims to define a globally applicable 3rd generation (3G) mobile phone specification. 3GPP Long Term Evolution (LTE) is a 3GPP project aimed at improving the Universal Mobile Telecommunications System (UMTS) mobile phone standard. The 3GPP may define specifications for the next generation of mobile networks, mobile systems and mobile devices. In 3GPP LTE, a mobile station or device may be referred to as a "user equipment" (UE).

[0026] 3GPP specifications are based on evolved Global System for Mobile Communications (GSM) specifications, which are generally known as the Universal Mobile Telecommunications System (UMTS). 3GPP standards are structured as releases. Discussion of 3GPP thus frequently refers to the functionality in one release or another. For example, Release 99 specifies the first UMTS third generation (3G) networks, incorporating a CDMA air interface. Release 6 integrates operation with wireless local area networks (LAN) networks and adds High Speed Uplink Packet Access (HSUPA). Release 8 introduces dual downlink carriers and Release 9 extends dual carrier operation to uplink for UMTS.

[0027] CDMA2000 is a family of 3rd generation (3G) technology standards that use code division multiple access (CDMA) to send voice, data and signaling between wireless devices. CDMA2000 may include CDMA2000 1×, CDMA2000 EV-DO Rev. 0, CDMA2000 EV-DO Rev. A and CDMA2000 EV-DO Rev. B. 1× or 1×RTT refers to the core CDMA2000 wireless air interface standard. 1× more specifically refers to 1 times Radio Transmission Technology and indicates the same radio frequency (RF) bandwidth as used in IS-95. 1×RTT adds 64 additional traffic channels to the forward link. EV-DO refers to Evolution-Data Optimized. EV-DO is a telecommunications standard for the wireless transmission of data through radio signals.

[0028] FIG. **1** shows a wireless communication device **104** for use in the present systems and methods. A wireless communication device **104** may also be referred to as, and may include some or all of the functionality of, a terminal, an access terminal, a user equipment (UE), a subscriber unit, a station, etc. A wireless communication device **104** may be a cellular phone, a personal digital assistant (PDA), a wireless device, a wireless modem, a handheld device, a laptop computer, a PC card, compact flash, an external or internal modem, a wireline phone, etc. A wireless communication device **104** may be mobile or stationary. A wireless communication device **104** may communicate with zero, one or multiple base stations on a downlink and/or an uplink at any given moment. The downlink (or forward link) refers to the communication link from a base station to a wireless communication device **104**, and the uplink (or reverse link) refers to the communication link from a wireless communication device **104** to a base station. Uplink and downlink may refer to the communication link or to the carriers used for the communication link.

[0029] A wireless communication device **104** may operate in a wireless communication system that includes other wireless devices, such as base stations. A base station is a station that communicates with one or more wireless communication devices **104**. A base station may also be referred to as, and may include some or all of the functionality of, an access point, a broadcast transmitter, a Node B, an evolved Node B, etc. Each base station provides communication coverage for a particular geographic area. A base station may provide communication coverage for one or more wireless communication devices **104**. The term "cell" can refer to a base station and/or its coverage area, depending on the context in which the term is used.

[0030] Communications in a wireless communication system (e.g., a multiple-access system) may be achieved through transmissions over a wireless link. Such a communication link may be established via a single-input and single-output (SISO) or a multiple-input and multiple-output (MIMO) system. A multiple-input and multiple-output (MIMO) system includes transmitter(s) and receiver(s) equipped, respectively, with multiple (NT) transmit antennas and multiple (NR) receive antennas for data transmission. SISO systems are particular instances of a multiple-input and multiple-output (MIMO) system. The multiple-input and multiple-output (MIMO) system can provide improved performance (e.g., higher throughput, greater capacity or improved reliability) if the additional dimensionalities created by the multiple transmit and receive antennas are utilized.

[0031] The wireless communication system may utilize both single-input and multiple-output (SIMO) and multiple-input and multiple-output (MIMO). The wireless communication system may be a multiple-access system capable of supporting communication with multiple wireless communication devices **104** by sharing the available system resources (e.g., bandwidth and transmit power). Examples of such multiple-access systems include code division multiple access (CDMA) systems, wideband code division multiple access (W-CDMA) systems, time division multiple access (TDMA)

systems, frequency division multiple access (FDMA) systems, orthogonal frequency division multiple access (OFDMA) systems, single-carrier frequency division multiple access (SC-FDMA) systems, 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE) systems and spatial division multiple access (SDMA) systems.

[0032] The wireless communication device **104** may include a primary antenna **106** and a secondary antenna **108**. In one configuration, the primary antenna **106** may be used for transmitting wireless signals and receiving a primary signal while the secondary antenna **108** may be used for receiving a secondary signal. Both the primary antenna **106** and the secondary antenna **108** may be coupled to a transceiver chip **110** on the wireless communication device **104**.

[0033] The transceiver chip **110** may include a transmitter **112**, a primary receiver (PRx) **114**, a diversity receiver (DRx) **116**, a feedback receiver **147** and a Tx leakage signal reduction module **118**. The Tx leakage signal reduction module include a notch filter or an adjustable impedance. In one configuration, portions of the Tx leakage signal reduction module **118** may be located on the transceiver chip **110** while other portions of the Tx leakage signal reduction module **118** may be located off the transceiver chip **110**.

[0034] In full duplex systems, wireless devices may transmit and receive simultaneously. The transmit frequency and the receive frequency may be separated to prevent interference. Typically, the transmit signal broadcast by a wireless device has a significantly larger amplitude than the signals received by the wireless device. This is due to the attenuation of wireless signals (i.e., received signals have attenuated during wireless travel while transmit signals need higher amplitude to ensure proper reception). For this reason, transmit signals often interfere with receive signals. The noise from the transmit signal that interferes with the receive signal may be referred to as the Tx leakage signal. It is desirable to reduce or eliminate the Tx leakage signal in the receive signal. The Tx leakage signal may be removed using filters. The Tx leakage signal reduction module **118** may reduce the amplitude of the Tx leakage signal using feedback while simultaneously improving the second order intercept point (IIP2) and Rx local oscillator (LO) phase noise requirements. It is desirable for the Tx leakage signal reduction module **118** to reuse an existing feedback receiver. In one configuration, the Tx leakage signal reduction module **118** may improve the second order intercept point (IIP2) without burning a significant amount of current.

[0035] In one configuration, the use of the Tx leakage signal reduction module may allow for the elimination of an external diversity surface acoustic wave (SAW) filter on the wireless communication device **104**. Removing an external diversity surface acoustic wave (SAW) filter on the wireless communication device **104** may reduce the cost, size and power consumption of the wireless communication device **104**.

[0036] FIG. **2** is a flow diagram of a method **200** for minimizing a Tx leakage signal in a primary receive signal. The method **200** may be performed by a wireless communication device **104**. In one configuration, the method **200** may be performed by a Tx leakage signal reduction module **118** on a transceiver chip **110** in the wireless communication device **104**. The wireless communication device **104** may receive **202** a receive signal. The receive signal may be received by the primary antenna **106**. The receive signal may include the desired receive signal and a Tx leakage signal.

[0037] The wireless communication device **104** may process **204** the receive signal in a receiver. In one configuration, the wireless communication device **104** may process **204** the receive signal in a primary receiver (PRx) **114** or a diversity receiver (DRx) **116**. The wireless communication device **104** may provide **206** a feedback signal from the receiver to a feedback downconverter in a feedback receiver. In one configuration, the feedback signal may be output from a cascode stage in the receiver. The wireless communication device **104** may then downconvert **208** the frequency of the feedback signal using the feedback downconverter in the feedback receiver. The wireless communication device **104** may filter **210** the feedback signal in the feedback receiver. The wireless communication device **104** may then convert **212** the feedback signal to a digital leakage reduction signal using an analog-to-digital converter (ADC) and a digital signal processor (DSP). In one configuration, the digital signal processor (DSP) may be located on a modem.

[0038] The wireless communication device **104** may apply **214** the digital leakage reduction signal to a Tx leakage signal reduction module **118** to minimize the Tx leakage signal in the receive signal. For example, the digital leakage reduction signal may be used to adjust the values of a notch filter. The notch filter may be part of the receiver. Alternatively, the notch filter may be located off the transceiver chip **110** on the wireless communication device **104**. The notch filter may filter out the Tx leakage signal prior to the cascode stage. Thus, the configuration of the notch filter may be adjusted using feedback to minimize the Tx leakage signal in the receive signal. As another example, the digital leakage reduction signal may be used to adjust a tunable impedance in a hybrid transformer on the wireless communication device **104**. Adjusting a tunable impedance in a hybrid transformer is discussed in additional detail below in relation to FIG. **6**. Adjusting the tunable impedance may reduce the Tx leakage signal in the wireless signal.

[0039] FIG. **3** is a block diagram illustrating a transceiver chip **310** that includes a Tx leakage signal reduction module **318**. The transceiver chip **310** of FIG. **3** may be one configuration of the transceiver chip **110** of FIG. **1**. The transceiver chip **310** may include a transmitter **312**, a feedback receiver **347** and a receiver **314**. The receiver **314** may be a primary receiver (PRx) or a diversity receiver (DRx). In one configuration, the feedback receiver **347** may be part of the transmitter **312**.

[0040] The transmitter **312** may receive a Tx inphase/quadrature (I/Q) signal **326**. The Tx inphase/quadrature (I/Q) signal **326** may be passed through a Tx baseband filter (BBF) **324** before being upconverted to a transmit frequency by an upconverter **322**. The upconverted transmit signal may then be amplified by a drive amplifier (DA) **320** before being transmitted. The transmitter **312** may include a phase lock loop (PLL) **334**, a Tx voltage controlled oscillator (VCO) **332** and a Div stage **330** that are used to generate a Tx local oscillator (LO) signal **337**. The Tx local oscillator (LO) signal **337** may be provided to the upconverter **322**.

[0041] The feedback receiver **347** may be used to regulate the transmitter **312** (e.g., to provide periodic feedback about the power levels of the transmitter **312** to ensure that the transmitter **312** is transmitting with the proper amount of power). During regular operation, the feedback receiver **347** may be off for considerable amounts of time (to save power). In other words, the feedback receiver **347** may normally be turned on for short amounts of time to track the power of the

transmitter **312** and then turned off. Thus, the circuitry in the feedback receiver **347** may be reused to tune a notch filter **350**. For example, the feedback baseband filter (BBF) **342** and the Rx analog-to-digital converter (ADC) **344** may be reused to tune the notch filter **350**.

[0042] The circuitry in the feedback receiver **347** may include a feedback low noise amplifier (LNA) **336** that receives transmit signals. The output of the feedback low noise amplifier (LNA) **336** may be coupled to a feedback downconverter **338** that reuses the synthesizer of the transmitter **312**. Thus, the feedback downconverter **338** may receive the Tx local oscillator (LO) signal **337**. The output of the feedback downconverter **338** may be coupled to a feedback baseband filter (BBF) **342**. The feedback baseband filter (BBF) **342** may output the feedback inphase/quadrature (I/Q) signal **354** to the modem. The output of the feedback baseband filter (BBF) **342** may also be passed through an analog-to-digital converter (ADC) **344** before being provided to the modem (although only one analog-to-digital converter (ADC) **344** is shown, two analog-to-digital converters (ADCs) **344** may be used, one for the inphase signal and one for the quadrature signal).

[0043] To reuse the feedback receiver **347**, the receiver **314** may provide a feedback signal **343** to the feedback downconverter **338**. The feedback signal **343** may be current that is bled from a cascode stage **348** in a Tx leakage signal reduction module **318**. For example, the cascode stage **348** may include a first amplifier **331***a* and a second amplifier **331***b*. The output of the first amplifier **331***a* may be provided to the feedback downconverter **338** as the feedback signal **343**. The feedback signal **343** may be either a voltage signal or a current signal. In one configuration, the feedback signal **343** may be current bled from a cascode stage **348**. The output of the second amplifier **331***b* may be provided to a downconverter **351** on the receiver **314** as the amplified receive signal **349**. The feedback signal **343** may provide feedback about a notch filter **350** in the Tx leakage signal reduction module **318**, allowing the notch filter **350** to be tuned. The feedback signal **343** may be processed by the feedback receiver **347** (via the Rx analog-to-digital converter (ADC) **344**) to obtain a digital leakage reduction signal **364**. Additional digital signal processing (e.g., by the modem) may be performed on the output of the Rx analog-to-digital converter (ADC) **344** (such as by a digital signal processor (DSP)) to obtain the digital leakage reduction signal **364**. The digital leakage reduction signal **364** may be used to tune the Tx leakage signal reduction module **318** in the receiver **314**.

[0044] The receiver **314** may include a low noise amplifier (LNA) **346**. The low noise amplifier (LNA) **346** may receive a receive signal **345**. The receive signal **345** may include undesirable Tx leakage. To reduce the Tx leakage in the receive signal **345**, the primary **314** may include a Tx leakage reduction module **318**. The Tx leakage signal reduction module **318** may include the cascode stage **348** and the notch filter **350**. The notch filter **350** may be coupled to the output of the low noise amplifier (LNA) **346**. The notch filter **350** may also receive the digital leakage reduction signal **364**. The digital leakage reduction signal **364** may provide accurate notch filter **350** tuning across process, voltage and temperature (PVT) to minimize the Tx leakage in the receive signal **345**. The Tx leakage signal reduction module **318** may use existing hardware (such as the feedback receiver **347**) to reduce the Tx leakage signal (by tuning the notch filter **350** to remove the Tx leakage signal).

[0045] The output of the low noise amplifier (LNA) **346** may be coupled to the notch filter **350**. The output of the notch filter **350** may be coupled to the cascode stage **348**. As discussed above, the cascode stage **348** may include a first amplifier **331***a* and a second amplifier **331***b*. The output of the second amplifier may be provided to a downconverter **351** on the receiver **314**. In one configuration, 10% of the current is bled as the feedback signal **343**.

[0046] The receiver **314** may include a phase lock loop (PLL) **362**, an Rx voltage controlled oscillator (VCO) **360** and a Div stage **358** that provide an Rx local oscillator (LO) signal **339** to the downconverter **351**. The downconverter **351** may convert signals to baseband frequency. The output of the downconverter **351** may be coupled to an Rx baseband filter (BBF) **352**. The Rx baseband filter (BBF) **352** may then output the inphase/quadrature (I/Q) signal **356**. Using the feedback receiver **347** to tune the notch filter **350** may provide reliable rejection of the Tx leakage signal across process, voltage and temperature (PVT).

[0047] FIG. **4** is a block diagram illustrating another transceiver chip **410** that includes a Tx leakage signal reduction module **418**. The Tx leakage signal reduction module **418** may include a notch filter **450** that is located off the transceiver chip **410**. The transceiver chip **410** of FIG. **4** may be one configuration of the transceiver chip **110** of FIG. **1**. The transceiver chip **410** may include a transmitter **412**, a feedback receiver **447** and a receiver **414**. In one configuration, the feedback receiver **447** may be part of the transmitter **412**. The receiver **414** may be a primary receiver (PRx) or a diversity receiver (DRx).

[0048] The transmitter **412** may receive a Tx inphase/quadrature (I/Q) signal **426**. The Tx inphase/quadrature (I/Q) signal **426** may be passed through a Tx baseband filter (BBF) **424** before being upconverted to a transmit frequency by an upconverter **422**. The transmit signal may then be amplified by a drive amplifier (DA) **420** before being transmitted. The transmitter **412** may include a phase lock loop (PLL) **434**, a Tx voltage controlled oscillator (VCO) **432** and a Div stage **430** that are used to generate a Tx local oscillator (LO) signal **437**. The Tx local oscillator (LO) signal **437** may be provided to the upconverter **422**.

[0049] The feedback receiver **447** may be used to regulate the transmitter **412** (e.g., to provide periodic feedback about the power levels of the transmitter **412** to ensure that the transmitter **412** is transmitting with the proper amount of power). During regular operation, the feedback receiver **447** may be off for considerable amounts of time (to save power). In other words, the feedback receiver **447** may normally be turned on for short amounts of time to track the power of the transmitter **412** and then turned off Thus, the circuitry in the feedback receiver **447** may be reused to tune a notch filter **450**. Tuning using the feedback receiver **447** may be performed only one time or performed periodically, when the feedback receiver **447** is idle.

[0050] The circuitry in the feedback receiver **447** may include a feedback low noise amplifier (LNA) **436** that receives transmit signals. The output of the feedback low noise amplifier (LNA) **436** may be coupled to a feedback downconverter **438** that reuses the synthesizer of the transmitter **412**. Thus, the feedback downconverter **438** may receive the Tx local oscillator (LO) signal **437**. The output of the feedback downconverter **438** may be coupled to a feedback baseband filter (BBF) **442**. The feedback baseband filter (BBF) **442** may output the feedback inphase/quadrature (I/Q)

signal **454** to the modem. The output of the feedback baseband filter (BBF) **442** may also be passed through an analog-to-digital converter (ADC) **444** before being provided to the modem.

[0051] To reuse the feedback receiver **447**, the receiver **414** may provide a feedback signal **443** to the feedback downconverter **438**. The feedback signal **443** may be current that is bled from a cascode stage **448** in a Tx leakage signal reduction module **418**. For example, the cascode stage **448** may include a first amplifier **431***a* and a second amplifier **431***b*. The output of the first amplifier **431***a* may be provided to the feedback downconverter **438** as the feedback signal **443**. The output of the second amplifier **431***b* may be provided to a downconverter **451** on the receiver **414** as the amplified receive signal **449**. The feedback signal **438** may provide feedback about a notch filter **450** in the Tx leakage signal reduction module **418**, allowing the notch filter **450** to be tuned. The feedback signal **443** may be processed by the feedback receiver **447** (via the Rx analog-to-digital converter (ADC) **444**) to obtain a digital leakage reduction signal **464**. Additional digital signal processing (e.g., by the modem) may be performed on the output of the Rx analog-to-digital converter (ADC) **444** to obtain the digital leakage reduction signal **464**. The digital leakage reduction signal **464** may be used to tune the Tx leakage signal reduction module **418** in the receiver **414**.

[0052] The Tx leakage signal reduction module **418** may include a notch filter **450**. In one configuration, the notch filter **450** may not be located on the transceiver chip **410** (and thus may be located off-chip). The notch filter **450** may receive a receive signal **445**. The notch filter **450** may also receive the digital leakage reduction signal **464** (which tunes the notch filter **450**). The output of the notch filter **450** may be provided to the cascode stage **448**. As discussed above, the cascode stage **448** may include a first amplifier **431***a* and a second amplifier **431***b*. The output of the first amplifier **431***a* may be the feedback signal **443** provided to the feedback receiver **447**. The output of the second amplifier **431***b* may be the amplified receive signal **349** provided to the downconverter **451**. In one configuration, 10% of the current in the cascode stage **448** may be bled as the feedback signal **443**.

[0053] The digital leakage reduction signal **464** may provide accurate notch filter **450** tuning across process, voltage and temperature (PVT) to minimize the Tx leakage in the receive signal **445**. The Tx leakage signal reduction module **418** may use existing hardware (such as the feedback receiver **447**) to reduce the Tx leakage signal (by tuning the notch filter **450** to remove the Tx leakage signal).

[0054] The receiver **414** may include a phase lock loop (PLL) **462**, an Rx voltage controlled oscillator (VCO) **460** and a Div stage **458** that provide an Rx local oscillator (LO) signal **439** to the downconverter **451**. The downconverter **451** may convert signals to baseband frequency. The output of the downconverter **451** may be coupled to an Rx baseband filter (BBF) **452**. The Rx baseband filter (BBF) **452** may then output the inphase/quadrature (I/Q) signal **456**. Using the feedback receiver **447** to tune the notch filter **450** may provide reliable rejection of the Tx leakage signal across process, voltage and temperature (PVT).

[0055] FIG. **5** is a flow diagram of another method **500** for minimizing a Tx leakage signal in a receive signal **345**. The method **500** may be performed by a wireless communication device **104**. In one configuration, the method **500** may be performed by a Tx leakage signal reduction module **318** on a transceiver chip **310** in the wireless communication device **104**. The wireless communication device **104** may receive **502** a receive signal **345**. The receive signal **345** may be received by an antenna **106**, **108**. The receive signal **345** may include undesirable Tx leakage.

[0056] The wireless communication device **104** may pass **504** the receive signal **345** through a notch filter **350**. The wireless communication device **104** may amplify **506** the receive signal using a cascode stage **348**. The wireless communication device **104** may provide **508** a feedback signal **343** from the cascode stage **348** to a feedback receiver **347**. The wireless communication device **104** may obtain **510** a digital leakage reduction signal **364** from the feedback signal **343** using the feedback receiver **347**. For example, the feedback signal **343** may be downconverted by a feedback downconverter **338**, filtered by a feedback baseband filter (BBF) **342** and converted to a digital signal by an Rx analog-to-digital converter (ADC) **344** in the feedback receiver **347**.

[0057] The wireless communication device **104** may perform **512** process tuning on the notch filter **350** using the digital leakage reduction signal **364** to minimize Tx leakage in the receive signal **345**. For example, the digital leakage reduction signal **364** may be used to adjust the values of the notch filter **350** (and thus adjust the frequencies filtered by the notch filter **350**).

[0058] FIG. **6** is a block diagram illustrating Tx leakage signal reduction using an integrated duplexer. The integrated duplexer may be implemented using a hybrid transformer **670**. The hybrid transformer **670** may include a first inductor L**1** **666***a*, a second inductor L**2** **666***b* and a third inductor L**3** **666***c*. A coupling may occur between the first inductor L**1** **666***a*, the second inductor L**2** **666***b* and the third inductor L**3** **666***c*. The first inductor L1 **666***a* may be coupled between a primary antenna **606** and the second inductor L**2** **666***b*. The second inductor L**2** **666***b* may be coupled between the first inductor L**1** **666***a* and a balancing impedance ZL **668**. The balancing impedance ZL **668** may also be coupled to ground. The third inductor L**3** **666***c* may be coupled to both a first differential input and a second differential input of a low noise amplifier (LNA) **646** on a transceiver chip **610**. The low noise amplifier (LNA) **646** may be part of a receiver **614**.

[0059] The transceiver chip **610** of FIG. **6** may be one configuration of the transceiver chip **110** of FIG. **1**. The transceiver chip **610** may include a transmitter **612**, a feedback receiver **647** and the receiver **614**. In one configuration, the feedback receiver **647** may be part of the transmitter **612**. The receiver **614** may be a primary receiver (PRx) or a diversity receiver (DRx). The transmitter **612** may receive a Tx inphase/quadrature (I/Q) signal **626**. The Tx inphase/quadrature (I/Q) signal **626** may be passed through a Tx baseband filter (BBF) **624** before being upconverted to a transmit frequency by an upconverter **622**. The transmit signal may then be amplified by a drive amplifier (DA) **620**. The output of the drive amplifier (DA) **620** may be coupled to the input of a power amplifier (PA) **690**. The power amplifier (PA) **690** may be located off the transceiver chip **610**. The output of the power amplifier (PA) **690** may be coupled between the first inductor L**1** **666***a* and the second inductor L**2** **666***b*. The transmitter **612** may include a phase lock loop (PLL) **634**, a Tx voltage controlled oscillator (VCO) **632** and a Div stage **630** that are used to generate a Tx local oscillator (LO) signal **637**. The Tx local oscillator (LO) signal **637** may be provided to the upconverter **622**.

[0060] The feedback receiver **647** may be used to regulate the transmitter **612** (e.g., to provide periodic feedback about the power levels of the transmitter **612** to ensure that the transmitter **612** is transmitting with the proper amount of power). During regular operation, the feedback receiver **647** may be off for considerable amounts of time (to save power). In other words, the feedback receiver **647** may normally be turned on for short amounts of time to track the power of the transmitter **612** and then turned off. Thus, the circuitry in the feedback receiver **647** may be reused to tune the balancing impedance ZL **668**. Tuning using the feedback receiver **447** may be performed only one time or performed periodically, when the feedback receiver **447** is idle.

[0061] The circuitry in the feedback receiver **647** may include a feedback low noise amplifier (LNA) **636** that receives transmit signals. The output of the feedback low noise amplifier (LNA) **436** may be coupled to a feedback downconverter **438** that reuses the synthesizer of the transmitter **412**. Thus, the feedback downconverter **638** may receive the Tx local oscillator (LO) signal **637**. The output of the feedback downconverter **638** may be coupled to a feedback baseband filter (BBF) **642**. The feedback baseband filter (BBF) **642** may output the feedback inphase/quadrature (I/Q) signal **654** to the modem. The output of the feedback baseband filter (BBF) **642** may also be passed through an analog-to-digital converter (ADC) **644** before being provided to the modem.

[0062] To reuse the feedback receiver **647**, the receiver **614** may provide a feedback signal **643** to the feedback downconverter **638**. The feedback signal **643** may be current that is bled from a cascode stage **648** in the receiver **614**. For example, the cascode stage **648** may include a first amplifier **631***a* and a second amplifier **631***b*. The output of the first amplifier **631***a* may be provided to the feedback downconverter **638** as the feedback signal **643**. The output of the second amplifier **631***b* may be provided to a downconverter **651** on the receiver **614** as the amplified receive signal **649**. The feedback signal **638** may provide feedback about the balancing impedance ZL **668** in the hybrid transformer **670**, allowing the balancing impedance ZL **668** to be tuned. The feedback signal **643** may be processed by the feedback receiver **647** (via the Rx analog-to-digital converter (ADC) **644**) to obtain a digital leakage reduction signal **664**. Additional digital signal processing (e.g., by the modem) may be performed on the output of the Rx analog-to-digital converter (ADC) **644** to obtain the digital leakage reduction signal **664**.

[0063] The digital leakage reduction signal **664** may be used to tune the balancing impedance ZL **668** in the hybrid transformer **670**. Using the feedback receiver **647** to tune the balancing impedance ZL **668** may provide reliable rejection of the Tx leakage signal across process, voltage and temperature (PVT). The impedance measured by the primary antenna **606** may be too course for application in a hybrid transformer **670**. By using the balancing impedance ZL **668**, better sensitivity may be obtained. Continuous feedback (via the digital leakage reduction signal **664**) may be used to tune the antenna load.

[0064] The output of the low noise amplifier (LNA) **646** may be coupled to the input of the cascode stage **648**. As discussed above, the cascode stage **648** may include a first amplifier **631***a* and a second amplifier **631***b*. The first amplifier **631***a* may output the feedback signal **643** to the feedback receiver **647**. The second amplifier **631***b* may output the amplified receive signal **649** to a downconverter **651** on the receiver **614**. In one configuration, the cascode stage **648** may bleed off 10% of the current to the feedback receiver **647**.

[0065] The receiver **614** may include a phase lock loop (PLL) **662**, an Rx voltage controlled oscillator (VCO) **660** and a Div stage **658** that provide an Rx local oscillator (LO) signal **639** to the downconverter **651**. The downconverter **651** may convert signals to baseband frequency. The output of the downconverter **651** may be coupled to an Rx baseband filter (BBF) **652**. The Rx baseband filter (BBF) **652** may then output the inphase/quadrature (I/Q) signal **656**.

[0066] FIG. **7** is a circuit diagram illustrating a notch filter **750**. The notch filter **750** of FIG. **7** may be one configuration of the notch filter **350** of FIG. **3** or the notch filter **450** of FIG. **4**. The notch filter **750** may have an input and an output. The notch filter **750** may include a first variable capacitor C**1** **770***a* and a second variable capacitor C**2** **770***b*. The first variable capacitor C**1** **770***a* may be coupled between the second variable capacitor C**2** **770***b* and ground. The second variable capacitor C**2** **770***b* may be coupled to the input of the notch filter **750**.

[0067] The notch filter **750** may also include a resistor R**1** **774** and an inductor L**1** **772**. The resistor R**1** **774** may be coupled between the inductor L**1** **772** and ground. The inductor L**1** **772** may be coupled between the resistor R**1** **774** and the second variable capacitor C**2** **770***b*. The notch filter **750** may also include a resistor Rneg **776**. The resistor Rneg **776** may be coupled between ground and the second variable capacitor C**2** **770***b*. The resistor Rneg **776** is the equivalent negative resistor of a circuit (such as a negative-gm circuit) that is used to improve the equivalent Quality factor (Q) of the inductor L**1** **772**. The Quality factor (Q) of the notch filter **750** may be found using Equation (1):

$$Q = \left(\frac{\omega_0 L_1}{R_1}\right). \tag{1}$$

[0068] In Equation (1), ω_0 is the notch frequency of the notch filter **750**. The effective paddle inductance Lp from the bottom of the capacitor C**2** **770***b* to ground may be found using Equation (2):

$$L_p = L_1 \cdot \left(\frac{Q^2+1}{Q^2}\right). \tag{2}$$

[0069] The passband frequency f_p of the notch filter **750** may be found using Equation (3):

$$f_p = \frac{1}{2\pi\sqrt{L_p \cdot C_1}}. \tag{3}$$

[0070] The notch frequency f_n of the notch filter **750** may be found using Equation (4):

$$f_n = \frac{1}{2\pi\sqrt{L_p \cdot (C_1 + C_2)}}. \tag{4}$$

[0071] The value for the first variable capacitor C1 **770***a* may be found using Equation (5):

$$C_1 = \frac{1}{(2\pi \cdot f_p)^2 \cdot L_p}. \quad (5)$$

[0072] Likewise, the value for the second variable capacitor C2 **770***b* may be found using Equation (6):

$$C_2 = C_1 \cdot \left[\left(\frac{f_p}{f_n}\right)^2 - 1\right]. \quad (6)$$

[0073] The equivalent resistance Rp from the capacitor C2 **770***b* to ground may be found using Equation (7):

$$R_p = R_1 \cdot (Q^2+1) \| R_{neg}. \quad (7)$$

[0074] The equivalent resistance Req may be found using Equation (8):

$$R_{eq} \approx R_p \cdot \left(1 + \frac{C_1}{C_2}\right)^2. \quad (8)$$

[0075] FIG. **8** is a flow diagram of a method **800** for process tuning a notch filter **750**. The method **800** may be performed by a wireless communication device **104**. The wireless communication device **104** may determine **802** a measured notch frequency. Determining the measured notch frequency is discussed in additional detail below in relation to FIG. **9**. The measured notch frequency may be found using Equation (9):

$$F_{n,meas} = \frac{1}{2\pi\sqrt{L_p \cdot (1+\alpha)(C_1 + C_2)}}. \quad (9)$$

[0076] In Equation (9), α is the process error that occurs from the notch frequency shifting due to process error. The wireless communication device **104** may determine **804** the process error α. The process error a may be determined using Equation (10:

$$\alpha = \left[\left(\frac{f_n}{f_{n,meas}}\right)^2 - 1\right]. \quad (10)$$

[0077] The wireless communication device **104** may calculate **806** a first capacitor code (i.e., a code that adjusts the value of the first variable capacitor Cl **770***a*) and a second capacitor code (i.e., a code that adjusts the value of the second variable capacitor C2 **770***b*) that meets the C_{1_aim} and C_{2_aim} for a given channel. The wireless communication device **104** may then apply **808** the first capacitor code and the second capacitor code to the notch filter **750**.

[0078] FIG. **9** is a flow diagram of a method **900** for finding the measured notch frequency of a notch filter **750**. The method **900** may be performed by a wireless communication device **104**. Notch tuning may be performed with any search-efficient algorithm, such as a gradient search algorithm. The wireless communication device **104** may apply **902** a transmit tone on three different frequencies to the notch filter **750**. The wireless communication device **104** may then measure **904** the DC gain through the feedback receiver **347**. The wireless communication device **104** may calculate **906** the gradient. The wireless communication device **104** may determine **908** a notch frequency using a gradient search algorithm. The notch frequency found using the gradient search algorithm may have better results than a linear search. The steps in the method **900** may need to be repeated to precisely locate the notch frequency and fine tune the notch filter **750**.

[0079] FIG. **10** illustrates certain components that may be included within a wireless communication device **1004**. The wireless communication device **1004** may be an access terminal, a mobile station, a user equipment (UE), etc. The wireless communication device **1004** includes a processor **1003**. The processor **1003** may be a general purpose single- or multi-chip microprocessor (e.g., an ARM), a special purpose microprocessor (e.g., a digital signal processor (DSP)), a microcontroller, a programmable gate array, etc. The processor **1003** may be referred to as a central processing unit (CPU). Although just a single processor **1003** is shown in the wireless communication device **1004** of FIG. **10**, in an alternative configuration, a combination of processors (e.g., an ARM and DSP) could be used.

[0080] The wireless communication device **1004** also includes memory **1005**. The memory **1005** may be any electronic component capable of storing electronic information. The memory **1005** may be embodied as random access memory (RAM), read-only memory (ROM), magnetic disk storage media, optical storage media, flash memory devices in RAM, on-board memory included with the processor, EPROM memory, EEPROM memory, registers and so forth, including combinations thereof

[0081] Data **1007***a* and instructions **1009***a* may be stored in the memory **1005**. The instructions **1009***a* may be executable by the processor **1003** to implement the methods disclosed herein. Executing the instructions **1009***a* may involve the use of the data **1007***a* that is stored in the memory **1005**. When the processor **1003** executes the instructions **1009**, various portions of the instructions **1009***b* may be loaded onto the processor **1003**, and various pieces of data **1007***b* may be loaded onto the processor **1003**.

[0082] The wireless communication device **1004** may also include a transmitter **1011** and a receiver **1013** to allow transmission and reception of signals to and from the wireless communication device **1004** via a first antenna **1017***a* and a second antenna **1017***b*. The transmitter **1011** and receiver **1013** may be collectively referred to as a transceiver **1015**. The wireless communication device **1004** may also include (not shown) multiple transmitters, additional antennas, multiple receivers and/or multiple transceivers.

[0083] The wireless communication device **1004** may include a digital signal processor (DSP) **1021**. The wireless communication device **1004** may also include a communications interface **1023**. The communications interface **1023** may allow a user to interact with the wireless communication device **1004**.

[0084] The various components of the wireless communication device **1004** may be coupled together by one or more buses, which may include a power bus, a control signal bus, a status signal bus, a data bus, etc. For the sake of clarity, the various buses are illustrated in FIG. **10** as a bus system **1019**.

[0085] The term "determining" encompasses a wide variety of actions and, therefore, "determining" can include cal-

culating, computing, processing, deriving, investigating, looking up (e.g., looking up in a table, a database or another data structure), ascertaining and the like. Also, "determining" can include receiving (e.g., receiving information), accessing (e.g., accessing data in a memory) and the like. Also, "determining" can include resolving, selecting, choosing, establishing and the like.

[0086] The phrase "based on" does not mean "based only on," unless expressly specified otherwise. In other words, the phrase "based on" describes both "based only on" and "based at least on."

[0087] The term "processor" should be interpreted broadly to encompass a general purpose processor, a central processing unit (CPU), a microprocessor, a digital signal processor (DSP), a controller, a microcontroller, a state machine and so forth. Under some circumstances, a "processor" may refer to an application specific integrated circuit (ASIC), a programmable logic device (PLD), a field programmable gate array (FPGA), etc. The term "processor" may refer to a combination of processing devices, e.g., a combination of a DSP and a microprocessor, a plurality of microprocessors, one or more microprocessors in conjunction with a DSP core, or any other such configuration.

[0088] The term "memory" should be interpreted broadly to encompass any electronic component capable of storing electronic information. The term memory may refer to various types of processor-readable media such as random access memory (RAM), read-only memory (ROM), non-volatile random access memory (NVRAM), programmable read-only memory (PROM), erasable programmable read-only memory (EPROM), electrically erasable PROM (EEPROM), flash memory, magnetic or optical data storage, registers, etc. Memory is said to be in electronic communication with a processor if the processor can read information from and/or write information to the memory. Memory that is integral to a processor is in electronic communication with the processor.

[0089] The terms "instructions" and "code" should be interpreted broadly to include any type of computer-readable statement(s). For example, the terms "instructions" and "code" may refer to one or more programs, routines, subroutines, functions, procedures, etc. "Instructions" and "code" may comprise a single computer-readable statement or many computer-readable statements.

[0090] The functions described herein may be implemented in software or firmware being executed by hardware. The functions may be stored as one or more instructions on a computer-readable medium. The terms "computer-readable medium" or "computer-program product" refers to any tangible storage medium that can be accessed by a computer or a processor. By way of example, and not limitation, a computer-readable medium may comprise RAM, ROM, EEPROM, CD-ROM or other optical disk storage, magnetic disk storage or other magnetic storage devices, or any other medium that can be used to carry or store desired program code in the form of instructions or data structures and that can be accessed by a computer. Disk and disc, as used herein, includes compact disc (CD), laser disc, optical disc, digital versatile disc (DVD), floppy disk and Blu-ray® disc where disks usually reproduce data magnetically, while discs reproduce data optically with lasers. It should be noted that a computer-readable medium may be tangible and non-transitory. The term "computer-program product" refers to a computing device or processor in combination with code or instructions (e.g., a "program") that may be executed, processed or computed by the computing device or processor. As used herein, the term "code" may refer to software, instructions, code or data that is/are executable by a computing device or processor.

[0091] Software or instructions may also be transmitted over a transmission medium. For example, if the software is transmitted from a website, server, or other remote source using a coaxial cable, fiber optic cable, twisted pair, digital subscriber line (DSL), or wireless technologies such as infrared, radio and microwave, then the coaxial cable, fiber optic cable, twisted pair, DSL, or wireless technologies such as infrared, radio and microwave are included in the definition of transmission medium.

[0092] The methods disclosed herein comprise one or more steps or actions for achieving the described method. The method steps and/or actions may be interchanged with one another without departing from the scope of the claims. In other words, unless a specific order of steps or actions is required for proper operation of the method that is being described, the order and/or use of specific steps and/or actions may be modified without departing from the scope of the claims.

[0093] Further, it should be appreciated that modules and/or other appropriate means for performing the methods and techniques described herein, such as those illustrated by FIGS. **2**, **5**, **8** and **9**, can be downloaded and/or otherwise obtained by a device. For example, a device may be coupled to a server to facilitate the transfer of means for performing the methods described herein. Alternatively, various methods described herein can be provided via a storage means (e.g., random access memory (RAM), read-only memory (ROM), a physical storage medium such as a compact disc (CD) or floppy disk, etc.), such that a device may obtain the various methods upon coupling or providing the storage means to the device. Moreover, any other suitable technique for providing the methods and techniques described herein to a device can be utilized.

[0094] It is to be understood that the claims are not limited to the precise configuration and components illustrated above. Various modifications, changes and variations may be made in the arrangement, operation and details of the systems, methods and apparatus described herein without departing from the scope of the claims.

What is claimed is:

1. A wireless communication device configured for reducing Tx leakage in a receive signal, comprising:

a transceiver chip, comprising:

a receiver;

a feedback receiver; and

a transmitter; and

a Tx leakage signal reduction module, wherein the Tx leakage signal reduction module reuses the feedback receiver.

2. The wireless communication device of claim **1**, wherein the Tx leakage signal reduction module comprises a notch filter that reduces Tx leakage in the receive signal.

3. The wireless communication device of claim **2**, wherein the notch filter is located on the transceiver chip, and wherein the notch filter is coupled to an output of a low noise amplifier that receives the receive signal.

4. The wireless communication device of claim **2**, wherein the notch filter is located off the transceiver chip, wherein the notch filter receives the receive signal, and wherein an output

of the notch filter is coupled to an input of a low noise amplifier on the transceiver chip.

5. The wireless communication device of claim **1**, wherein the receiver provides a feedback signal to the feedback receiver, and wherein the feedback receiver provides a digital leakage reduction signal to the Tx leakage signal reduction module.

6. The wireless communication device of claim **5**, wherein the digital leakage reduction signal tunes a notch filter in the Tx leakage signal reduction module to minimize Tx leakage in the receive signal.

7. The wireless communication device of claim **6**, wherein the notch filter comprises a first variable capacitor, a second variable capacitor, a first resistor, a second resistor and an inductor.

8. The wireless communication device of claim **6**, wherein the notch filter is tuned to provide reliable rejection of Tx leakage across process, voltage and temperature.

9. The wireless communication device of claim **5**, wherein the digital leakage reduction signal tunes a balancing impedance in a hybrid transformer on the wireless communication device.

10. The wireless communication device of claim **9**, wherein the hybrid transformer comprises a first inductor, a second inductor and a third inductor, and wherein the balancing impedance is coupled between the second inductor and ground.

11. The wireless communication device of claim **5**, wherein the feedback signal is provided to a feedback downconverter in the feedback receiver by a first amplifier in a cascode stage in the receiver.

12. The wireless communication device of claim **11**, wherein an output of the feedback downconverter is coupled to an analog-to-digital converter via a feedback baseband filter, and wherein an output of the analog-to-digital converter is converted to the digital leakage reduction signal by a digital signal processor.

13. A method for reducing Tx leakage in a receive signal, comprising:

receiving the receive signal;

processing the receive signal in a receiver;

providing a feedback signal from the receiver to a feedback downconverter;

converting the feedback signal to a digital leakage reduction signal using an analog-to-digital converter and a digital signal processor; and

using the digital leakage reduction signal to reduce Tx leakage in the receive signal.

14. The method of claim **13**, further comprising:

downconverting the feedback signal using the feedback downconverter; and

filtering the downconverted feedback signal using a feedback baseband filter.

15. The method of claim **13**, wherein processing the receive signal in the receiver comprises passing the receive signal through a notch filter.

16. The method of claim **13**, wherein the method is performed by a wireless communication device comprising:

a transceiver chip, comprising:

the receiver;

a feedback receiver; and

a transmitter; and

a Tx leakage signal reduction module, wherein the Tx leakage signal reduction module reuses the feedback receiver.

17. The method of claim **16**, wherein the Tx leakage signal reduction module comprises a notch filter, and further comprising performing process tuning on the notch filter using the digital leakage reduction signal.

18. The method of claim **17**, wherein the notch filter is located on the transceiver chip, and wherein the notch filter is coupled to an output of a low noise amplifier that receives the receive signal.

19. The method of claim **17**, wherein the notch filter is located off the transceiver chip, wherein the notch filter receives the receive signal, and wherein an output of the notch filter is coupled to an input of a low noise amplifier on the transceiver chip.

20. The method of claim **16**, wherein the receiver provides the feedback signal to the feedback receiver, and wherein the feedback receiver provides the digital leakage reduction signal to the Tx leakage signal reduction module.

21. The method of claim **20**, wherein the digital leakage reduction signal tunes a notch filter in the Tx leakage signal reduction module to minimize Tx leakage in the receive signal.

22. The method of claim **21**, wherein the notch filter comprises a first variable capacitor, a second variable capacitor, a first resistor, a second resistor and an inductor.

23. The method of claim **22**, further comprising:

determining a measured notch frequency of the notch filter;

determining a process error;

calculating a first capacitor code and a second capacitor code that meet requirements for a channel; and

applying the first capacitor code to the first variable capacitor and the second capacitor code to the second variable capacitor.

24. The method of claim **23**, wherein determining a measured notch frequency of the notch filter comprises:

applying a transmit tone on three different frequencies to the notch filter;

measuring a DC gain through the feedback receiver;

calculating a gradient; and

determining the measured notch frequency using a gradient search algorithm.

25. The method of claim **21**, wherein the notch filter is tuned to provide reliable rejection of Tx leakage across process, voltage and temperature.

26. The method of claim **20**, wherein the digital leakage reduction signal tunes a balancing impedance in a hybrid transformer on the wireless communication device.

27. The method of claim **26**, wherein the hybrid transformer comprises a first inductor, a second inductor and a third inductor, and wherein the balancing impedance is coupled between the second inductor and ground.

28. The method of claim **20**, wherein the feedback signal is provided to a feedback downconverter in the feedback receiver by a first amplifier in a cascode stage in the receiver.

29. The method of claim **28**, wherein an output of the feedback downconverter is coupled to an analog-to-digital converter via a feedback baseband filter, and wherein an output of the analog-to-digital converter is provided to a digital signal processor that outputs the digital leakage reduction signal.

30. An apparatus for reducing Tx leakage in a receive signal, comprising:

means for receiving the receive signal;
means for processing the receive signal in a receiver;
means for providing a feedback signal from the receiver to a feedback downconverter;
means for converting the feedback signal to a digital leakage reduction signal; and
means for using the digital leakage reduction signal to reduce Tx leakage in the receive signal.

31. The apparatus of claim **30**, further comprising:
means for downconverting the feedback signal; and
means for filtering the downconverted feedback signal.

32. The apparatus of claim **30**, wherein the means for processing the receive signal in the receiver comprise means for passing the receive signal through a notch filter.

33. The apparatus of claim **30**, wherein the apparatus is a wireless communication device comprising:
a transceiver chip, comprising:
the receiver;
a feedback receiver; and
a transmitter; and
a Tx leakage signal reduction module, wherein the Tx leakage signal reduction module reuses the feedback receiver.

34. A computer-program product for reducing Tx leakage in a receive signal, the computer-program product comprising a non-transitory computer-readable medium having instructions thereon, the instructions comprising:
code for causing a wireless communication device to receive the receive signal;
code for causing the wireless communication device to process the receive signal in a receiver;
code for causing the wireless communication device to provide a feedback signal from the receiver to a feedback downconverter;
code for causing the wireless communication device to convert the feedback signal to a digital leakage reduction signal using an analog-to-digital converter and a digital signal processor; and
code for causing the wireless communication device to use the digital leakage reduction signal to reduce Tx leakage in the receive signal.

35. The computer-program product of claim **34**, wherein the instructions further comprise:
code for causing the wireless communication device to downconvert the feedback signal; and
code for causing the wireless communication device to filter the downconverted feedback signal.

36. The computer-program product of claim **34**, wherein the code for causing the wireless communication device to process the receive signal in the receiver comprise code for causing the wireless communication device to pass the receive signal through a notch filter.

37. The computer-program product of claim **34**, wherein the wireless communication device comprises:
a transceiver chip, comprising:
the receiver;
a feedback receiver; and
a transmitter; and
a Tx leakage signal reduction module, wherein the Tx leakage signal reduction module reuses the feedback receiver.

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