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(54) **RADIO FREQUENCY SELF-INTERFERENCE-CANCELLED FULL-DUPLEX RELAYS**

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H04B 7/155 (2006.01)

(52) **U.S. Cl.**
CPC ***H04B 7/15585*** (2013.01); *H04B 7/0413* (2013.01)

(58) **Field of Classification Search**
CPC H04B 7/0413
See application file for complete search history.

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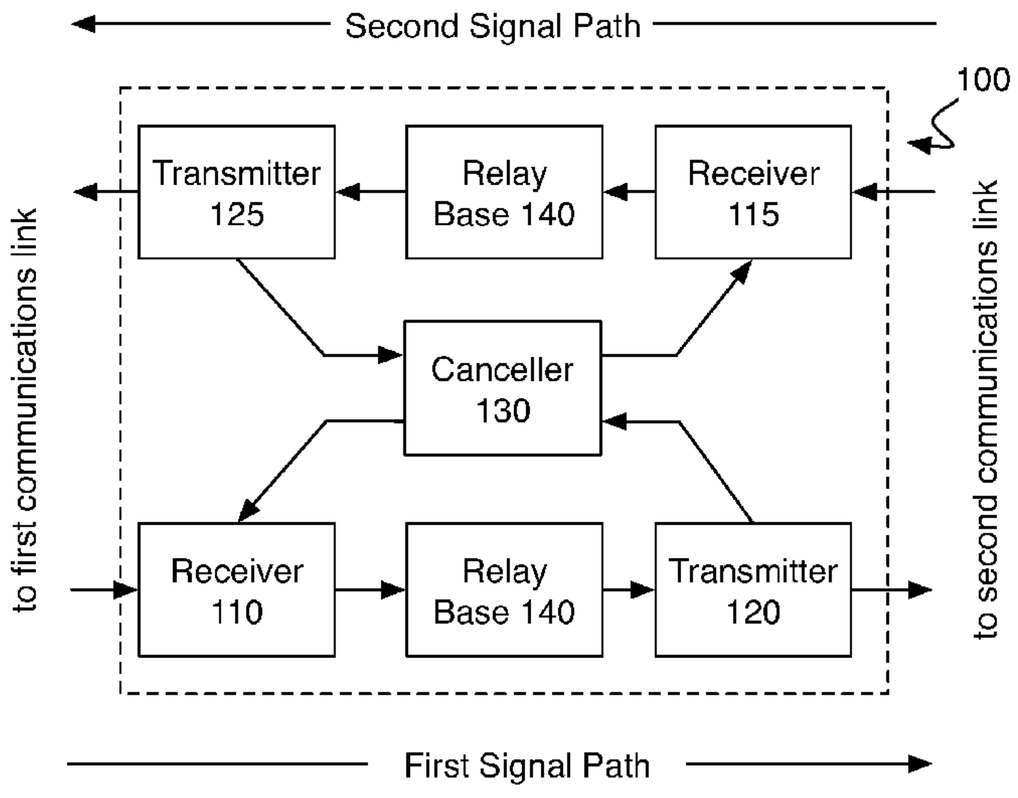
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(57) **ABSTRACT**

A relay including a first transmitter that converts a first digital transmit signal to a first analog transmit signal, a first receiver that converts a first analog receive signal to a first digital receive signal, a second transmitter that converts a second digital transmit signal to a second analog transmit signal, a second receiver that converts a second analog receive signal to a second digital receive signal, and a self-interference canceller that generates a first self-interference cancellation signal based on at least one of the first digital transmit signal and the first analog transmit signal, and combines the first self-interference cancellation signal with at least one of the first digital receive signal and the first analog receive signal.

8 Claims, 11 Drawing Sheets



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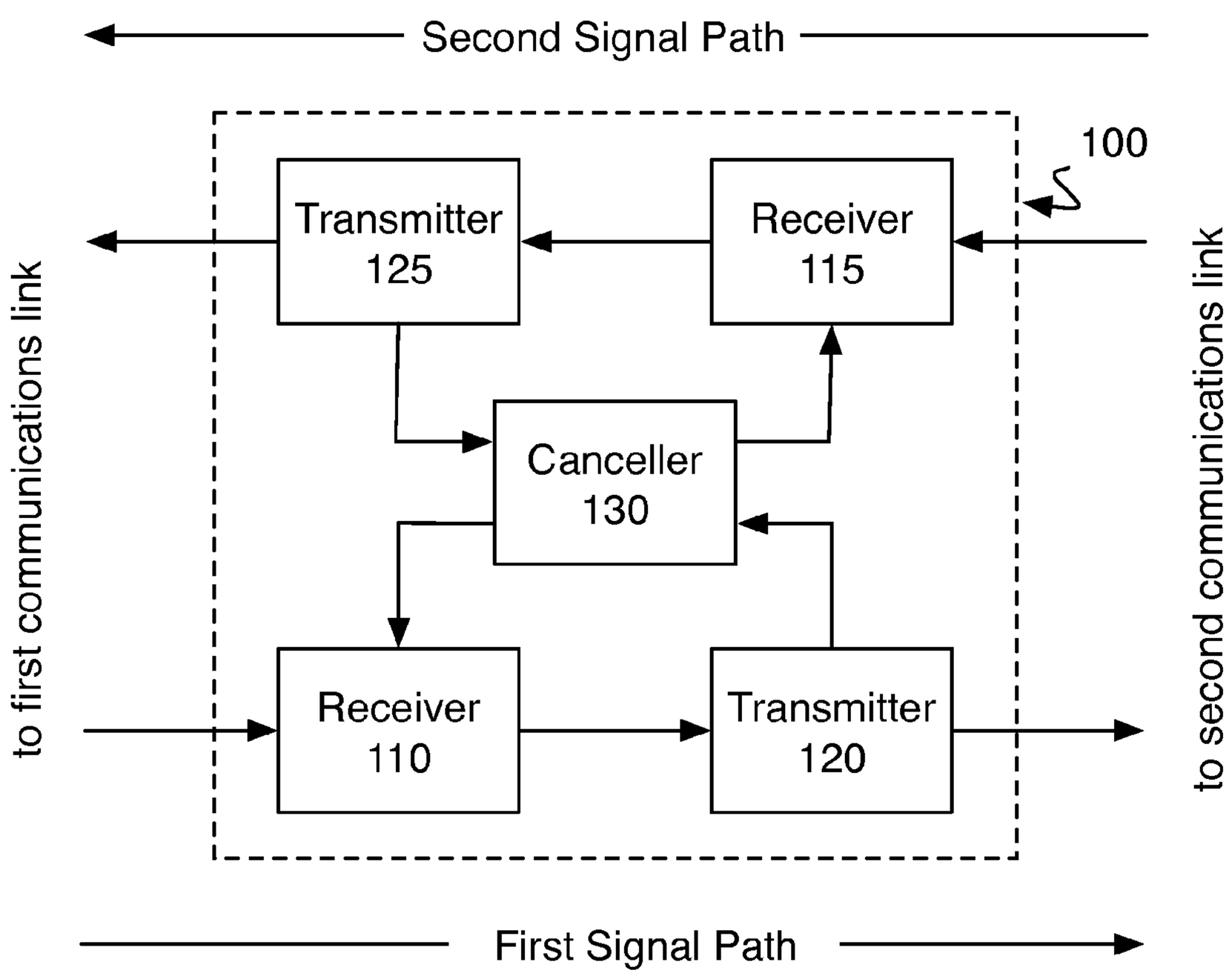

Second Signal Path
100
Transmitter 125
Receiver 115
Canceller 130
Receiver 110
Transmitter 120
to first communications link
to second communications link
First Signal Path

FIGURE 1

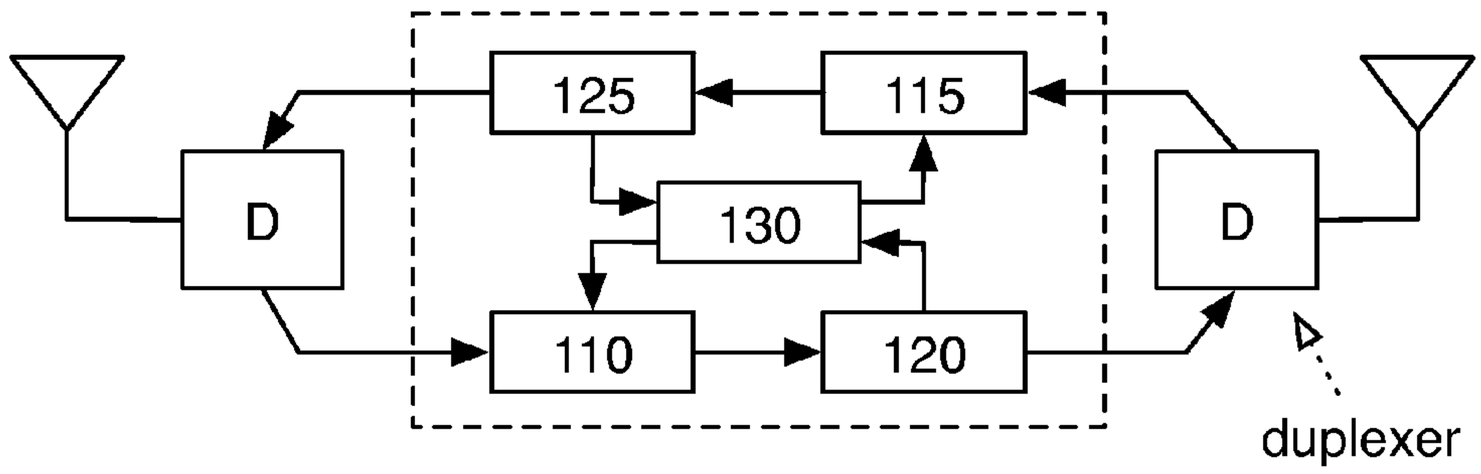


FIGURE 2A

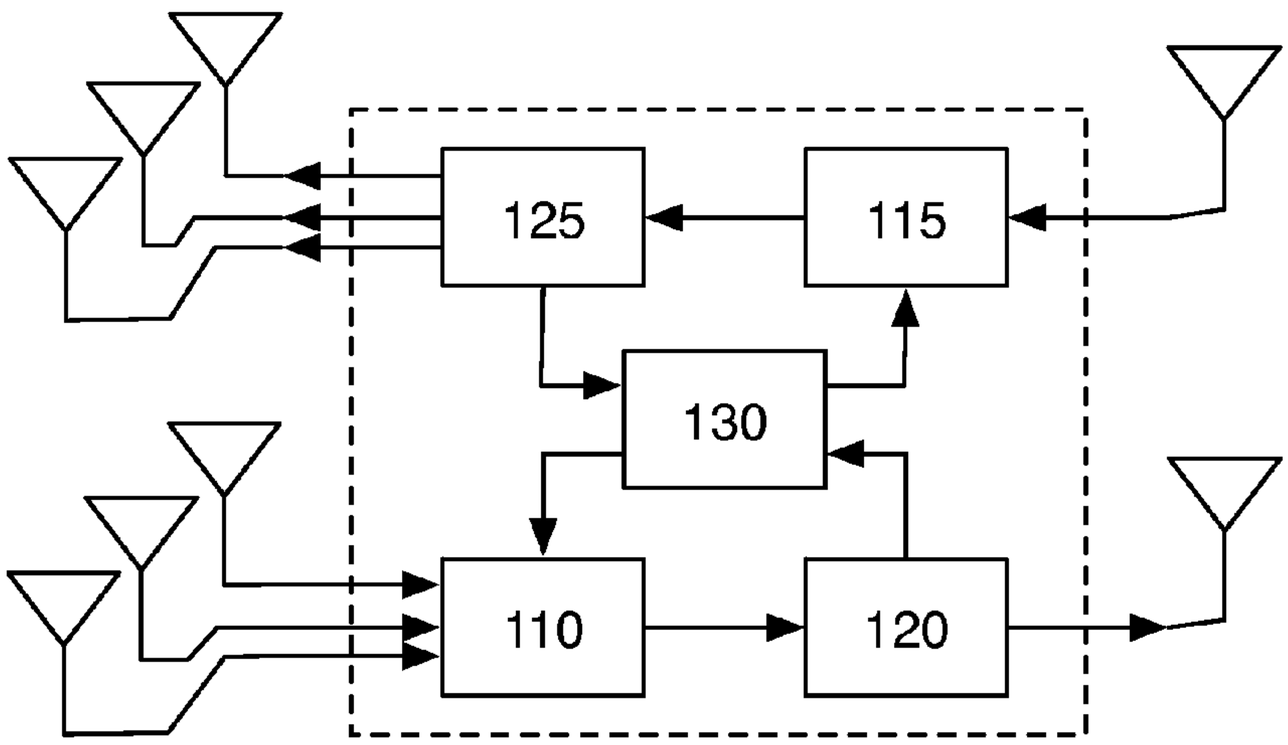


FIGURE 2B

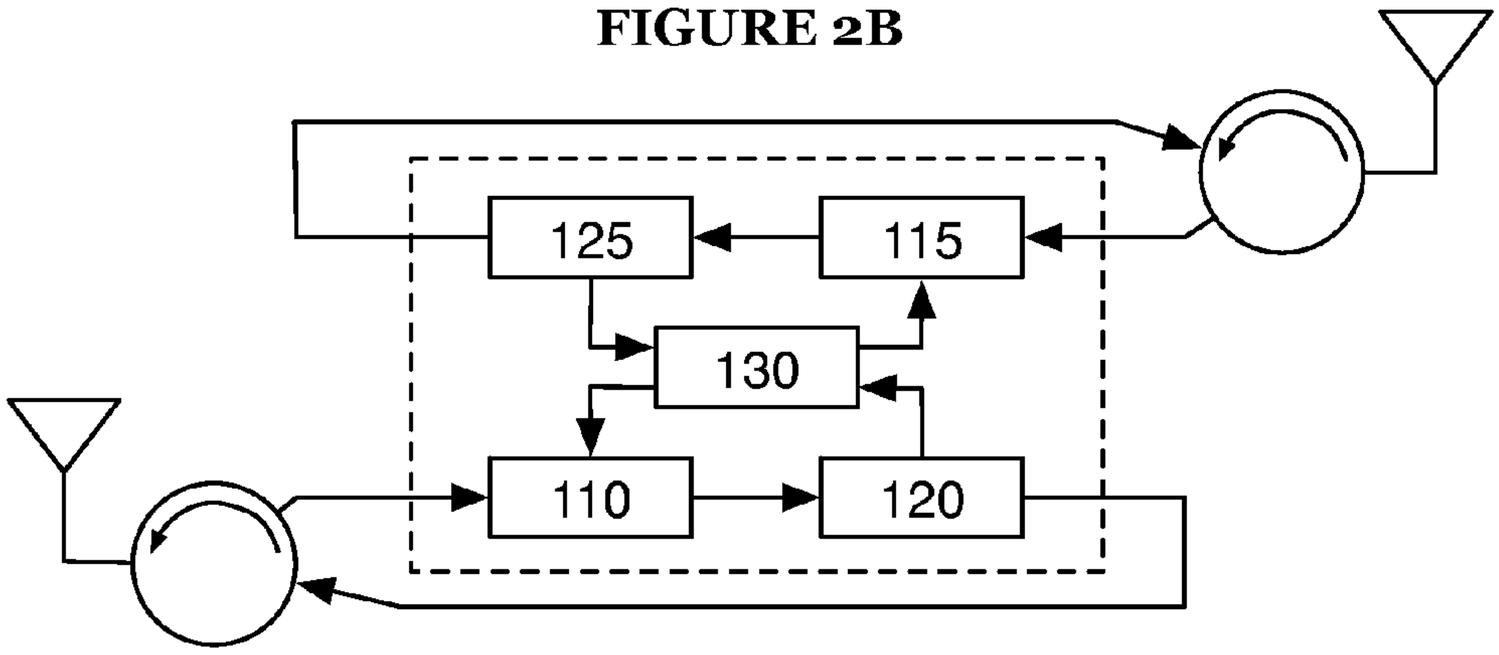


FIGURE 2C

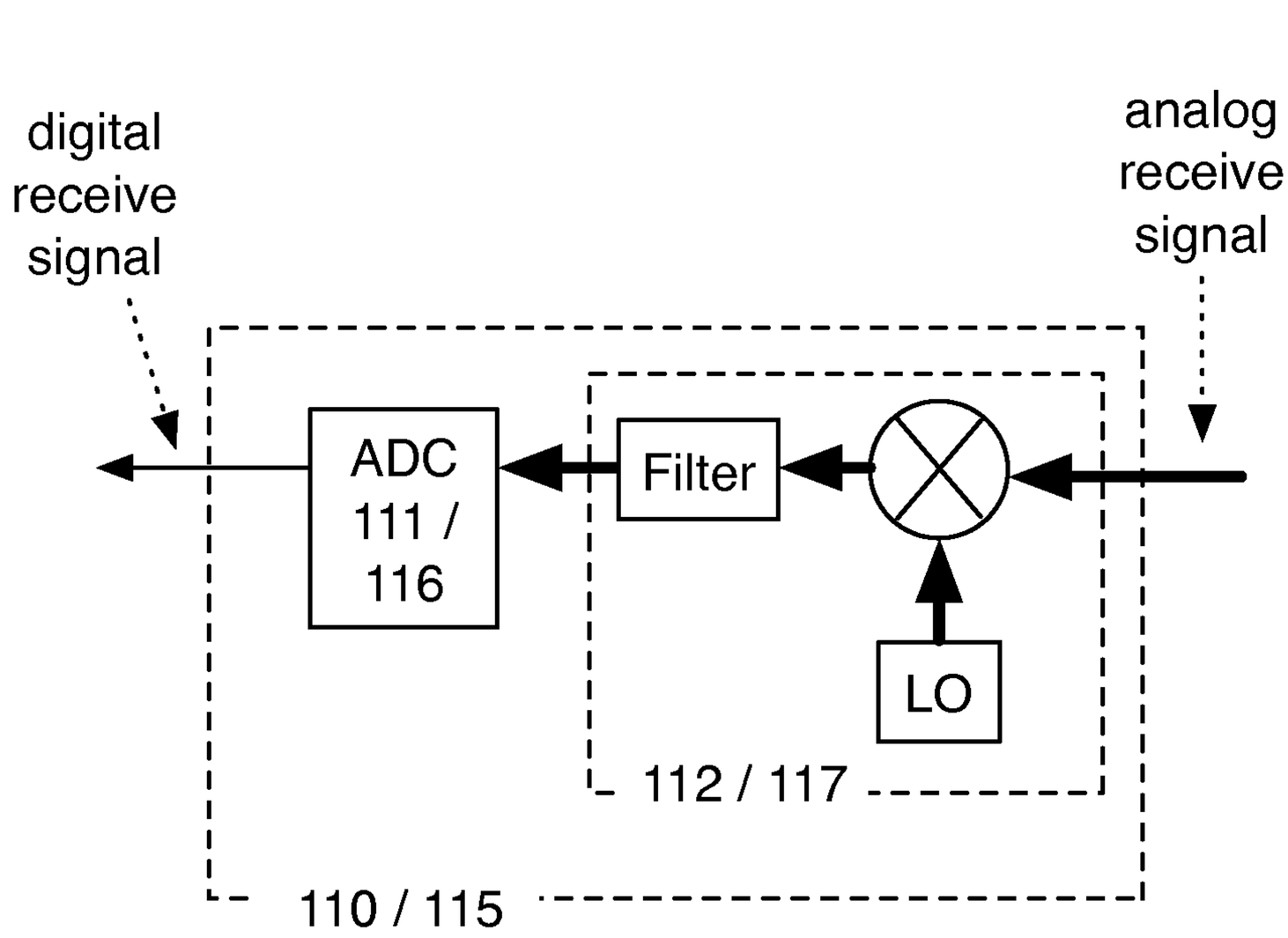

digital
receive
signal
analog
receive
signal
ADC
111 /
116
Filter
LO
112 / 117
110 / 115

FIGURE 3

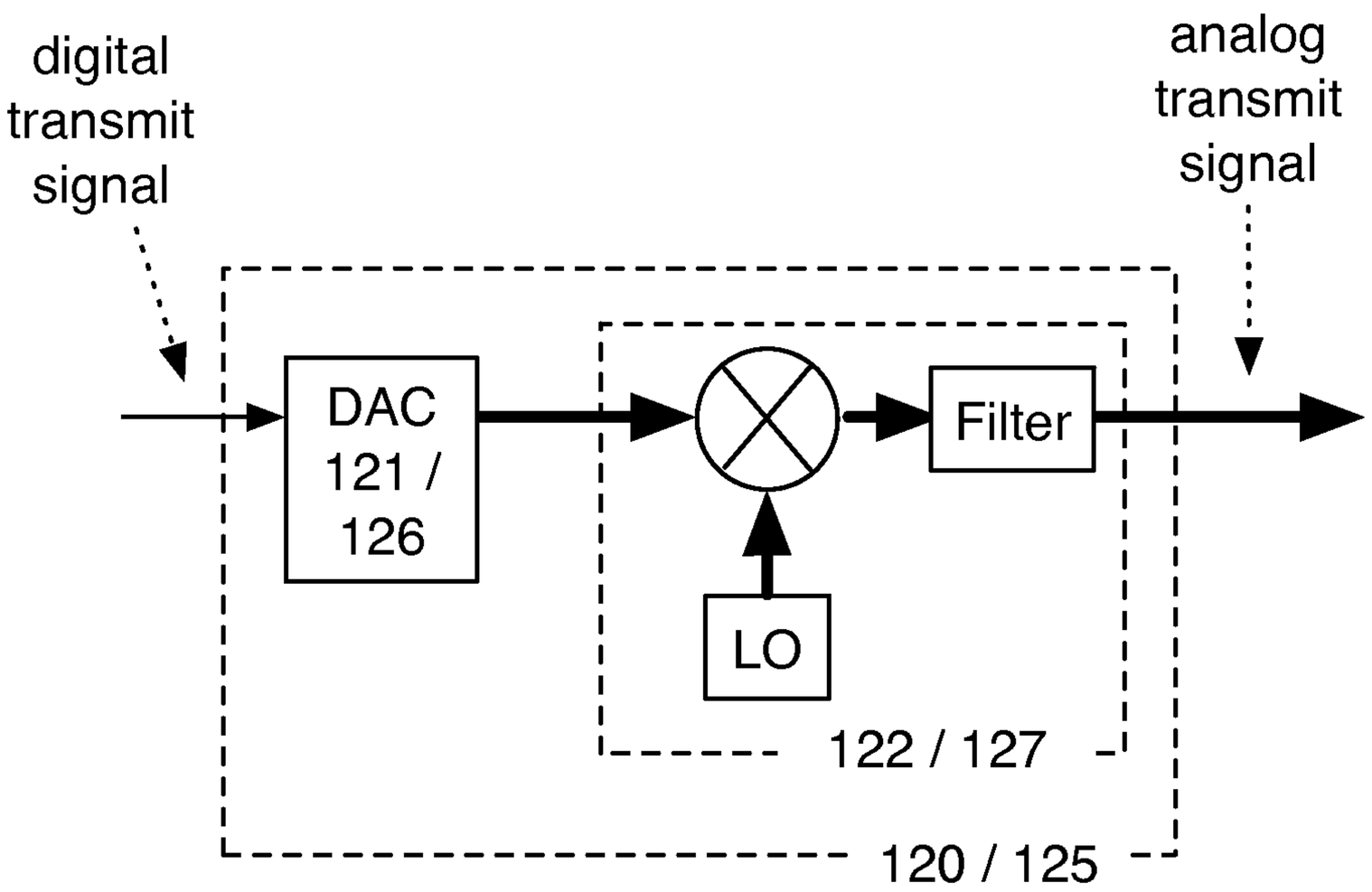

digital
transmit
signal
analog
transmit
signal
DAC
121 /
126
Filter
LO
122 / 127
120 / 125

FIGURE 4

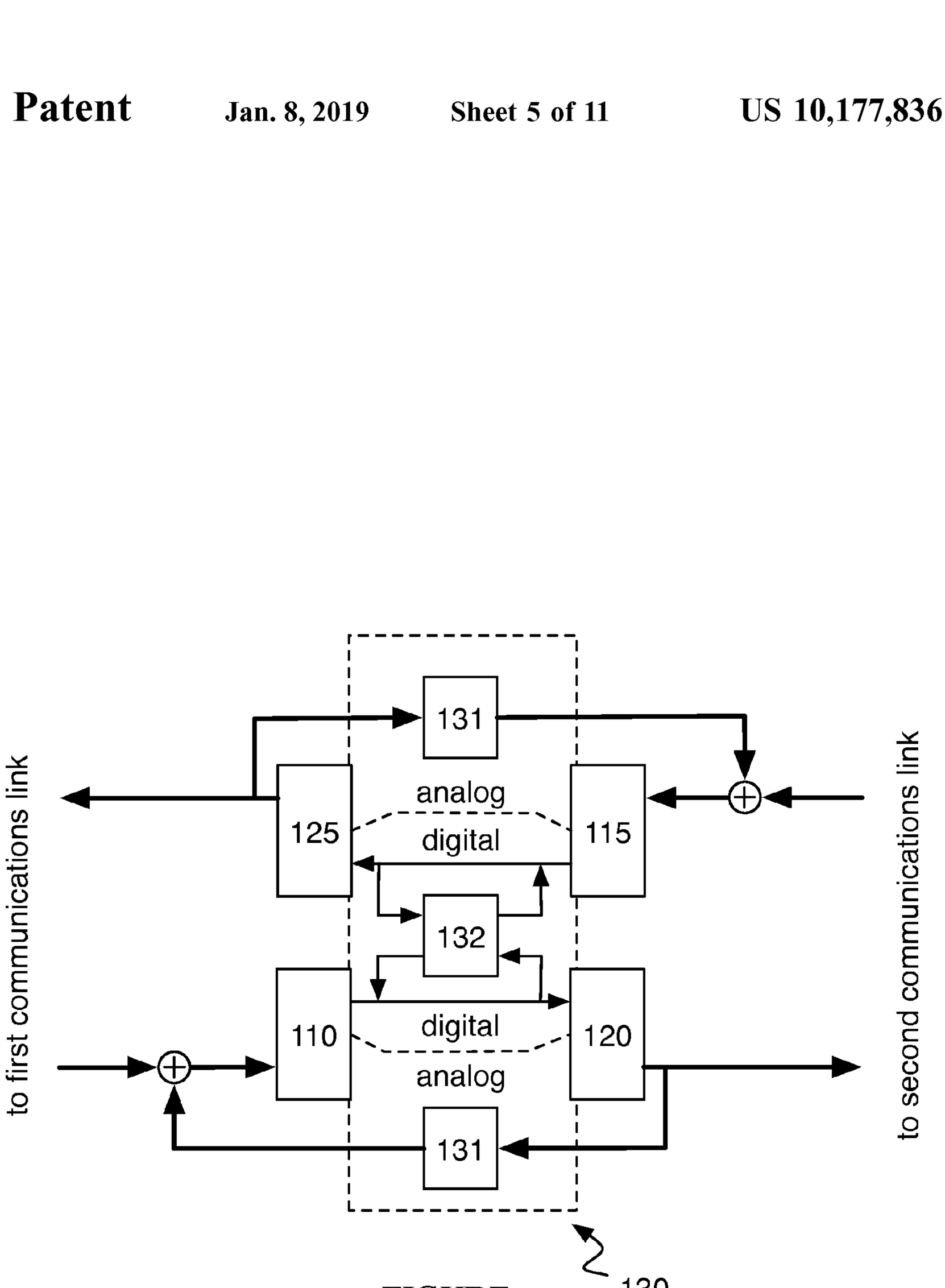

131
125
analog
digital
115
132
110
digital
120
analog
131
130
to first communications link
to second communications link

FIGURE 5

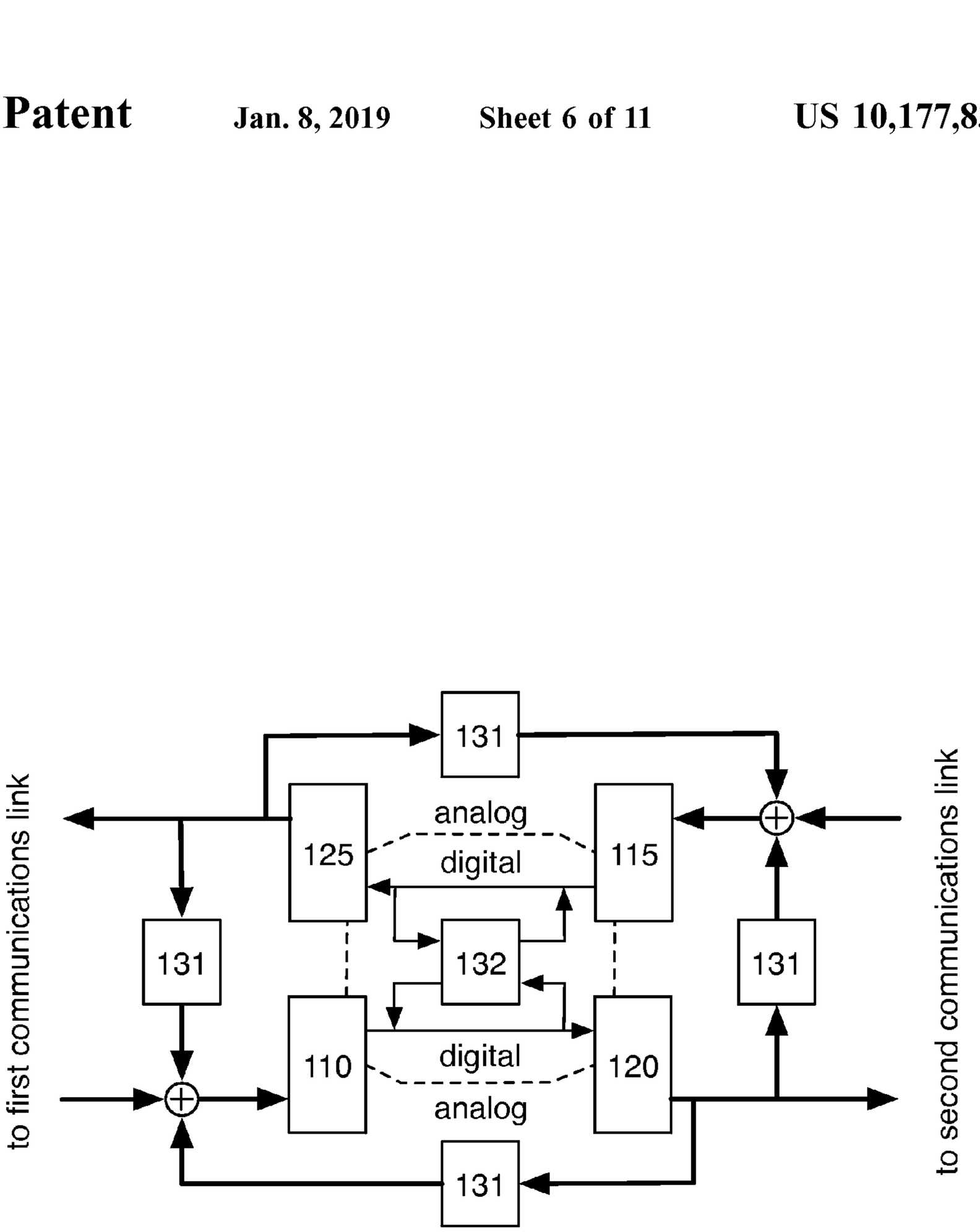

131
125
analog
digital
115
131
132
131
110
digital
120
analog
131
to first communications link
to second communications link

FIGURE 6

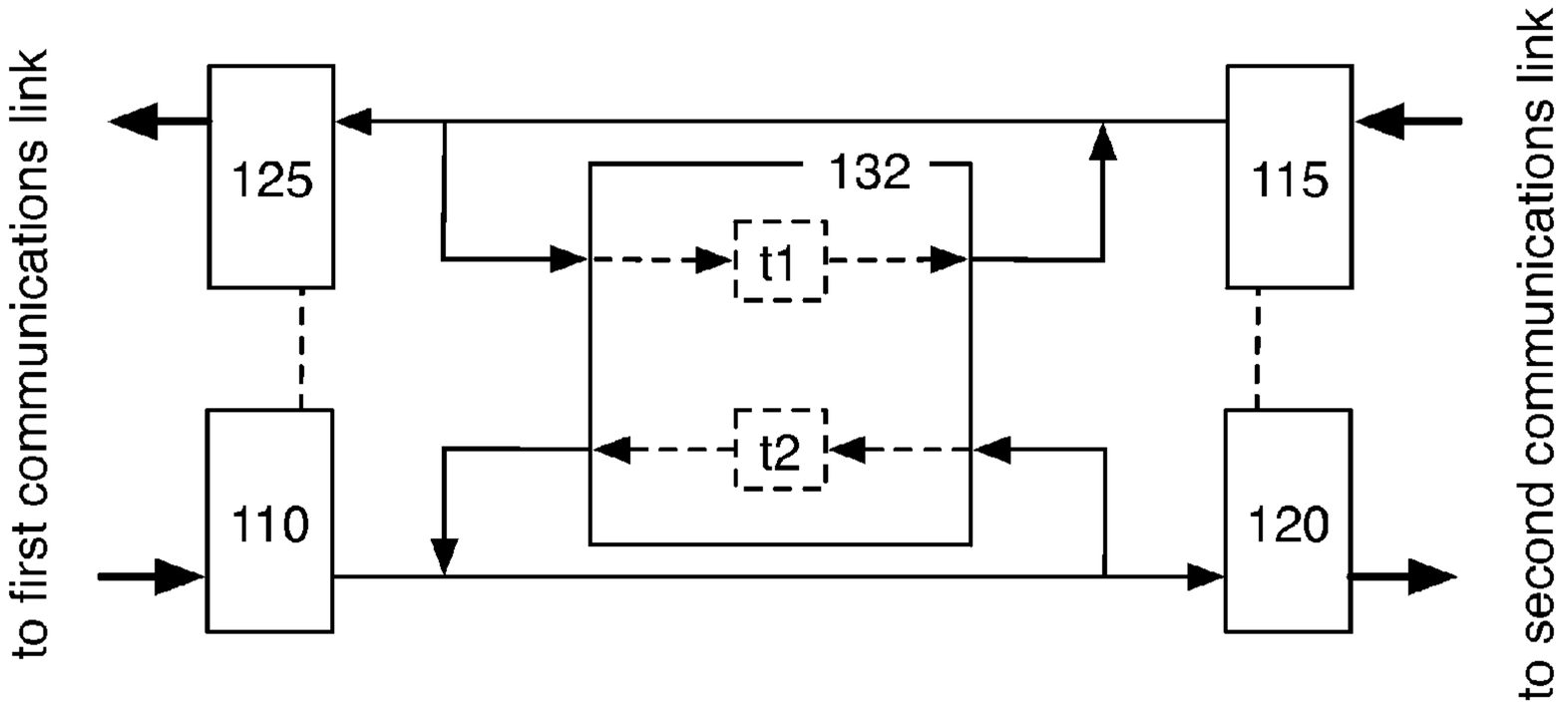


FIGURE 7A

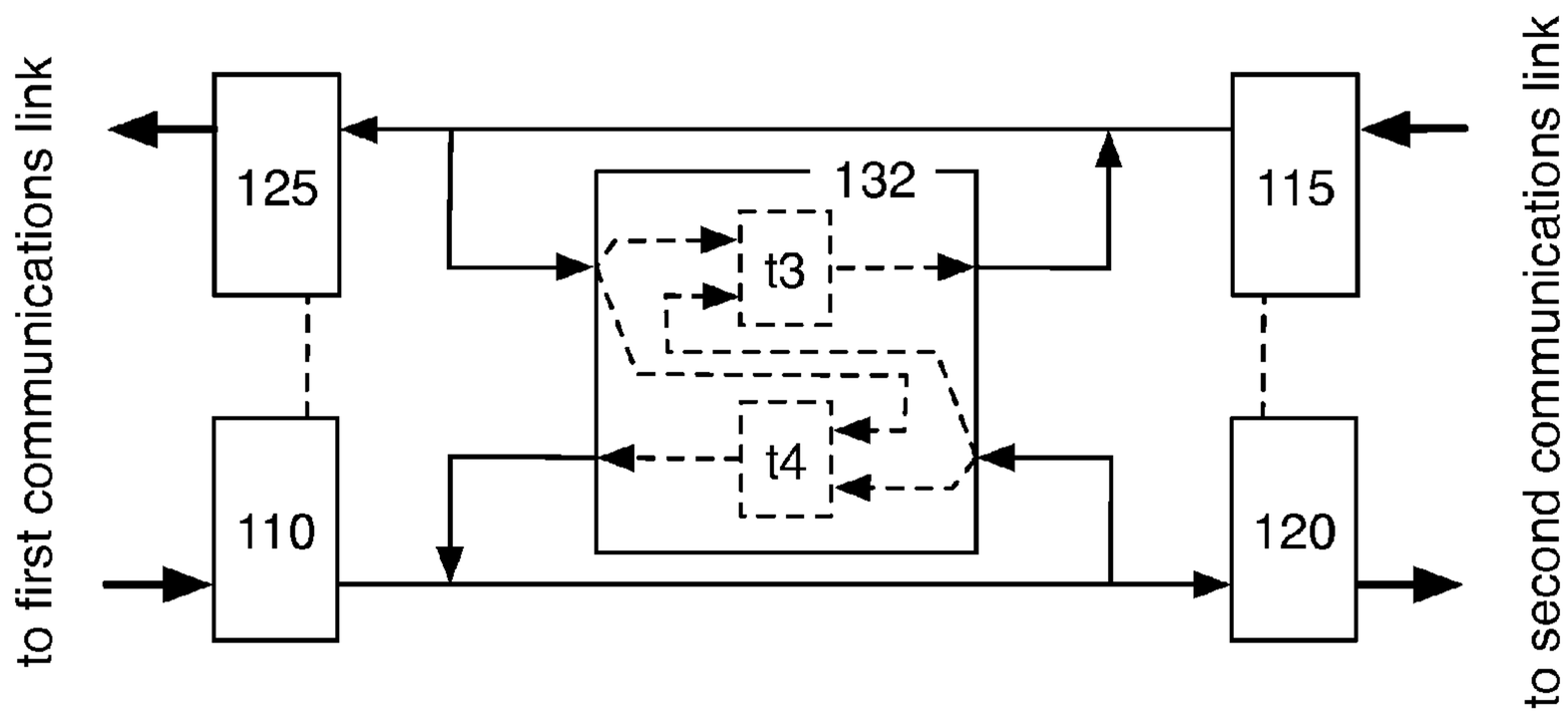


FIGURE 7B

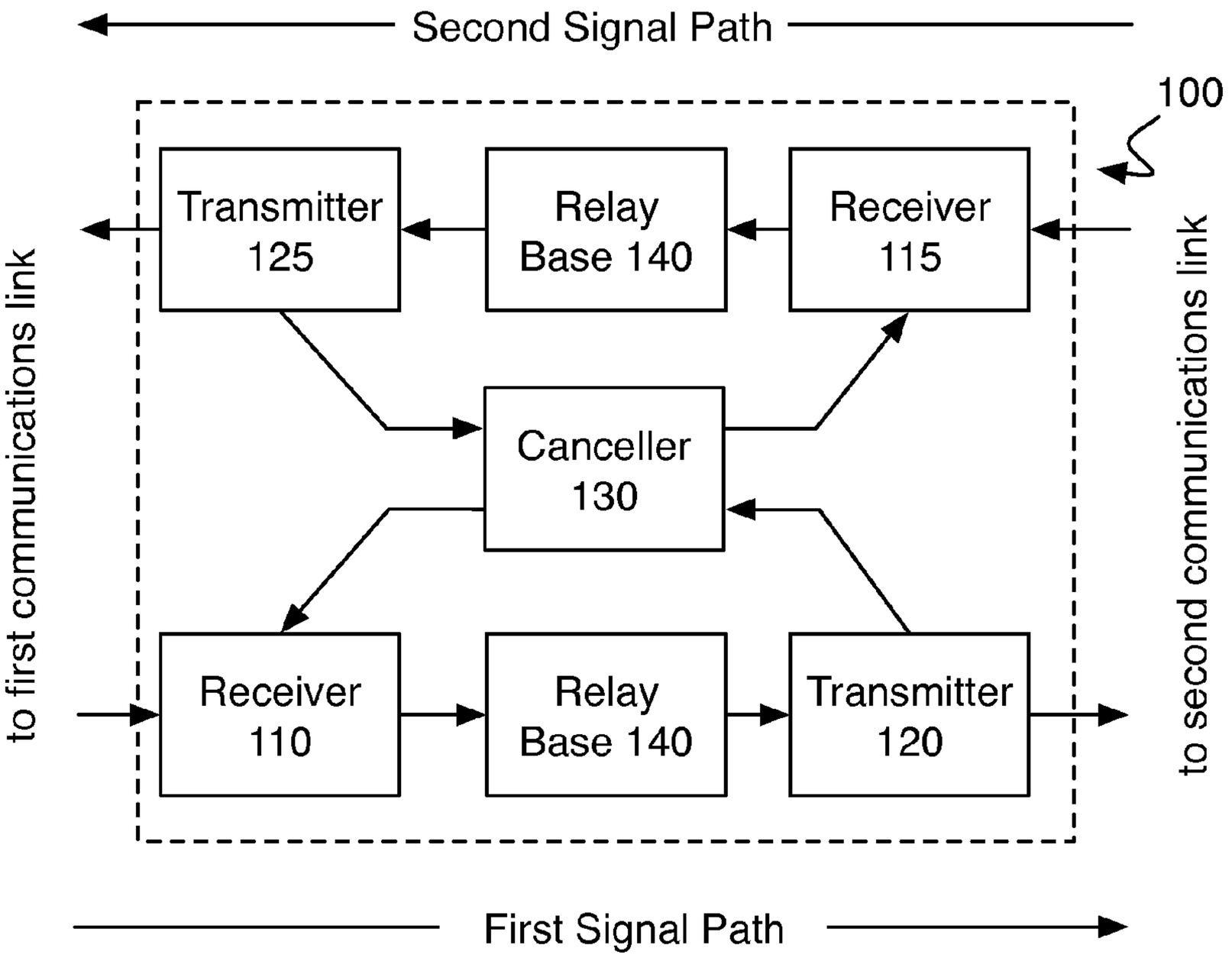

Second Signal Path
100
Transmitter 125
Relay Base 140
Receiver 115
Canceller 130
Receiver 110
Relay Base 140
Transmitter 120
to first communications link
to second communications link
First Signal Path

FIGURE 8

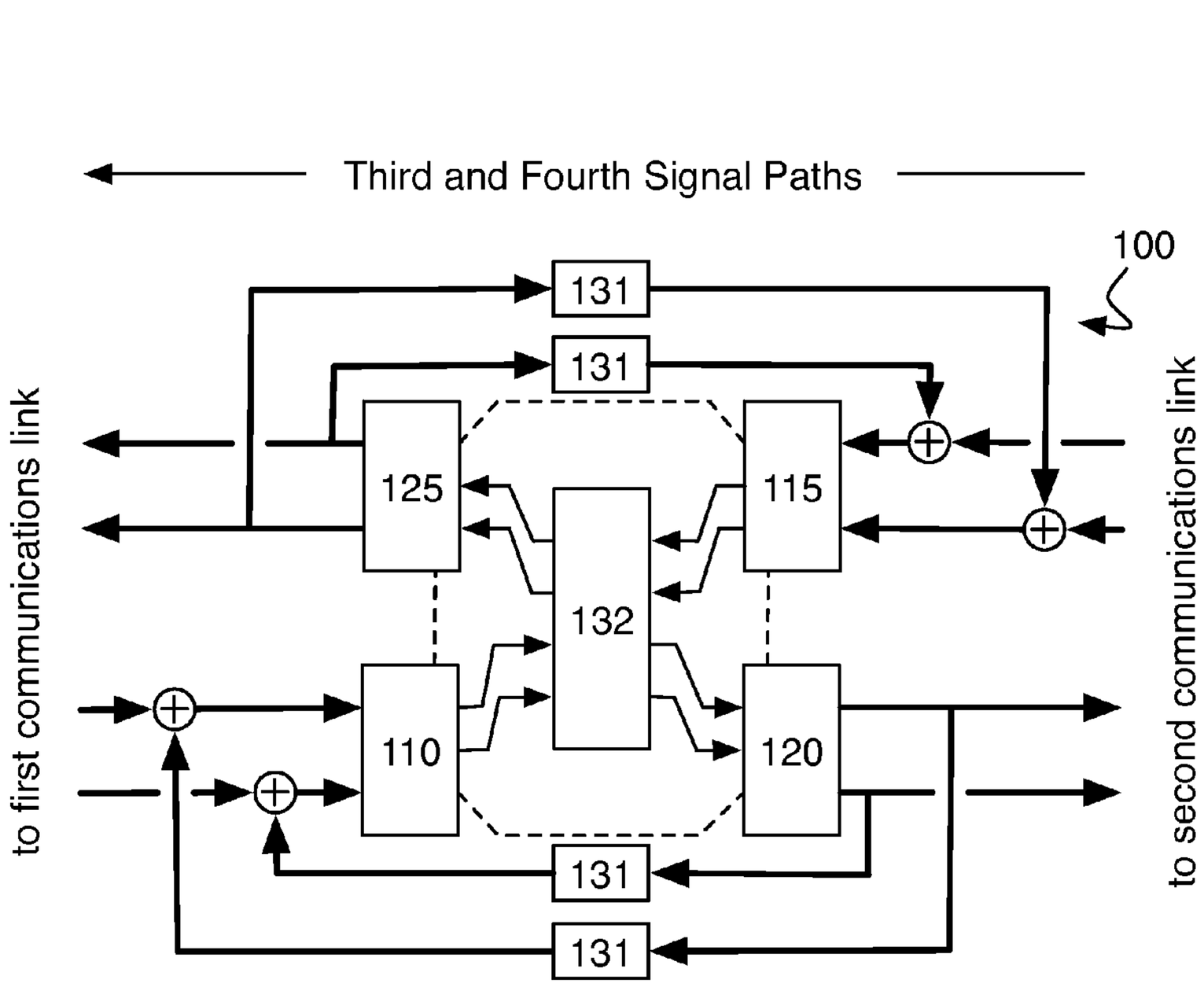

Third and Fourth Signal Paths
100
131
131
125
115
132
110
120
131
131
to first communications link
to second communications link
First and Second Signal Paths

FIGURE 9

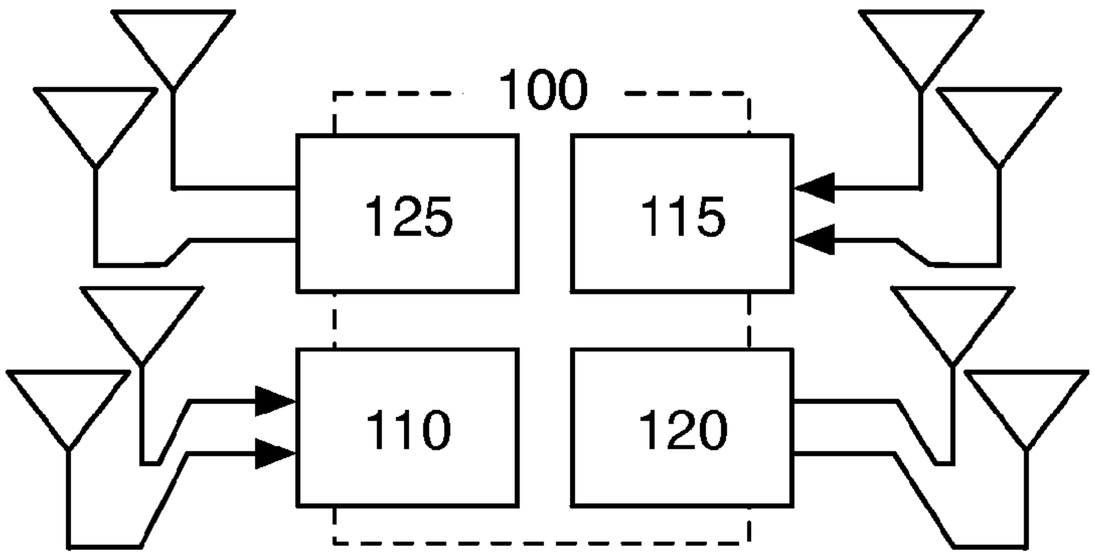


FIGURE 10A

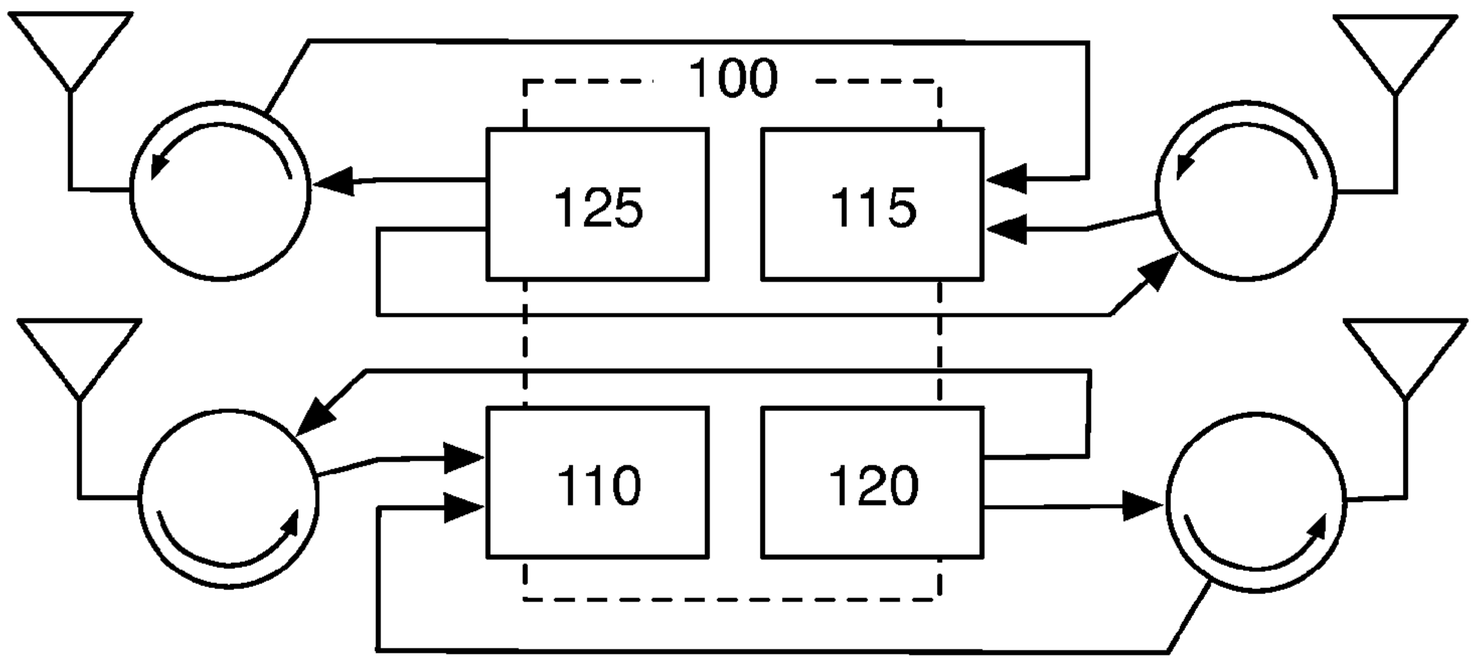


FIGURE 10B

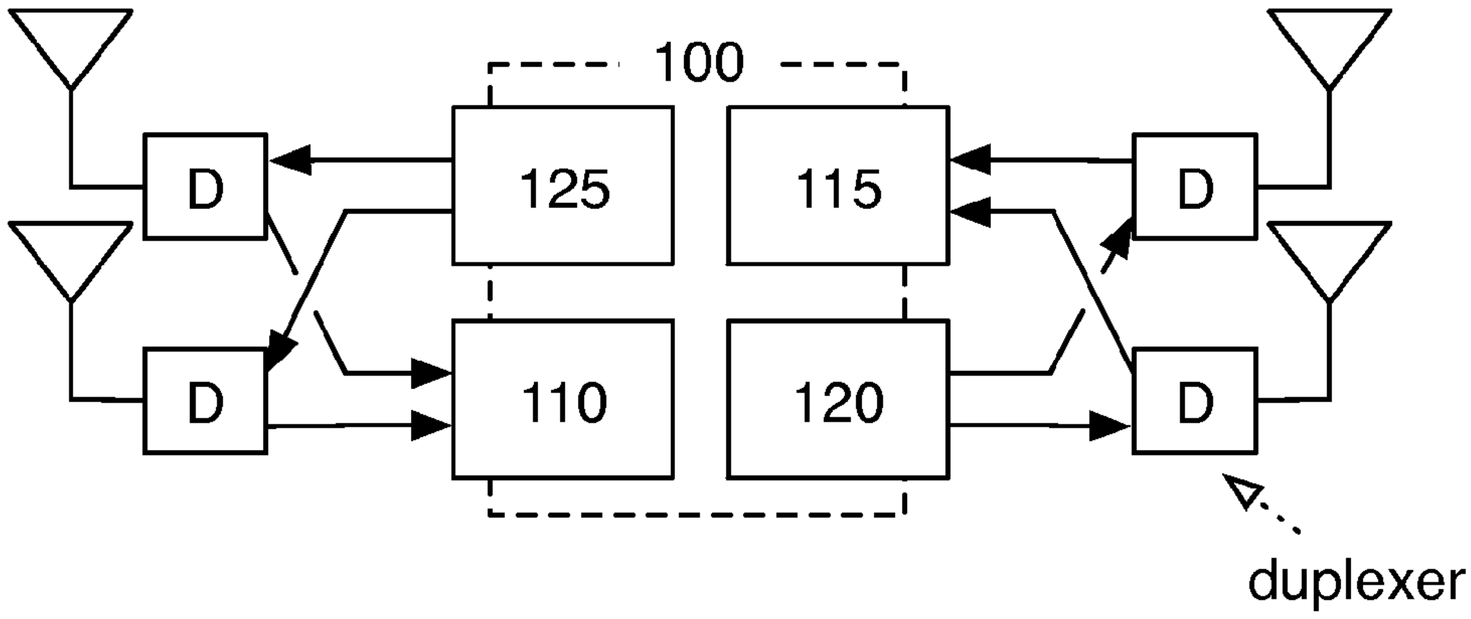


FIGURE 10C

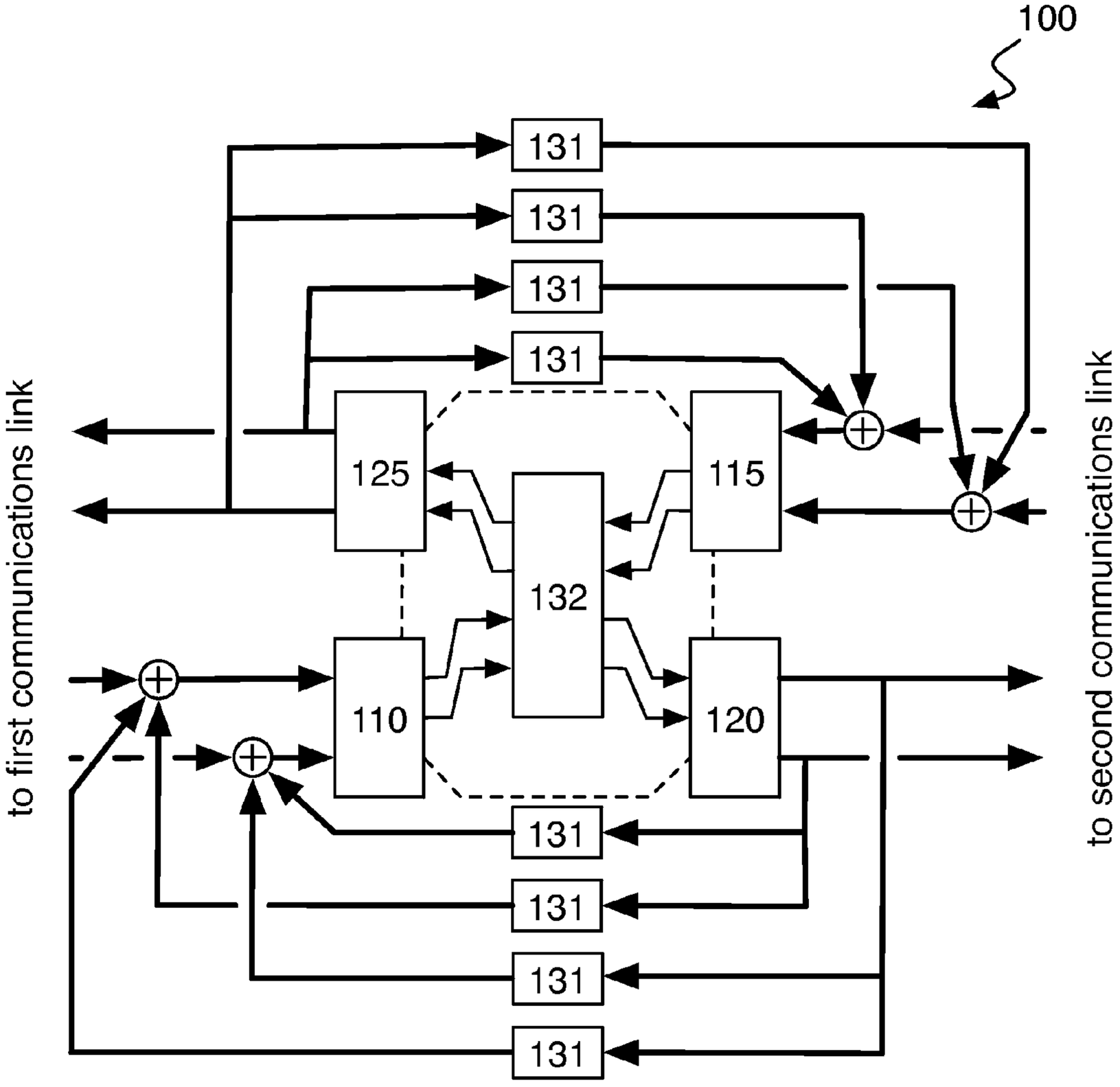

100
131
131
131
131
125
115
132
110
120
131
131
131
131
to first communications link
to second communications link

FIGURE 11

RADIO FREQUENCY SELF-INTERFERENCE-CANCELLED FULL-DUPLEX RELAYS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Application Ser. No. 61/871,519, filed on 29 Aug. 2013, which is incorporated in its entirety by this reference.

TECHNICAL FIELD

This invention relates generally to the wireless communications field, and more specifically to new and useful full-duplex relays.

BACKGROUND

In many wireless communication networks, there are areas that are not easily covered by access points due to signal attenuation by terrain or other structural obstacles. One approach to extending access point signal coverage involves using relay nodes that rebroadcast signals originating from and/or destined to access points.

One major roadblock to successful implementation of relays is the problem of self-interference; relays may suffer from issues resulting from cross-talk between transmitters and receivers, duplexer leakages, or other undesired electromagnetic couplings. Many modern relays use frequency or time division multiplexing techniques or antenna separation techniques to address self-interference. Each of these techniques has substantial drawbacks: frequency division multiplexing requires doubling spectrum usage, time division multiplexing requires halving signal capacity, and antenna separation is often expensive, if not impossible given space constraints. Full-duplex relays may address self-interference without any of these drawbacks. Thus, there is a need in the wireless communications field to create new and useful full-duplex relays. This invention provides such new and useful full-duplex relays.

BRIEF DESCRIPTION OF THE FIGURES

FIG. **1** is a diagram representation of a system of a preferred embodiment;

FIGS. **2**A, **2**B, and **2**C are diagram representations of antenna couplings of a system of a preferred embodiment;

FIG. **3** is a schematic representation of a receiver of a system of a preferred embodiment;

FIG. **4** is a schematic representation of a transmitter of a system of a preferred embodiment;

FIG. **5** is a diagram representation of a self-interference canceller of a system of a preferred embodiment;

FIG. **6** is a diagram representation of a self-interference canceller of a system of a preferred embodiment;

FIGS. **7**A and **7**B are diagram representations of a digital self-interference canceller of a system of a preferred embodiment;

FIG. **8** is a diagram representation of a system of a preferred embodiment;

FIG. **9** is a diagram representation of a system of a preferred embodiment;

FIGS. **10**A, **10**B and **10**C are diagram representations of antenna couplings of a system of a preferred embodiment; and

FIG. **11** is a diagram representation of a system of a preferred embodiment.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The following description of the preferred embodiments of the invention is not intended to limit the invention to these preferred embodiments, but rather to enable any person skilled in the art to make and use this invention.

As shown in FIG. **1**, a relay **100** includes a first receiver **110**, a first transmitter **120**, a second receiver **115**, a second transmitter **125**, and a self-interference canceller **130**. The relay **100** functions to repeat communication signals transmitted and received between two communications systems. In addition to repeating signals, the relay **100** preferably cancels self-interference between transmitted and received signals. The relay **100** may additionally or alternatively scale (e.g. amplify, attenuate), shift, or otherwise modify signals received or transmitted by the relay **100**.

The relay **100** is preferably used to repeat communication signals traveling bi-directionally between two wireless communication systems (e.g. a cell-phone tower and a cell phone, or a Wi-Fi™ access point and a computer, two wireless radios), but may additionally or alternatively be used to repeat communications signals between any other suitable wired or wireless communication systems. In a variation of a preferred embodiment, the relay **100** is a one-way relay and includes only a first receiver **110**, a first transmitter **120**, and a self-interference canceller **130**.

The relay **100** is preferably implemented using both digital and analog circuitry. Digital circuitry is preferably implemented using a general-purpose processor, a digital signal processor, an application specific integrated circuit (ASIC), a field programmable gate array (FPGA) and/or any suitable processor(s) or circuit(s). Analog circuitry is preferably implemented using analog integrated circuits (ICs) but may additionally or alternatively be implemented using discrete components (e.g., capacitors, resistors, transistors), wires, transmission lines, waveguides, digital components, mixed-signal components, or any other suitable components. The relay **100** preferably includes memory to store configuration data, but may additionally or alternatively be configured using externally stored configuration data or in any suitable manner.

In one example implementation, the relay **100** is used as a cellular repeater. The relay **100** is connected to a cell tower by a first communications link using a first transmit/receive antenna coupled to the relay **100** by a duplexer, and to a cell phone by a second communications link using a second transmit/receive antenna coupled to the relay **100** by a duplexer. The cell phone and cell tower natively communicate at an uplink frequency (from phone to tower) and a downlink frequency (from tower to phone). The relay **100** receives and re-transmits communication on both the uplink frequency (phone to relay to tower) and the downlink frequency (tower to relay to phone). The self-interference canceller **130** enables full-duplex operation for the first transmit/receive antenna and the second transmit receive/antenna. This is distinct from traditional relays, which must rely on techniques like time-division multiplexing or antenna isolation to avoid self-interference. More specifically, the self-interference canceller **130** may enable the relay **100** to receive downlink communications (from tower to relay), retransmit downlink communications (from relay to phone), receive uplink communications (from phone to relay), and retransmit uplink communications (from relay to

tower) simultaneously, without requiring antennas to be isolated from one another, the use of additional frequencies, or the use of time multiplexing. Thus, the relay **100** is able to provide network-relaying capability without excess cost, excess spectrum usage, or significantly decreased data capacity.

The first receiver **110** functions to receive analog receive signals transmitted by a first communications system over a first communications link (e.g., a wireless channel, a coaxial cable). The first receiver no preferably converts analog receive signals into digital receive signals for processing before re-transmission by the first transmitter **120**, but may additionally or alternatively not convert analog receive signals (passing them through directly without conversion).

The first receiver no is preferably a radio-frequency (RF) receiver, but may additionally or alternatively be any suitable receiver.

The first receiver **110** is preferably coupled to the first communications link by a duplexer-coupled RF antenna as shown in FIG. **2**A, but may additionally or alternatively be coupled to the first communications link in any suitable manner. Some examples of alternative couplings include coupling via one or more dedicated receive antennas (as shown in FIG. **2**B). In another alternative coupling, the first receiver no may be coupled to the first communications link by a circulator-coupled RF antenna as shown in FIG. **2**C.

The first receiver no preferably includes an analog-to-digital converter (ADC) in and a frequency downconverter **112**, as shown in FIG. **3**. The first receiver **110** may additionally or alternatively include amplifiers, filters, signal processors and/or any other suitable components. In one variation of a preferred embodiment, the first receiver no includes only analog processing circuitry (e.g., amplifiers, filters, attenuators, delayers). The first receiver may function to scale, shift, and/or otherwise modify the receive signal. The downconverter **112** functions to downconvert the analog receive signal from RF (or any other suitable frequency) to a baseband analog receive signal, and the analog-to-digital converter (ADC) in functions to convert the baseband analog receive signal to a digital receive signal.

The ADC **111** may be any suitable analog-to-digital converter; e.g., a direct-conversion ADC, a flash ADC, a successive-approximation ADC, a ramp-compare ADC, a Wilkinson ADC, an integrating ADC, a delta-encoded ADC, a time-interleaved ADC, or any other suitable type of ADC.

The frequency downconverter **112** functions to downconvert the carrier frequency of the analog receive signal to baseband, preparing it for conversion to a digital receive signal. The downconverter **112** preferably accomplishes signal downconversion using heterodyning methods, but may additionally or alternatively use any suitable upconversion methods.

The downconverter **112** preferably includes a local oscillator (LO), a mixer, and a baseband filter. The local oscillator functions to provide a frequency shift signal to the mixer; the mixer combines the frequency shift signal and the analog receive signal to create (usually two) frequency shifted signals, one of which is the baseband signal, and the baseband filter rejects signals other than the baseband analog receive signal.

The local oscillator is preferably a digital crystal variable-frequency oscillator (VFO) but may additionally or alternatively be an analog VFO or any other suitable type of oscillator. The local oscillator preferably has a tunable oscillation frequency but may additionally or alternatively have a static oscillation frequency.

The mixer is preferably an active mixer, but may additionally or alternatively be a passive mixer. The mixer may comprise discrete components, analog ICs, digital ICs, and/or any other suitable components. The mixer preferably functions to combine two or more electrical input signals into one or more composite outputs, where each output includes some characteristics of at least two input signals.

The baseband filter is preferably a lowpass filter with a tunable low-pass frequency. Additionally or alternatively, the baseband filter may be a lowpass filter with a set low-pass frequency, or any other suitable type of filter. The baseband filter is preferably a passive filter, but may additionally or alternatively be an active filter. The baseband filter is preferably implemented with analog circuit components, but may additionally or alternatively be digitally implemented.

The second receiver **115** functions to receive analog receive signals transmitted by a second communications system over a second communications link (e.g., a wireless channel, a coaxial cable). The second receiver **115** preferably converts analog receive signals into digital receive signals for processing before re-transmission by the second transmitter **125**, but may additionally or alternatively not convert analog receive signals (passing them through directly without conversion).

The second receiver **115** preferably includes an analog-to-digital converter (ADC) **116** and a frequency downconverter **117**, as shown in FIG. **3**. The second receiver **115** is preferably substantially similar to the first receiver **110**, but may additionally or alternatively be any suitable receiver.

The first transmitter **120** functions to retransmit signals received by the first receiver no. The first transmitter **120** preferably converts digital transmit signals into analog transmit signals, but may additionally or alternatively receive and retransmit analog transmit signals from the first receiver **110**, thus avoiding digital-to-analog conversion. The transmit signals are preferably formed by processing receive signals (which may include analog-to-digital conversion or frequency shifting, for example) by the first receiver no, but the transmit signals may additionally or alternatively be any signal intended for transmission by the relay **100**. The first transmitter **120** preferably transmits signals over a second communications link to a second communications system; these signals are preferably retransmitted signals from a first communication system sent to the relay **100** over a first communications link, but may additionally or alternatively be any suitable signals.

The first transmitter **120** is preferably a radio-frequency (RF) transmitter, but may additionally or alternatively be any suitable transmitter.

The first transmitter **120** is preferably coupled to the second communications link by a duplexer-coupled RF antenna as shown in FIG. **2**A, but may additionally or alternatively be coupled to the second communications link in any suitable manner. Some examples of alternative couplings include coupling via one or more dedicated transmit antennas (as shown in FIG. **2**B). In another alternative coupling, the first transmitter **120** may be coupled to the second communications link by a duplexer-coupled RF antenna as shown in FIG. **2**C.

The first transmitter **120** preferably includes a digital-to-analog converter (DAC) **121** and a frequency upconverter **122**, as shown in FIG. **4**. The first transmitter **120** may additionally or alternatively include amplifiers, filters, signal processors and/or any other suitable components. The first transmitter **120** may function to scale, shift, and/or otherwise modify the transmit signal. The digital-to-analog converter

(DAC) **121** functions to convert the digital transmit signal to a baseband analog transmit signal, and the upconverter **122** functions to upconvert the baseband analog transmit signal from baseband to RF (or any other intended transmission frequency).

The DAC **121** may be any suitable digital-to-analog converter; e.g., a pulse-width modulator, an oversampling DAC, a binary-weighted DAC, an R-2R ladder DAC, a cyclic DAC, a thermometer-coded DAC, or a hybrid DAC.

The frequency upconverter **122** functions to upconvert the carrier frequency of the baseband analog transmit signal to a radio frequency, preparing it for transmission over the communications link. The upconverter **122** preferably accomplishes signal upconversion using heterodyning methods, but may additionally or alternatively use any suitable upconversion methods.

The upconverter **122** preferably includes a local oscillator (LO), a mixer, and an RF filter. The local oscillator functions to provide a frequency shift signal to the mixer; the mixer combines the frequency shift signal and the baseband analog transmit signal to create (usually two) frequency shifted signals, one of which is the RF analog transmit signal, and the RF filter rejects signals other than the RF analog transmit signal.

The local oscillator is preferably a digital crystal variable-frequency oscillator (VFO) but may additionally or alternatively be an analog VFO or any other suitable type of oscillator. The local oscillator preferably has a tunable oscillation frequency but may additionally or alternatively have a static oscillation frequency.

The mixer is preferably an active mixer, but may additionally or alternatively be a passive mixer. The mixer may comprise discrete components, analog ICs, digital ICs, and/or any other suitable components. The mixer preferably functions to combine two or more electrical input signals into one or more composite outputs, where each output includes some characteristics of at least two input signals.

The RF filter is preferably a bandpass filter centered around a tunable radio frequency. Additionally or alternatively, the RF filter may be a bandpass filter centered around a set radio frequency, or any other suitable type of filter. The RF filter is preferably a passive filter, but may additionally or alternatively be an active filter. The RF filter is preferably implemented with analog circuit components, but may additionally or alternatively be digitally implemented.

The second transmitter **125** functions to retransmit signals received by the second receiver **115**. The second transmitter **125** preferably converts digital transmit signals into analog transmit signals, but may additionally or alternatively receive and retransmit analog signals from the second receiver **115**, thus avoiding digital-to-analog conversion. The transmit signals are preferably formed by processing receive signals (which may include analog-to-digital conversion or frequency shifting, for example) by the second receiver **115**, but the transmit signals may additionally or alternatively be any signal intended for transmission by the relay **100**. The second transmitter **125** preferably transmits signals over a first communications link to a first communications system; these signals are preferably retransmitted signals from a second communication system sent to the relay **100** over a second communications link, but may additionally or alternatively be any suitable signals.

The second transmitter **125** preferably includes a digital-to-analog converter (DAC) **126** and a frequency upconverter **127**, as shown in FIG. **4**. The second transmitter **125** is preferably substantially similar to the first transmitter **120**, but may additionally or alternatively be any suitable transmitter.

The self-interference canceller **130** functions to reduce self-interference in the relay **100** by canceling self-interference components present in receive signals of the relay **100**. The self-interference canceller **130** preferably includes one or more analog self-interference cancellers **131**; the self-interference canceller **130** may additionally or alternatively include a digital self-interference canceller **132**, as shown in FIG. **5**.

Analog self-interference cancellers **131** preferably reduce self-interference by sampling an analog transmit signal and generating an analog self-interference cancellation signal based on the input analog transmit signal. The analog self-interference cancellation signal is preferably combined with an analog receive signal before the analog receive signal is received by a receiver (e.g., **110** or **115**), but may additionally or alternatively be combined with the receive signal at any suitable location or time.

Analog self-interference cancellers **131** preferably generate self-interference cancellation signals for a given analog receive signal from a corresponding direction analog transmit signal as shown in FIG. **5** (e.g., the self-interference cancellation signal combined with a re-transmitted uplink signal is preferably generated from the received uplink signal). Additionally or alternatively, analog self-interference cancellers **131** may generate self-interference cancellation signals for a given analog receive signal from any other analog transmit signal.

For example, in situations where the relay **100** relays bi-directional communication (e.g., uplink/downlink) on well-separated frequencies, self-interference in the downlink receiver occurring from the uplink transmitter may be negligible (or vice versa); however, in situations where the uplink and downlink frequencies are closer, self-interference may occur across channels. In these situations it might be desirable to have hetero-channel as well as homo-channel self-interference cancellation, as shown in FIG. **6**.

The analog self-interference canceller **131** is preferably implemented as an analog circuit that transforms an analog transmit signal into an analog self-interference cancellation signal by combining a set of filtered, scaled, and/or delayed versions of the analog transmit signal, but may additionally or alternatively be implemented as any suitable circuit. For instance, the analog self-interference canceller **131** may perform a transformation involving only a single version or copy of the analog transmit signal. The transformed signal (i.e. the analog self-interference cancellation signal) preferably represents at least a part of the self-interference component received at a coupling point of the relay **100** to a communications link (e.g. a receive antenna).

The analog self-interference canceller **131** is preferably adaptable to changing self-interference parameters in addition to changes in the analog transmit signal; for example, transmitter temperature, ambient temperature, antenna configuration, humidity, and transmitter power. Adaptation of the analog self-interference canceller **131** is preferably performed by a control circuit or other control mechanism included in the canceller **131**, but may additionally or alternatively be performed by any suitable controller.

The analog self-interference canceller **131** is preferably coupled to signal paths by short section directional transmission line couplers, but may additionally or alternatively be coupled by any power dividers, power combiners, direc-

tional couplers, or other types of signal splitters suitable for coupling signal paths of the relay **100** to the analog self-interference canceller **131**.

The digital self-interference canceller **132** functions to reduce self-interference in the relay **100** by canceling self-interference components present in digital receive signals. The digital self-interference canceller **132** preferably performs both linear and non-linear digital self-interference cancellation, but alternatively may only perform one of the two.

The digital self-interference canceller **132** preferably reduces digital self-interference by sampling one or more digital transmit signals and generating one or more digital self-interference cancellation signals based on input sampled digital transmit signals (and a transform configuration). Digital self-interference cancellation signals may be combined with corresponding receive signals at any time or location. The digital self-interference canceller **132** preferably removes self-interference signal components not removed by analog self-interference cancellers **131**.

The digital self-interference canceller **132** preferably samples digital transmit signals of the relay **100** (additionally or alternatively, the canceller **132** may sample analog transmit signals or any other suitable transmit signals) and transforms the digital transmit signals to digital self-interference cancellation signals based on one or more digital transform configurations. The digital transform configuration preferably includes settings that dictate how the digital self-interference canceller **132** transforms a digital transmit signal to a digital self-interference cancellation signal (e.g. coefficients of a generalized memory polynomial used to transform the transmit signal to a self-interference signal).

The digital self-interference canceller **132** preferably generates self-interference cancellation signals for a given digital receive signal from a corresponding direction digital transmit signal as shown in FIG. **7**A (e.g., the self-interference cancellation signal combined with a re-transmitted uplink signal is preferably generated from the received uplink signal). Additionally or alternatively, the digital self-interference canceller **132** may generate self-interference cancellation signals for a given digital receive signal from any other transmit signal or combination of transmit signals (including analog transmit signals converted using ADCs).

For example, in situations where the relay **100** relays bi-directional communication (e.g., uplink/downlink) on well-separated frequencies, self-interference in the downlink receiver occurring from the uplink transmitter may be negligible (or vice versa); however, in situations where the uplink and downlink frequencies are closer, self-interference may occur across channels. In these situations it might be desirable to have hetero-channel as well as homo-channel self-interference cancellation, as shown in FIG. **7**B.

Each self-interference cancellation signal generated by the digital self-interference canceller **132** is preferably associated with a configuration transform (e.g., t1, t2, t3, and t4 of FIGS. **7**A and **7**B); additionally or alternatively, configuration transforms may be associated with digital self-interference cancellation signals in any suitable manner.

In the above description of the preferred embodiments, it is mentioned that the relay **100** may form transmit signals by processing receive signals (e.g., by phase shifting, amplifying, attenuating, frequency shifting, etc.). In a variation of a preferred embodiment, processing may be performed by relay bases **140** positioned between transmitters and receivers, as shown in FIG. **8**. A relay base **140** may be a layer 1 (L1) relay, a layer 2 (L2) relay, a layer 3 (L3) relay, or any other suitable relay. Relay bases **140** preferably function to prepare signals for retransmission; for example, a relay base **140** may reorganize information before retransmitting to increase transmission efficiency. As another example, a relay base **140** may delay a signal before retransmission to time it with a particular transmission window.

While the examples above are directed to single-in/single-out (SISO) relays, it is understood that the relay **100** may also be used for multiple-in/multiple-out (MIMO) communications, as shown in FIG. **9**. MIMO technology may offer increased data throughput and link range without the need for additional bandwidth or increased transmitter power.

The example relay **100** as shown in FIG. **9** represents a 2×2 MIMO system, but it is understood that the relay **100** may additionally or alternatively utilize any suitable number of transmit and receive signals. Each signal path may have separate antennas; alternatively, signal paths may share antennas via a duplexer or other coupler. In one example, each signal path of a 2×2 MIMO relay has four antennas: a TX1 antenna, a TX2 antenna, an RX1 antenna, and an RX2 antenna, as shown in FIG. **10**A. In another example, each signal path of a 2×2 MIMO system has two antennas: a TX1/RX1 antenna (coupled to both TX1 and RX1 signal paths via a circulator) and a TX2/RX2 antenna (coupled to both TX2 and RX2 signal paths via a circulator), as shown in FIG. **10**B. In a third example, each signal path of a 2×2 MIMO system is again associated with four antennas, but the relay **100** has only four antennas total; a duplexer is used to couple each antenna to both a TX and an RX signal (where the TX and RX signals are from different signal paths), as shown in FIG. **10**C.

As shown in FIGS. **10**A and **10**B, the first and second transmitters **120** and **125** are preferably implementations having multiple inputs and outputs. In particular, each transmitter preferably includes a DAC and frequency upconverter for each transmit signal path; additionally or alternatively, transmit signal paths may share DACs and/or frequency upconverters. Additionally or alternatively, each transmitter may be any suitable MIMO transmitter; for example, transmitters may include MIMO signal splitting or processing circuitry (which may be used to process a single digital signal into multiple MIMO analog signals).

The first and second receivers **110** and **115** are preferably implementations having multiple inputs and outputs. In particular, each receiver preferably includes an ADC and frequency downconverter for each receive signal path; additionally or alternatively, receive signal paths may share ADCs and/or frequency downconverters. Additionally or alternatively, receivers may be any suitable MIMO receiver; for example, receivers may include MIMO signal splitting or processing circuitry (which may be used to process multiple MIMO analog signals into a single digital signal).

In an embodiment of the relay **100** designed for MIMO operating environments (i.e., multiple transmit and/or receive signals), the relay **100** preferably includes analog self-interference cancellers **131** for each pair of receive/transmit signals, as shown in FIG. **9**. In MIMO operating environments, self-interference may occur across communications streams in addition to in them; for example, a TX1 signal may cause interference in both of RX1 and RX2 signals. As a result, the relay **100** may additionally or alternatively include analog self-interference cancellers **131** for self-interference cancellation across communications streams, as shown in FIG. **11**. Cross-stream cancellation may additionally or alternatively be combined with cross-directional cancellation (which is as shown in FIG. **6**).

In an embodiment of the relay **100** designed for MIMO operating environments (i.e., multiple transmit and/or

receive signals), the digital self-interference canceller **132** may perform digital self-interference cancellation on each MIMO digital receive signal, but may additionally or alternatively perform digital self-interference cancellation on a combined digital receive signal (resulting from the combination of MIMO digital receive signals). If the digital self-interference canceller **132** performs self-interference cancellation for multiple MIMO digital receive signals, cancellation may be performed for each TX/RX pairing, similarly to those described in the section on the analog self-interference canceller **131**.

As a person skilled in the art will recognize from the previous detailed description and from the figures and claims, modifications and changes can be made to the preferred embodiments of the invention without departing from the scope of this invention defined in the following claims.

We claim:

1. A single-input, single-output relay comprising:

a first transmitter, coupled to a first signal path of the relay, that converts a first digital transmit signal received via the first signal path to a first analog transmit signal, and transmits the first analog transmit signal via the first signal path;

a first receiver, coupled to the first signal path of the relay, that receives a first analog receive signal via the first signal path, and converts the first analog receive signal to a first digital receive signal;

a second transmitter, coupled to a second signal path of the relay, that converts a second digital transmit signal received via the second signal path to a second analog transmit signal, and transmits the second analog transmit signal via the second signal path;

a second receiver, coupled to the second signal path of the relay, that receives a second analog receive signal via the second signal path, and converts the second analog receive signal to a second digital receive signal;

a first analog self-interference canceller that generates, in the RF domain and without performing frequency downconversion, a first self-interference cancellation signal based on the first analog transmit signal, and combines the first self-interference cancellation signal with the first analog receive signal;

a second analog self-interference canceller that generates, in the RF domain and without performing frequency downconversion, a second self-interference cancellation signal based on the second analog transmit signal, and combines the second self-interference cancellation signal with the second analog receive signal;

a third analog self-interference canceller that generates, in the RF domain and without performing frequency downconversion, a third self-interference cancellation signal based on the first analog transmit signal, and combines the third self-interference cancellation signal with the second analog receive signal; and

a fourth analog self-interference canceller that generates, in the RF domain and without performing frequency downconversion, a fourth self-interference cancellation signal based on the second analog transmit signal, and combines the fourth self-interference cancellation signal with the first analog receive signal;

wherein the first transmitter and the second transmitter may transmit simultaneously.

2. The relay of claim **1**, wherein the first digital transmit signal is substantially similar to the first digital receive signal; wherein the second digital transmit signal is substantially similar to the second digital receive signal.

3. The relay of claim **1**, wherein the first, second, third, and fourth analog self-interference cancellers generate self-interference cancellation signals by combining filtered, scaled, and delayed versions of analog transmit signals.

4. The relay of claim **1**, further comprising a digital self-interference canceller, wherein the digital self-interference canceller generates a fifth self-interference cancellation signal based on the first digital transmit signal; wherein the fifth self-interference cancellation signal is combined with the first digital receive signal.

5. The relay of claim **4**, wherein the digital self-interference canceller generates a sixth self-interference cancellation signal based on the second digital transmit signal; wherein the sixth self-interference cancellation signal is combined with the second digital receive signal.

6. The relay of claim **5**, wherein the fifth self-interference cancellation signal is generated based on both of the first and second digital transmit signals; wherein the sixth self-interference cancellation signal is generated based on both of the first and second digital transmit signals.

7. The relay of claim **5**, wherein the digital self-interference canceller generates the fifth and sixth self-interference cancellation signals according to a digital transform configuration.

8. A MIMO relay comprising:

a first transmitter, that communicates with a first wireless communication device, coupled to first and second signal paths of the relay, that converts first and second digital transmit signals received via the first and second signal paths to first and second analog transmit signals, and transmits the first and second analog transmit signals via the first and second signal paths;

a first receiver, that communicates with the first wireless communication device, coupled to the first and second signal paths of the relay, that receives first and second analog receive signals via the first and second signal paths, and converts the first and second analog receive signals to first and second digital receive signals;

a second transmitter, that communicates with a second wireless communication device independent from the first wireless communication device, coupled to third and fourth signal paths of the relay, that converts third and fourth digital transmit signals received via the third and fourth signal paths to third and fourth analog transmit signals, and transmits the third and fourth analog transmit signals via the third and fourth signal paths;

a second receiver, that communicates with the second wireless communication device, coupled to the third and fourth signal paths of the relay, that receives third and fourth analog receive signals via the third and fourth signal paths, and converts the third and fourth analog receive signals to third and fourth digital receive signals;

a first analog self-interference canceller that generates, in the RF domain and without performing frequency downconversion, a first self-interference cancellation signal based on the first analog transmit signal and combines the first self-interference signal with the first analog receive signal;

a second analog self-interference canceller that generates a second self-interference cancellation signal based on the second analog transmit signal and combines the second self-interference signal with the second analog receive signal;

a third analog self-interference canceller that generates a third self-interference cancellation signal based on the

third analog transmit signal and combines the third self-interference signal with the third analog receive signal;

a fourth analog self-interference canceller that generates a fourth self-interference cancellation signal based on the fourth analog transmit signal and combines the fourth self-interference signal with the fourth analog receive signal;

a fifth analog self-interference canceller that generates a fifth self-interference cancellation signal from the first analog transmit signal and combines the fifth self-interference cancellation signal with the second analog receive signal;

a sixth analog self-interference canceller that generates a sixth self-interference cancellation signal from the second analog transmit signal and combines the sixth self-interference cancellation signal with the first analog receive signal;

a seventh analog self-interference canceller that generates a seventh self-interference cancellation signal from the first analog transmit signal and combines the seventh self-interference cancellation signal with the fourth analog receive signal; and

an eighth analog self-interference canceller that generates an eighth self-interference cancellation signal from the second analog transmit signal and combines the eighth self-interference cancellation signal with the third analog receive signal;

wherein the first transmitter and the second transmitter may transmit simultaneously.

* * * * *