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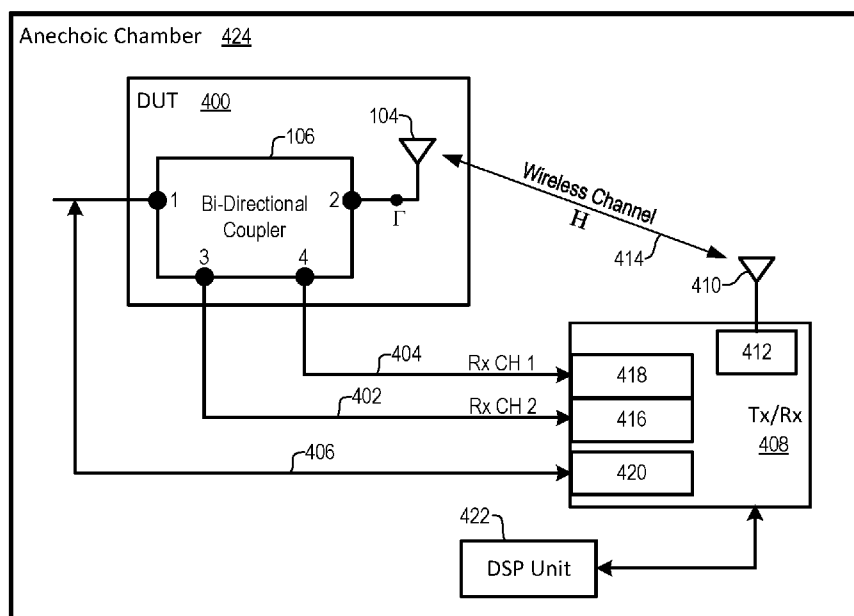


Figure 4B

(57) Abstract: Embodiments of a method of calibrating a bi-directional coupler integrated with an antenna. The method comprises: supplying combinations of first and second signals, each combination comprising at least one of: a first input signal supplied to the antenna via a wireless channel; and a second input signal supplied to an input port of the bi-directional coupler; measuring, for each combination of first and second signals, a corresponding set of output signal power levels emitted from the bi-directional coupler; and calculating a set of calibration values based on the measured sets of output signal power levels.

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Method and Apparatus for Over the Air Calibration for Integrated Antenna VSWR Monitoring

Technical Field

[0001] The present disclosure relates to wireless communications devices, and in particular to techniques for over the air calibration for integrated antenna Voltage Standing Wave Ratio (VSWR) monitoring.

Background

[0002] Voltage standing wave ratio (VSWR) is a fundamental parameter that is always measured in radio equipment to detect antenna failure and/or obstructions in the proximity of the radiating antenna and to monitor transmission efficiency. Currently, VSWR is calculated by measuring forward and reverse power levels using a bi-directional coupler inserted between the radio equipment and the antenna.

[0003] As is well known in the art, a bi-directional coupler is a 4-port device that includes a “through” path between ports 1 and 2, a “forward” path between ports 1 and 3, and a “reverse” path between ports 2 and 4. In operation, so-called forward signals being transmitted by a radio transceiver, for example, enter the bi-directional coupler at port 1, and are transmitted via the through-path to port 2 which is connected to the antenna. A portion of the forward signal is coupled into port 3, which enables the forward power level to be measured by means of a detector coupled to port 3. Conversely, reflected signals from the antenna enter the bi-directional coupler at port 2 and are transmitted via the through-path to port 1 which is connected to the radio transceiver. A portion of the reflected (or reverse) signal is coupled into port 4, which enables the reflected power level to be measured by means of a detector coupled to port 4. As is well known in the art, comparison between the forward and reverse power levels enables calculation of a reflection ratio, from which the VSWR can be calculated.

[0004] One well known issue of exploiting bi-directional couplers for determining the reflection ratio is systematic errors caused by the coupler. For example, in an ideal bi-directional coupler, port 3 would be perfectly isolated from ports 2 and 4, while port 4 would be perfectly isolated from ports 1 and 3. However, in a real bi-directional

coupler at least some leakage between ports 2 and 3 and between ports 1 and 4 always occurs. For example, when measuring the forward signal coupled from port 1 through port 3, an undesired signal is leaked into port 3 from port 2, and produces an error in the forward power measurement. Similarly, when collecting the reflected
5 signal coupled from port 2 to port 4, an undesired signal is leaked into port 4 from port 1 and produces an error in the reflected power measurement.

[0005] Another prominent source of error is a difference in gain between the forward and reverse coupling paths. For example, the respective proportions of the forward power coupled into port 3, and the reflected power coupled into port 4 must be
10 known in order to accurately calculate the reflection coefficient. Any errors between the expected proportions and the actual proportions will produce corresponding errors in the calculated reflection coefficient.

[0006] To overcome the problem of systematic errors, bi-directional couplers are calibrated prior to being used for measuring forward and reverse power levels.

15 Various methods are known performing the required calibration process. In general, these methods involve connecting a known resistive load to port 2, and using the radio transceiver to transmit a known signal into port 1. Calibrated sensors coupled to ports 3 and 4 then measure the forward and reverse power level, from which the reflection coefficient can be calculated. In some techniques, this process is repeated with
20 different resistive loads attached to port 2 to obtain a set of reflection coefficient values. Using these reflection coefficient values in combination with the known values of the resistive loads and a linear error model for the coupler, a set of calibration parameters of the coupler can be calculated and saved for future use to compensate systemic errors of the coupler.

25 **[0007]** Because systemic errors are highly sensitive to manufacturing variations, it is common for the bi-directional coupler(s) in each radio unit to be individually calibrated in order to achieve the best possible performance.

[0008] A limitation of known calibration methods is that the antenna must be disconnected from port 2 in order to permit the resistive load(s) to be connected.

30 However, in order to minimize the size of each radio unit it is desirable to integrate the antenna and the directional coupler together as a single component, for example on a

common printed circuit (PC) board. In some case, the antenna and directional coupler may even be integrated onto a common PC board with the radio transceiver. This raises a problem in that it precludes disconnecting the antenna from port2, which means that conventional calibration methods cannot be used.

5 Summary

[0009] An object of the present invention is to provide methods and apparatus for calibrating a bi-directional coupler integrated with an antenna.

[0010] Accordingly, an aspect of the present invention provides a method comprising: supplying combinations of first and second signals, each combination
10 comprising at least one of: a first input signal supplied to the antenna via a wireless channel; and a second input signal supplied to an input port of the bi-direction coupler; measuring, for each combination of first and second signals, a corresponding set of output signal power levels emitted from the bi-directional coupler; and calculating a set of calibration values based on the measured sets of output signal power levels.

15 **[0011]** Other aspects of the present invention provide an apparatus configured to implement the methods described herein.

[0012] Advantages of the present invention provide methods and apparatus enabling the accurate calibration of a bi-directional coupler integrated with an antenna. This, in turn, enables the deployment of smaller and lower-cost wireless devices that
20 still exhibit excellent performance.

Brief Description of the Drawings

[0013] The accompanying drawing figures incorporated in and forming a part of this specification illustrate several aspects of the disclosure, and together with the description serve to explain principles of the disclosure.

25 **[0014]** Figures 1A and 1B are block diagrams illustrating a wireless device including a bi-directional coupler integrated with an antenna;

[0015] Figures 2A and 2B illustrate effects of directivity of a bi-directional coupler;

[0016] Figure 3 illustrates nomenclature associated with a bi-directional coupler integrated with an antenna;

[0017] Figures 4A and 4B respectively illustrate an example process and apparatus in accordance with embodiments of the present invention;

[0018] Figure 5 illustrates operation of the apparatus of Figure 4B in a first example method in accordance with embodiments of the present invention;

5 [0019] Figure 6 illustrates further operation of the apparatus of Figure 4B in the first example method in accordance with embodiments of the present invention;

[0020] Figure 7 illustrates further operation of the apparatus of Figure 4B in the first example method in accordance with embodiments of the present invention; and

10 [0021] Figure 8 illustrates operation of the apparatus of Figure 4B in a further methods in accordance with embodiments of the present invention;

Detailed Description

[0022] The embodiments set forth below represent information to enable those skilled in the art to practice the embodiments and illustrate the best mode of practicing the embodiments. Upon reading the following description in light of the accompanying
15 drawing figures, those skilled in the art will understand the concepts of the disclosure and will recognize applications of these concepts not particularly addressed herein. It should be understood that these concepts and applications fall within the scope of the disclosure.

[0023] Figure 1A is a block diagram illustrating a wireless device of a type in which
20 embodiments of the present invention may be used. In the illustrated example, the wireless device 100 includes a radio unit 102 connected to an antenna 104. A Bi-Directional coupler 106 is connected between the radio unit 102 and the antenna 104 to enable measurements of forward and reverse (or reflected) radio signal power flows between the radio unit 102 and the antenna 104.

25 [0024] As may be appreciated, the wireless device 100 is configured to transmit and/or receive radio signals via the antenna 104, and so may be incorporated within any device or equipment in which such functionality may be desired. In very general terms, the radio unit 102 may include hardware components defining a transmitter and/or a receiver, and may be connected to other hardware components including, for
30 example, a power supply (not shown). The radio unit 102 may also be connected to

one or more signal and/or data processing devices, which may include a controller configured to control operation of the radio unit 102. The antenna 104 may be any suitable type of antenna including single element and/or multi-element configurations. In some embodiments, the antenna 104 may be an element within a larger multi-element antenna array.

[0025] In the illustrated example, the Bi-Directional coupler 106 is configured with four ports (labeled as ports 1...4). In a conventional bi-directional coupler, port 1 is directly connected port 2 via a so-called "through" path (not shown), so that radio frequency (RF) signals can propagate through the coupler between ports 1 and 2 with very low loss. Accordingly, in the illustrated example, port 1 is connected to the radio unit 102 and port 2 is connected to the antenna 104. This allows RF signals to be transmitted and/or received by the radio unit 102, via the antenna 104, with low losses being incurred through the bi-directional coupler 106.

[0026] For the purposes of the present disclosure, signals emitted by the radio unit 102 and propagating toward the antenna 104 are referred to as forward propagating signals, while RF signals propagating from the antenna 104 toward the radio unit 102 are referred to as reverse propagating signals.

[0027] In a conventional bi-directional coupler, port 1 is also coupled to port 3, such that a portion of forward propagating signals arriving at port 1 from the radio unit 102 are coupled to port 3, which allows the power level of the forward propagating signals to be measured. Similarly, port 2 is coupled to port 4, such that a portion of reverse propagating signals arriving at port 2 are coupled to port 4, which allows the power level of the reverse propagating signals to be measured. It is customary to refer to port 3 as a forward coupled port, and to refer to port 4 as the reverse coupled port.

[0028] Voltage standing wave ratio (VSWR) is one paramount parameter that is always measured by radios to detect antenna failure and/or obstruction within the proximity of the radiating antenna and to monitor transmission efficiency. Currently bi-directional couplers are used to measure forward power (i.e. the power level of forward propagating signals emitted by the radio unit 102) through port 3 as described above and reflected power (i.e. the power level of reverse propagating signals reflected from the antenna) through port 4. By estimating the ratio between the forward power, V_f ,

and reflected power, V_r , an estimate of the reflection coefficient, Γ , is calculated according to

$$\Gamma = \frac{V_r}{V_f} \quad (\text{Equ.1})$$

5 **[0029]** From which estimates of the VSWR and the Return Loss (RL) can be calculated as

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|} \quad (\text{Equ.2})$$

$$RL = 20 \log_{10} |\Gamma| \quad (\text{Equ.3})$$

[0030] However, one well known issue of exploiting bi-directional couplers when measuring the reflection coefficient is systematic errors caused by the coupler itself.

10 The coupler's directivity, which is a measure of how well the coupler isolates forward and reverse propagating signals, is one significant source of error. For example, leaked signals through the coupler are a major source of error in RL and VSWR measurements. Figure 1B schematically illustrates signal propagation paths in the bi-directional coupler 106. As may be seen in Figure 1B, the signal power measured at

15 port 3 includes both the desired forward power coupled from port 1 (at 108), and an undesired leakage signal (at 110) from port 2. Similarly, the signal power measured at port 4 includes both the desired reverse power coupled from port 2 (at 112), and an undesired leakage signal (at 114) from port 1. Directivity is the parameter that describes the power of the leaked signal and hence is important for improving the

20 accuracy of the RL/ VSWR estimation algorithm. In other words, the higher the directivity, the lower the power of the leaked signal(s) and the better the accuracy of the RL estimation algorithm.

[0031] Differences in gain between forward and reverse coupling paths (i.e. between ports 1 and 3, and between ports 2 and 4) is another prominent source of

25 error. Systematic error causes the measured RL to deviate from the actual RL. To overcome this problem, the coupler is calibrated prior to measurement to account for that deviation. For example, a calibration process may be used, in which three loads with known RL values are applied to port 2 of the coupler and then the reflection coefficient is measured. Using the three measured reflection coefficient values, the

values of the three known loads and a linear error model for the coupler, some inherent parameters of the coupler are estimated and saved for future use.

[0032] One main point to note is that this calibration process mandates access to port 2 of the coupler to connect the three known loads.

5 **[0033]** However, if the antenna is integrated with the coupler, there is no access to port 2, and existing calibration processes cannot be used to calibrate the systematic error of the coupler, which may result in the measured RL being deviated from the actual RL by several dB's. In Figures 2A and 2B, respective plots for the impact of directivity are shown. As can be seen in Figure 2A, for a Directivity of 20 dB, the RL measurement exhibits an error of up to +7dB and -3.7dB at RL = 15 dB. Referring to
10 Figure 2B, for a directivity of 25 dB, the error is +3.2 dB and -2.3 dB at RL = 15 dB. Note the positive and negative error ranges are due to the phase of the leaked signal, which affects how it combines with the desired signal and hence estimating a RL value that is greater than the actual one and hence the error is positive or RL value that is
15 lower than the actual one and hence a negative error.

[0034] Adding the difference in gain between the forward and reverse coupling paths, which can be around 2 dB, the error now due to that difference and 20 dB Directivity is within +9 dB and -5.7at RL = 15 dB. This shows that with more systematic error, the estimated RL becomes subject to increasing uncertainty which renders the
20 measurement process unreliable.

[0035] In the following, a mathematical model of the received forward and reflected signal through the bi-directional coupler is presented. Let's first define Γ , as the reflection coefficient looking towards the antenna. In addition to (Equ.1), the reflection coefficient can also be defined in terms of impedances. We have $\Gamma = (Z_A - Z_C)/(Z_A + Z_C)$, where Z_A is the impedance of the antenna and Z_C is the impedance of the
25 coupler circuitry. The reflection coefficient looking towards the coupler can be defined as $\Gamma_C = (Z_C - Z_A)/(Z_A + Z_C)$. Hence, we have $\Gamma = -\Gamma_C$.

[0036] Assuming that the device under test, which comprises the coupler and the antenna, is deployed and a signal X_{in} is being applied through port 1 of the coupler as
30 shown in Figure 3, and using the coupler's S-parameters, we have the forward and reflected signals defined as follows.

[0037] The received forward signal through port 3 is defined as:

$$X_F = S_{31} x_{in} + S_{21} S_{32} \Gamma x_{in} \quad (\text{Equ.4})$$

[0038] Where S_{31} is the coupler's forward coupling, S_{21} is the coupler's insertion loss, and S_{32} is the forward isolation. Note that the isolation is defined as directivity multiplied by coupling. The first term in (Equ.4) is the forward coupled desired signal, while the second term is the leaked undesired signal.

[0039] The received reflected signal through port 4 is defined as:

$$X_{REFL} = S_{21} S_{42} \Gamma x_{in} + S_{41} x_{in} \quad (\text{Equ.5})$$

[0040] Where S_{42} is the coupler's reverse coupling and S_{41} is the reverse path isolation. The first term in (Equ.5) is the desired reflected signal, while the second term is the leaked undesired signal.

[0041] The measured reflection coefficient, Γ_m , is then estimated as

$$\Gamma_m = \frac{X_{REFL}}{X_F} = \frac{S_{21} S_{42} \Gamma + S_{41}}{S_{31} + S_{21} S_{32} \Gamma} \quad (\text{Equ.6})$$

[0042] Which can be written as

$$\Gamma_m = \frac{X_{REFL}}{X_F} = \frac{A + C \Gamma}{1 + B \Gamma} \quad (\text{Equ.7})$$

[0043] Where $A = \frac{S_{41}}{S_{31}}$, $B = \frac{S_{21} S_{32}}{S_{31}}$ and $C = \frac{S_{21} S_{42}}{S_{31}}$. Since the objective is to determine Γ , It is clear now that due to coupler's systematic error, the estimated reflection coefficient, Γ_m , is a deviated version of the actual value Γ .

[0044] However, if the coupler's S-parameters in (Equ.6) or the calibration parameters A , B and C in (Equ.7) are measured and saved, they could then be used to correct the measured value Γ_m . In other words, we would have

$$\Gamma = \frac{A - \Gamma_m}{B \Gamma_m - C} \quad (\text{Equ.8})$$

[0045] Existing solutions, which require access to the antenna port, i.e., port 2 in Figure 3 employ the following steps:

[0046] Step 1: Apply three known loads with Γ_1 , Γ_2 and Γ_3

[0047] Step 2: Measure the corresponding Γ_{m1} , Γ_{m2} and Γ_{m3}

[0048] Step 3: Solve (Equ.7) for the unknowns A , B , C and save them as calibration parameters of the bi-directional coupler 106.

[0049] In subsequent run-time operation, determine Γ_m and using the saved calibration parameter values, substitute in (Equ.7) to determine the actual reflection coefficient, Γ . VSWR and RL can then be estimated as shown above in (Equ.2) and (Equ.3).

[0050] As may be appreciated, existing calibration procedures such as those described above, require access to the antenna port, which is not applicable in the case of integrated antenna systems. In other words, it is not possible to apply three known loads at the antenna port to generate three equations to solve for the coupler's unknown S-Parameters. Hence, existing techniques cannot be used and the need for a new calibration process is inevitable.

[0051] In embodiments of the present invention, an over the air calibration process is described. By transmitting an external signal to the antenna and collecting it through different ports of the coupler, it is possible to calibrate the coupler and measure its inherent parameters and save them for future use to improve estimates of the RL and/or VSWR. Example embodiments of the calibration process are described below.

[0052] Figure 4A is a flow-chart illustrating steps in a method in accordance with an example embodiment of the present invention. In the example of Figure 4A, combinations of first and second input signals are supplied. Each combination comprises at least one of: a first input signal supplied to the antenna (104) via a wireless channel (414); and a second input signal supplied to an input port of the bi-direction coupler (106). A second step includes measuring, for each combination of first and second signals, a corresponding set of output signal power levels emitted from the bi-directional coupler (106). Finally, a set of calibration values based on the measured sets of output signal power levels are calculated.

[0053] This apparatus and methods described in greater detail below are configured to estimate the unknown parameters A , B and C . Then save them for future use when the antenna is deployed to monitor the efficiency of the transmission and to detect any fault in the antenna.

[0054] Figure 4 is a block diagram illustrating an apparatus in accordance with an example embodiment of the present invention. In the example of Figure 4, a device under test (DUT) 400 is connected via suitable RF signal paths 402, 404, 406 (such as coaxial cables, for example) to a transceiver unit 408. It is contemplated that the DUT
5 400 will include at least the bi-direction coupler 106 and the integrated antenna 104, as shown in Figure 4. In embodiments in which the bi-direction coupler 106 and the integrated antenna 104 are also integrated with the radio unit 102, then the DUT 400 will also include the radio unit 102.

[0055] The transceiver unit 408 includes an antenna 410 and appropriate radio
10 circuitry 412 configured to establish a wireless channel 414 with the antenna 104 of the DUT 400. In addition, the transceiver 408 includes a pair of wired RF signal receiver circuits 416 and 418 configured to receive RF signals from coupler ports 3 and 4 via signal paths 402, 404 and an RF transceiver circuit 420 configured to send and receive RF signals to and from coupler port 1 via signal path 406.

[0056] In the illustrated example, the transceiver unit 408 is also connected to a
15 digital signal processor (DSP) unit 422 configured to control operation of the transceiver unit 408 and analyze received RF signals to calculate estimates of the calibration parameters as described below. Alternatively, the DSP unit 422 may be integrated within the transceiver unit 408. In still further alternative embodiments, one
20 or more of the RF circuits 412, 416, 418 and 420 may be provided as separate units, which may be connected together (and to the DSP unit 422) via suitable cable connections, for example.

[0057] Preferably, for the purposes of performing the calibration methods described below, at least the DUT 400 and the transceiver unit antenna 410 are
25 located within a chamber 424 (such as an anechoic chamber) configured to prevent multipath effects between the DUT 400 and the transceiver unit antenna 410. In the illustrated embodiment, both the DUT 400 and the transceiver unit 408 are located with the chamber 424, but this is not essential. The purpose of the chamber 424 is to enable the channel coefficient H of the wireless channel 414 between the DUT 400
30 and the transceiver unit antenna 410 to be measured and characterized using conventional techniques and equipment such as, for example, a commercially

available Vector Network Analyzer (VNA). Any suitable configuration of the chamber 424, DUT 400 and transceiver unit 408 that achieves this purpose may be used.

[0058] In the following, detailed steps for the over-the-air calibration of the bi-directional coupler 106 of the DUT 400 is presented, using three example scenarios in the apparatus illustrated in Figure 4.

Scenario 1: Access to the coupler's input port (port 1) is available.

[0059] In the first scenario, access to the coupler's input port, (i.e., port 1) is available. This scenario applies to embodiments in which the coupler 106 and the antenna 104 (i.e. the DUT 400) can be disconnected from the radio unit 102, and then reconnected after calibration of the bi-directional coupler 106. In this case, it is possible to transmit and receive RF signals through port 1, using the transceiver circuit 420 and signal path 406. Referring now to Figures 5-7, calibration of the coupler 106 can be performed according to the following steps:

[0060] Step 1: Connect ports 3 and 4 to matched loads and control the radio circuit 412 of the transceiver unit 408 to emit an external RF signal X_E from the antenna 410, as may be seen in Figure 5. In some embodiments, the radio circuits 416 and 418 incorporate matched loads and can be controlled to connect the coupler ports 3 and 4 to the matched loads via RF signal paths 402 and 404. In other embodiments, RF signal paths 402 and 404 may be connected to matched loads externally to the radio circuits 416 and 418. The resulting input signal to the antenna 104 of the DUT 400 will be

$$X_{in} = X_E H \quad (\text{Equ.9})$$

[0061] Where X_E is the transmitted known external RF signal, H is the channel coefficient of the wireless channel 414, that may be determined using conventional methods as described above.

[0062] After traversing the bi-directional coupler 106, the signal X_{R1} output through port 1 of the coupler 106, and thus received by the transceiver circuit 420, may be defined as

$$X_{R1} = S_{12} (1 - \Gamma_C) X_{in} = S_{12} (1 + \Gamma) X_{in} \quad (\text{Equ.10})$$

[0063] From which we can calculate a first "measured" reflection coefficient Γ_{m_1} as:

$$\Gamma_{m1} = \frac{X_{R1}}{X_{in}} = S_{12} (1 + \Gamma) \quad (\text{Equ.11})$$

[0064] Hence, by measuring Γ_{m1} and with prior knowledge of S_{12} , an estimate of the reflection coefficient Γ can be estimated. In practice, the value of S_{12} commonly varies only slightly among examples of a given type of coupler produced by a particular manufacturer. For example, measurements of S_{12} performed on 18 couplers from one manufacturer showed a variation of only 0.2 dB, which is considered to be negligible. In such a case, an average value of S_{12} taken over a suitable sample set may be determined and stored for subsequent use in calculating the estimated reflection coefficient Γ .

[0065] Step 2: Connect coupler port 1 to a matched load and connect coupler ports 3 and 4 to radio circuits 416 and 418 to enable measurement of received signals, or alternatively, configure the radio circuits 416 and 418 to measure RF signals received from coupler ports 3 and 4. The radio circuit 412 of the transceiver unit 408 is controlled to emit the external RF signal X_E from the antenna 410. In some embodiments, the transceiver circuit 420 may incorporate a matched load and can be controlled to connect the coupler port 1 to the matched loads via RF signal path 406. In other embodiments, RF signal path 406 may be connected to a matched load externally to the transceiver circuit 420.

[0066] After traversing the bi-directional coupler 106, the signals X_{F2} output through port 3 of the coupler 106 and X_{REFL2} output through port 4 of the coupler 106, and thus received by the radio circuits 416 and 418, may be defined as:

$$X_{F2} = X_{in}(1 + \Gamma)S_{32} \quad (\text{Equ.12})$$

$$X_{REFL2} = X_{in}(1 + \Gamma)S_{42} \quad (\text{Equ.13})$$

[0067] We can then define a second measured reflection coefficient as:

$$\Gamma_{m2} = \frac{X_{REFL2}}{X_{F2}} = \frac{S_{42}}{S_{32}} \quad (\text{Equ.14})$$

[0068] Step 3: Referring to Figure 6, coupler port 1 is connected to the transceiver circuit 420 which is configured to transmit an input signal X_{IN3} , while coupler ports 3 and 4 remain connected to radio circuits 416 and 418 to enable measurement of received signals. The radio circuit 412 of the transceiver unit 408 is controlled to not

emit the external RF signal X_E from the antenna 410. After traversing the bi-directional coupler 106, the signals X_{F3} output through port 3 of the coupler 106 and X_{REFL3} output through port 4 of the coupler 106, and thus received by the radio circuits 416 and 418, may be defined as:

$$X_{F3} = S_{31} X_{in3} + S_{21} S_{32} \Gamma X_{in3} \quad (\text{Equ.15})$$

$$X_{REFL3} = S_{41} X_{in3} + S_{21} S_{42} \Gamma X_{in3} \quad (\text{Equ.16})$$

[0069] We can then define a third measured reflection coefficient as:

$$\Gamma_{m3} = \frac{X_{REFL3}}{X_{F3}} = \frac{S_{41} + S_{21} S_{42} \Gamma}{S_{31} + S_{21} S_{32} \Gamma} \quad (\text{Equ.17})$$

[0070] Let $A = \frac{S_{41}}{S_{31}}$ and $B = \frac{S_{21} S_{32}}{S_{31}}$ and $C = \frac{S_{21} S_{42}}{S_{31}}$. From (Equ.14), it can be inferred

that $C = B \Gamma_{m2}$. Following these definitions, (Equ.17) can be rewritten as

$$\Gamma_{m3} = \frac{X_{REFL3}}{X_{F3}} = \frac{A + C \Gamma}{1 + B \Gamma} \quad (\text{Equ.18})$$

$$\Gamma_{m3} = \frac{A + B \Gamma \Gamma_{m2}}{1 + B \Gamma} \quad (\text{Equ.19})$$

[0071] Step 4: Referring to Figure 7, coupler port 1 is connected to the transceiver circuit 420 which is configured to transmit an input signal X_{in4} , while coupler ports 3 and 4 remain connected to radio circuits 416 and 418 to enable measurement of received signals. The radio circuit 412 of the transceiver unit 408 is controlled to emit the external RF signal X_E from the antenna 410, which is supplied to port 2 of the coupler 106 as X_{inE} . The transceiver circuit 420 and the radio circuit 412 are further controlled such that $X_{in4} = X_{inE} = X_{in}$.

[0072] After traversing the bi-directional coupler 106, the signals X_{F4} output through port 3 of the coupler 106 and X_{REFL4} output through port 4 of the coupler 106, and thus received by the radio circuits 416 and 418, may be defined as:

$$X_{F4} = S_{31} X_{in} + S_{21} S_{32} \Gamma X_{in} + S_{32} (1 + \Gamma) X_{in} \quad (\text{Equ.20})$$

$$X_{REFL4} = S_{41} X_{in} + S_{21} S_{42} \Gamma X_{in} + S_{42} (1 + \Gamma) X_{in} \quad (\text{Equ.21})$$

[0073] We can then define a fourth measured reflection coefficient as:

$$\Gamma_{m4} = \frac{X_{REFL4}}{X_{F4}} = \frac{S_{41} + S_{21} S_{42} \Gamma + S_{42} (1 + \Gamma)}{S_{31} + S_{21} S_{32} \Gamma + S_{32} (1 + \Gamma)} \quad (\text{Equ.22})$$

[0074] Which can be written as

$$\Gamma_{m_4} = \frac{X_{REFL_4}}{X_{F_4}} = \frac{A + B \Gamma \Gamma_{m_2} + (\frac{B}{S_{21}}) \Gamma_{m_2} (1 + \Gamma)}{1 + B \Gamma + (\frac{B}{S_{21}}) (1 + \Gamma)} \quad (\text{Equ.23})$$

[0075] From (Equ.22) and (Equ.23), we can solve for A and B as follows:

[0076] let $K = \frac{1 + \Gamma}{S_{21}}$, $Q = \Gamma \Gamma_{m_2} + K \Gamma_{m_2} - \Gamma \Gamma_{m_4} - K \Gamma_{m_4}$, $G = \frac{\Gamma_{m_4}}{Q} - \frac{\Gamma_{m_3}}{Q}$ and $R = 1 + \frac{\Gamma (\Gamma_{m_3} - \Gamma_{m_2})}{Q}$

5 **[0077]** then the estimated value of B can now be defined as

$$B = \frac{G}{R} \quad (\text{Equ.24})$$

[0078] From which A can be calculated as:

$$A = \Gamma_{m_3} + B \Gamma (\Gamma_{m_3} - \Gamma_{m_2}) \quad (\text{Equ.25})$$

[0079] Finally, C can be calculated as: $C = B \Gamma_{m_2}$.

10 **[0080]** Alternatively, since X_{in} is known, it is also possible to use (Equ.10), (Equ.12), (Equ.13), (Equ.15), (Equ.16), (Equ.20) and (Equ.21) to solve for all unknowns including S_{12} .

[0081] Step 5: The calculated values of calibration parameters A , B , C are saved.

In future deployment, the reflection coefficient Γ_m can be measured (for example using
15 input radio signals emitted from radio unit 102 into coupler port 1) and used with the saved calibration parameter values, to determine the actual reflection coefficient, Γ , as:

$$\Gamma = \frac{A - \Gamma_m}{B \Gamma_m - C} \quad (\text{Equ.26})$$

[0082] From which VSWR and RL can then be estimated as described above in (Equ.2) and (Equ.3).

20 Scenario 2: The coupler's input port is not accessible

[0083] In this second scenario, the coupler's input port (i.e., port 1) is not accessible, so that it cannot be connected to the transceiver unit 408. For example, the DUT 400 may also include the radio unit 102, either because the coupler 106 and integrated antenna 104 are not detachable from the radio unit 102, or it would be very
25 inconvenient and/or expensive to detach and subsequently reattach them.

[0084] Figure 8 illustrates an example apparatus in which this scenario may be implemented. As may be seen in Figure 8, the radio unit 102 may be connected to the DSP unit 422 to enable the DSP unit 422 to control operation of the radio unit 102. In addition, the radio signal channel inside the radio unit 102 and between the radio unit
 5 102 and the input port (port 1) of the coupler 106 can be fully characterized using known techniques.

[0085] Referring to Figure 8, calibration of the coupler 106 can be performed according to the following steps:

[0086] Step 1: Connect ports 3 and 4 of the bi-directional coupler 106 to matched
 10 loads and control the radio unit 102 to supply a known input signal X_{in1} , to port 1 of the coupler 106. In some embodiments, the radio circuits 416 and 418 incorporate matched loads and can be controlled to connect the coupler ports 3 and 4 to the matched loads via RF signal paths 402 and 404. In other embodiments, RF signal paths 402 and 404 may be connected to matched loads external to the radio circuits
 15 416 and 418.

[0087] The known input signal X_{in1} propagates through the coupler 106, the integrated antenna 104, then the wireless channel 414, and is finally received (as received signal X_{R1}) by the radio circuit 412 of the transceiver unit 408. The received signal X_{R1} is defined as

$$20 \quad X_{R1} = S_{21} (1 - \Gamma) H X_{in1} \quad (\text{Equ.27})$$

[0088] We can then define a first measured reflection coefficient as:

$$\Gamma_{m1} = \frac{X_{R1}}{H X_{in1}} = S_{21} (1 - \Gamma) \quad (\text{Equ.28})$$

[0089] The reflection coefficient Γ can then be calculated using Γ_{m1} and S_{21} as described above with reference to scenario 1.

25 **[0090]** The calibration process continues through steps 2-5 which follow steps 2-5 of scenario 1, except that in this case the radio unit 102 is used to generate input signals instead of transceiver circuit 420.

Scenario 3: No Access to Coupler's Input Port with Unknown Input Signal

[0091] This scenario is similar to scenario 2, except that in this case the input signal X_{IN1} , supplied to port 1 of the coupler 106 is not known. This scenario may arise when the radio signal channel inside the radio unit 102 and between the radio unit 102 and the input port (port 1) of the coupler 106 cannot be fully characterized, or exhibits unknown variations in magnitude and/or phase so that even if an input signal to the radio unit 102 is known, the input signal X_{IN1} , supplied to port 1 of the coupler 106 is not known. In this scenario, prior knowledge of S_{21} is not necessary. However, due to extreme assumptions of no access to port 1 and no prior knowledge of the input signal to port 1, the reflection coefficient of the integrated antenna should be known a priori.

[0092] Referring again to Figure 8, calibration of the coupler 106 can be performed according to the following steps:

[0093] Step 1: Although the input signal to coupler's port 1 is not known, it is still transmitted. In this case the received signal X_{R1} is defined as:

$$X_{R1} = S_{21} (1 - \Gamma) H X_{in1} \quad (\text{Equ.29})$$

[0094] The signal transmitted from the DUT antenna 104 can be defined as:

$$X_T = \frac{X_{R1}}{H} = S_{21} (1 - \Gamma) X_{in1} \quad (\text{Equ.30})$$

[0095] Using the measured received signal X_{R1} , and the known wireless channel coefficient H , the transmitted signal X_T can be calculated and saved for use in a later step. In embodiments in which S_{21} and the antenna's reflection coefficient Γ are known a priori, these values can be used to compute an estimate of X_{in} .

[0096] Step 2: Step 2 of Scenario 3 is similar to step 2 of scenarios 1 and 2. In this step, the radio circuit 412 of the transceiver unit 408 is controlled to emit an external signal X_E through the antenna 410. This external signal X_E can have any desired magnitude and phase, and if desired may correspond with the transmitted signal X_T stored in step 1.

[0097] As defined above, a second measured reflection coefficient can be defined as:

$$\Gamma_{m_2} = \frac{X_{REFL2}}{X_{F_2}} = \frac{S_{42}}{S_{32}} \quad (\text{Equ.31})$$

[0098] Again, let $A = \frac{S_{41}}{S_{31}}$ and $B = \frac{S_{21} S_{32}}{S_{31}}$, $C = \frac{S_{21} S_{42}}{S_{31}}$.

[0099] From (Equ.31), it can be inferred that $C = B \Gamma_{m_2}$.

[0100] Step 3: Step 3 of scenario 3 is similar to step 3 of Scenarios 1 and 2. In this step, knowledge of the input signal X_{in} is not required to calculate the third measured reflection coefficient since the ratio between the forward and received signal is used. Thus, the third measured reflection coefficient is defined as:

$$\Gamma_{m_3} = \frac{X_{REFL3}}{X_{F_3}} = \frac{A + B \Gamma \Gamma_{m_2}}{1 + B \Gamma} \quad (\text{Equ.32})$$

[0101] Step 4: In this step, the radio circuit 412 of the transceiver unit 408 is controlled to emit an external signal X_E through the antenna 410. This external signal X_E is calculated to generate a received signal, in the DUT antenna 104 that replicates the transmitted signal X_T stored in step 1. To counteract the impact of the channel coefficient, H , the external signal is transmitted as $X_E = \frac{X_T}{H}$. Consequently, the received signal input to port 2 of the coupler 106 (from the DUT antenna 104) is $S_{21} (1 - \Gamma) X_{in}$. This leads to

$$X_{F_4} = S_{31} X_{in} + S_{21} S_{32} \Gamma X_{in} + S_{21} S_{32} (1 - \Gamma^2) X_{in} \quad (\text{Equ.33})$$

$$X_{REFL_4} = S_{41} X_{in} + S_{21} S_{42} \Gamma X_{in} + S_{21} S_{42} (1 - \Gamma^2) X_{in} \quad (\text{Equ.34})$$

[0102] We can then define the fourth measured reflection coefficient as:

$$\Gamma_{m_4} = \frac{X_{REFL_4}}{X_{F_4}} = \frac{S_{41} + S_{21} S_{42} \Gamma + S_{21} S_{42} (1 - \Gamma^2)}{S_{31} + S_{21} S_{32} \Gamma + S_{21} S_{32} (1 - \Gamma^2)} \quad (\text{Equ.35})$$

[0103] Which can be written as

$$\Gamma_{m_4} = \frac{A + B \Gamma \Gamma_{m_2} + B \Gamma_{m_2} (1 - \Gamma^2)}{1 + B \Gamma + B (1 - \Gamma^2)} \quad (\text{Equ.36})$$

[0104] By solving (Equ.35) and (Equ.36) for A and B , we have

$$B = \frac{F}{E} \quad (\text{Equ.37})$$

[0105] Where $F = \Gamma_{m_3} - \Gamma_{m_4}$, $P = \Gamma_{m_3} - \Gamma_{m_2}$, $U = \Gamma_{m_4} - \Gamma_{m_2} - P$, $L = \Gamma_{m_4} - \Gamma_{m_2}$ and $E = U \Gamma + L (1 - \Gamma^2)$.

[0106] Once B is calculated, A can be calculated as

$$A = \Gamma_{m_3} + B \Gamma P \quad (\text{Equ.38})$$

[0107] And then $C = B \Gamma_{m_2}$.

[0108] Step 5: This step is similar to step 5 of scenario 2.

- 5 **[0109]** Those skilled in the art will recognize improvements and modifications to the embodiments of the present disclosure. All such improvements and modifications are considered within the scope of the concepts disclosed herein.

Claims

What is claimed is:

1. A method of calibrating a bi-directional coupler (106) integrated with an antenna (104), the method comprising:
 - supplying combinations of first and second input signals, each combination comprising at least one of: a first input signal supplied to the antenna (104) via a wireless channel (414); and a second input signal supplied to an input port of the bi-direction coupler (106);
 - measuring, for each combination of first and second signals, a corresponding set of output signal power levels emitted from the bi-directional coupler (106); and
 - calculating a set of calibration values based on the measured sets of output signal power levels.
2. The method as claimed in claim 1, wherein supplying the first input signal comprises transmitting an external signal through the wireless channel (414) from a radio circuit (412).
3. The method as claimed in claim 2, wherein supplying combinations of first and second input signals comprise:
 - supplying a first combination composed of the first input signal;
 - supplying a second combination composed of the second input signal; and
 - supplying a third combination composed of the first and second input signals.
4. The method as claimed in claim 3, wherein the second input signal is supplied by a transceiver circuit (420) connected to the bi-directional coupler (106), and

wherein supplying combinations of first and second signals comprises controlling the transceiver circuit (420) to emit the second input signal.

5. The method as claimed in claim 4, wherein measuring, for each combination of first and second signals, a corresponding set of output signal power levels, comprises:

measuring a first set of output signal power levels based on the first combination, with forward and reverse coupled ports of the bi-directional coupler connected to matched loads, the first set of output signal power levels comprising: a received signal power emitted at the input port of the bi-directional coupler (106);

measuring a second set of output signal power levels based on the first combination, with the input port of the bi-directional coupler connected to a matched load, the second set of output signal power levels comprising: a first forward signal power level emitted at the forward coupled port of the bi-directional coupler (106); and a first reflected power level emitted at the reverse coupled port of the bi-directional coupler (106);

measuring a third set of output signal power levels based on the second combination, the third set of output signal power levels comprising: a second forward signal power level emitted at the forward coupled port of the bi-directional coupler (106); and a second reflected power level emitted at the reverse coupled port of the bi-directional coupler (106); and

measuring a fourth set of output signal power levels based on the third combination, the fourth set comprising: a third forward signal power level emitted at the forward coupled port of the bi-directional coupler (106); and a third reflected power level emitted at the reverse coupled port of the bi-directional coupler (106).

6. The method as claimed in claim 5, wherein measuring the fourth set of output signal power levels further comprises controlling the transceiver circuit (420) and a radio circuit (412) configured to transmit the first input signal such that the first and second input signals are equal.

7. The method as claimed in claim 3, wherein the second input signal is supplied by a radio unit connected to the bi-directional coupler, and wherein supplying combinations of first and second input signals comprises controlling the radio unit to emit the second input signal.

8. The method as claimed in claim 7, wherein measuring, for each combination of first and second signals, a corresponding set of output signal power levels, comprises:

measuring a first set of output signal power levels based on the second combination, with forward and reverse coupled ports of the bi-directional coupler connected to matched loads, the first set of output signal power levels comprising: a received signal power detected at a radio circuit (412) via the wireless channel (414);

measuring a second set of output signal power levels based on the first combination, the second set of output signal power levels comprising: a first forward signal power level emitted at the forward coupled port of the bi-directional coupler; and a first reflected power level emitted at the reverse coupled port of the bi-directional coupler;

measuring a third set of output signal power levels based on the second combination, the third set of output signal power levels comprising: a second forward signal power level emitted at the forward coupled port of the bi-directional coupler; and a second reflected power level emitted at the reverse coupled port of the bi-directional coupler; and

measuring a fourth set of output signal power levels based on the third combination, the fourth set comprising: a third forward signal power level emitted at the forward coupled port of the bi-directional coupler; and a third reflected power level emitted at the reverse coupled port of the bi-directional coupler.

9. The method as claimed in claim 8, wherein:

measuring the first set of output signal power levels further comprises calculating an estimate of a transmitted signal emitted from the integrated antenna through the wireless channel; and

measuring the fourth set of output signal power levels comprises controlling the radio circuit (412) such that the second input signal is equal to the estimated transmitted signal.

10. An apparatus for calibrating a device under test, DUT, (400) comprising bi-directional coupler (106) integrated with an antenna (104), the apparatus comprising:

a transceiver unit (408) configured to:

supply combinations of first and second input signals to the DUT (400), each combination comprising at least one of: a first input signal supplied to the antenna (104) via a wireless channel (414); and a second input signal supplied to an input port of the bi-direction coupler (106); and

measure, for each combination of first and second signals, a corresponding set of output signal power levels emitted from the bi-directional coupler (106); and

a digital signal processing, DSP, unit (422) connected to the transceiver unit (408), the DSP unit (422) configured to calculate a set of calibration values based on the measured sets of output signal power levels.

11. The apparatus as claimed in claim 10, wherein the transceiver unit (408) comprises a radio circuit (412) configured to supply the first input signal by transmitting an external signal through the wireless channel (414).

12. The apparatus as claimed in claim 11, wherein supplying combinations of first and second input signals comprise:

supplying a first combination composed of the first input signal;

supplying a second combination composed of the second input signal; and

supplying a third combination composed of the first and second input signals.

13. The apparatus as claimed in claim 12, wherein the transceiver unit (408) comprises a transceiver circuit (420) connected to the bi-directional coupler

(106), the transceiver circuit (420) configured to supply the second input signal, and wherein supplying combinations of first and second signals comprises controlling the transceiver circuit (420) to emit the second input signal.

14. The apparatus as claimed in claim 13, wherein measuring, for each combination of first and second signals, a corresponding set of output signal power levels, comprises:

measuring a first set of output signal power levels based on the first combination, with forward and reverse coupled ports of the bi-directional coupler connected to matched loads, the first set of output signal power levels comprising: a received signal power emitted at the input port of the bi-directional coupler (106);

measuring a second set of output signal power levels based on the first combination, with the input port of the bi-directional coupler connected to a matched load, the second set of output signal power levels comprising: a first forward signal power level emitted at the forward coupled port of the bi-directional coupler (106); and a first reflected power level emitted at the reverse coupled port of the bi-directional coupler (106);

measuring a third set of output signal power levels based on the second combination, the third set of output signal power levels comprising: a second forward signal power level emitted at the forward coupled port of the bi-directional coupler (106); and a second reflected power level emitted at the reverse coupled port of the bi-directional coupler (106); and

measuring a fourth set of output signal power levels based on the third combination, the fourth set comprising: a third forward signal power level emitted at the forward coupled port of the bi-directional coupler (106); and a third reflected power level emitted at the reverse coupled port of the bi-directional coupler (106).

15. The apparatus as claimed in claim 14, wherein measuring the fourth set of output signal power levels further comprises controlling the transceiver circuit (420) and

a radio circuit (412) configured to transmit the first input signal such that the first and second input signals are equal.

16. The apparatus as claimed in claim 12, wherein the DUT 400 includes a radio unit (102) connected to the bi-directional coupler (106), and wherein the transceiver unit 408 is configured to supply combinations of first and second input signals by controlling the radio unit (102) to emit the second input signal.

17. The apparatus as claimed in claim 16, wherein measuring, for each combination of first and second signals, a corresponding set of output signal power levels, comprises:

measuring a first set of output signal power levels based on the second combination, with forward and reverse coupled ports of the bi-directional coupler connected to matched loads, the first set of output signal power levels comprising: a received signal power detected at a radio circuit (412) via the wireless channel (414);

measuring a second set of output signal power levels based on the first combination, the second set of output signal power levels comprising: a first forward signal power level emitted at the forward coupled port of the bi-directional coupler; and a first reflected power level emitted at the reverse coupled port of the bi-directional coupler;

measuring a third set of output signal power levels based on the second combination, the third set of output signal power levels comprising: a second forward signal power level emitted at the forward coupled port of the bi-directional coupler; and a second reflected power level emitted at the reverse coupled port of the bi-directional coupler; and

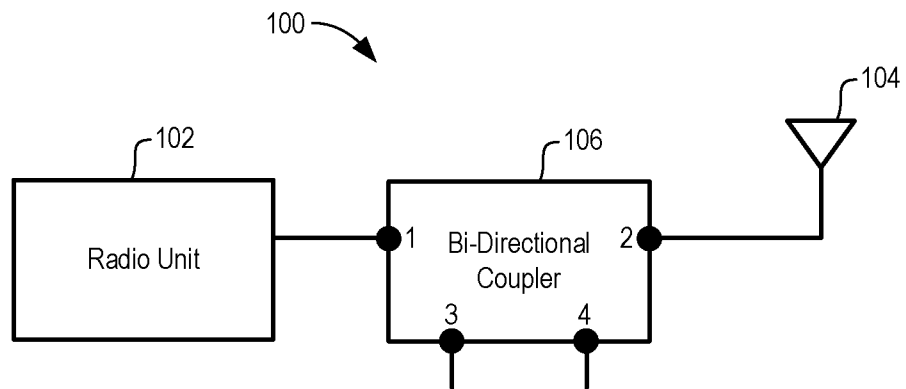
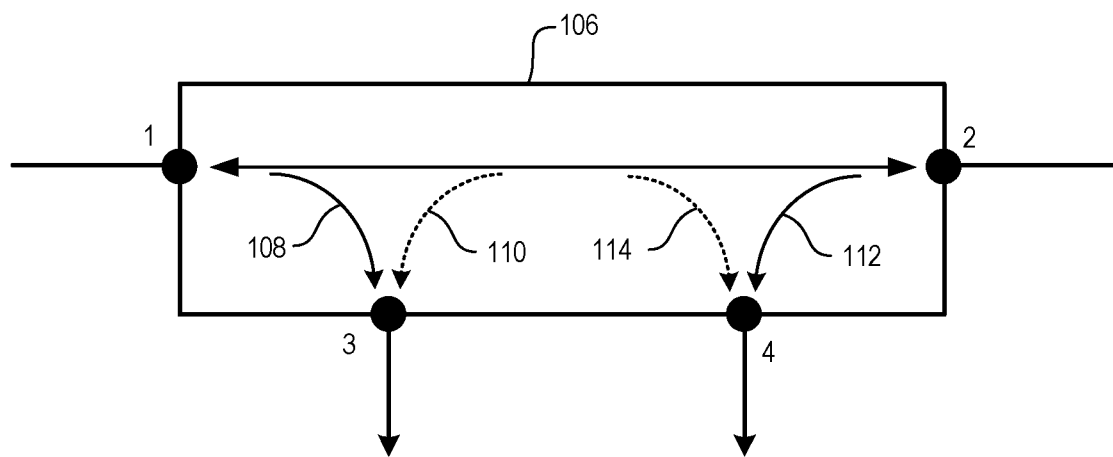
measuring a fourth set of output signal power levels based on the third combination, the fourth set comprising: a third forward signal power level emitted at the forward coupled port of the bi-directional coupler; and a third reflected power level emitted at the reverse coupled port of the bi-directional coupler.

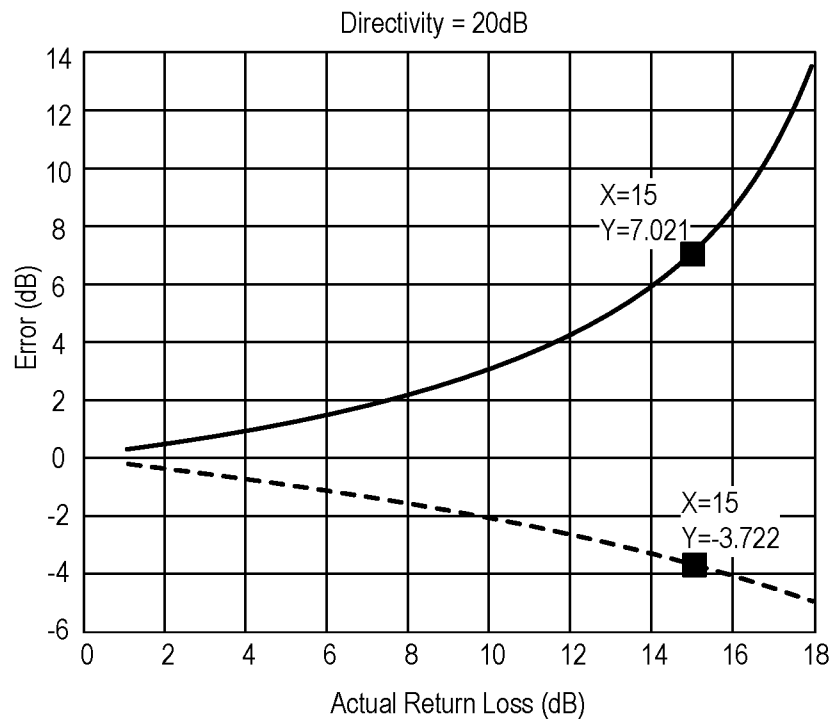
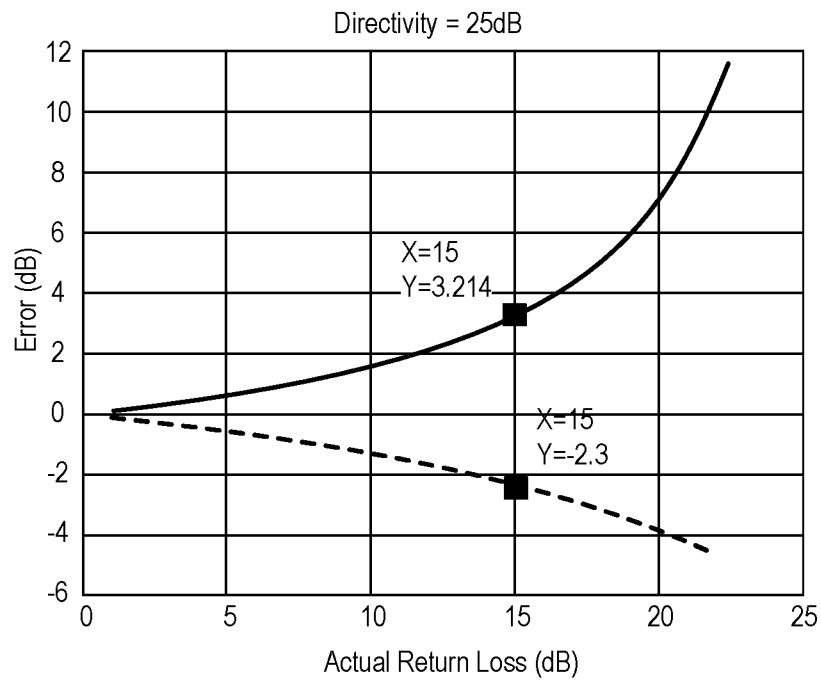
18. The apparatus as claimed in claim 17, wherein:

measuring the first set of output signal power levels further comprises calculating an estimate of a transmitted signal emitted from the integrated antenna through the wireless channel; and

measuring the fourth set of output signal power levels comprises controlling the radio circuit (412) such that the second input signal is equal to the estimated transmitted signal.

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**Figure 1A****Figure 1B**

2/8**Figure 2A****Figure 2B**

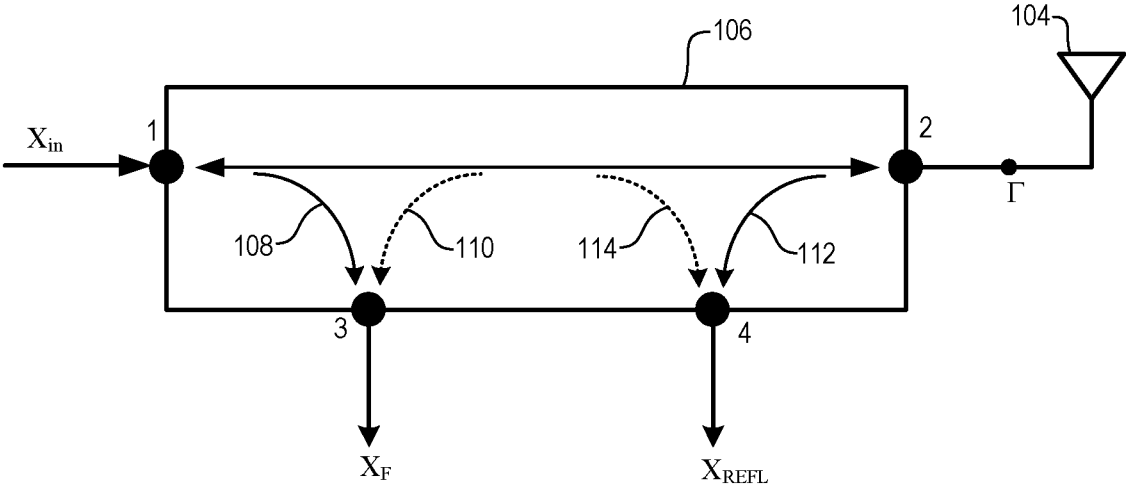
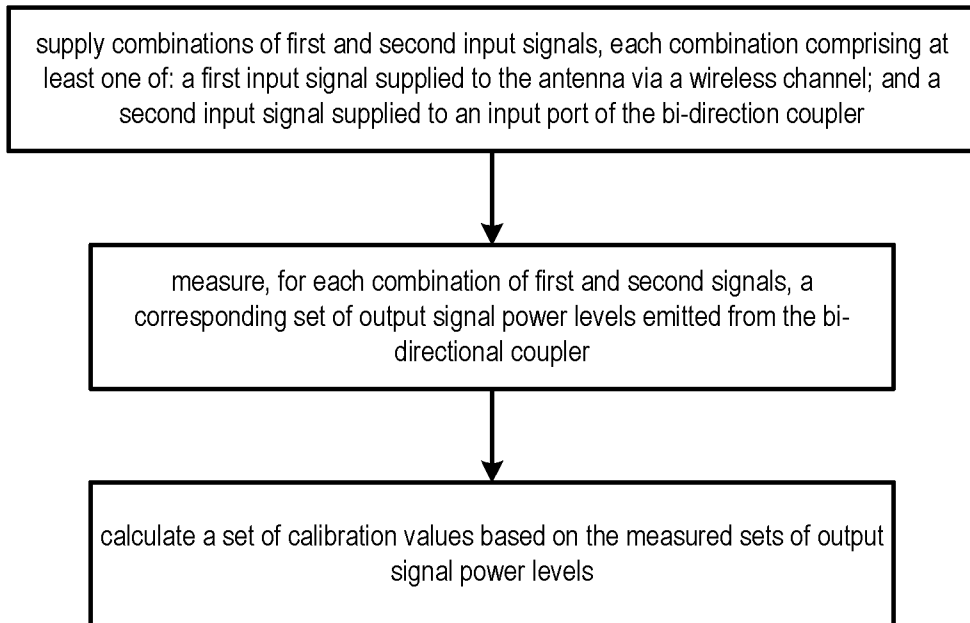
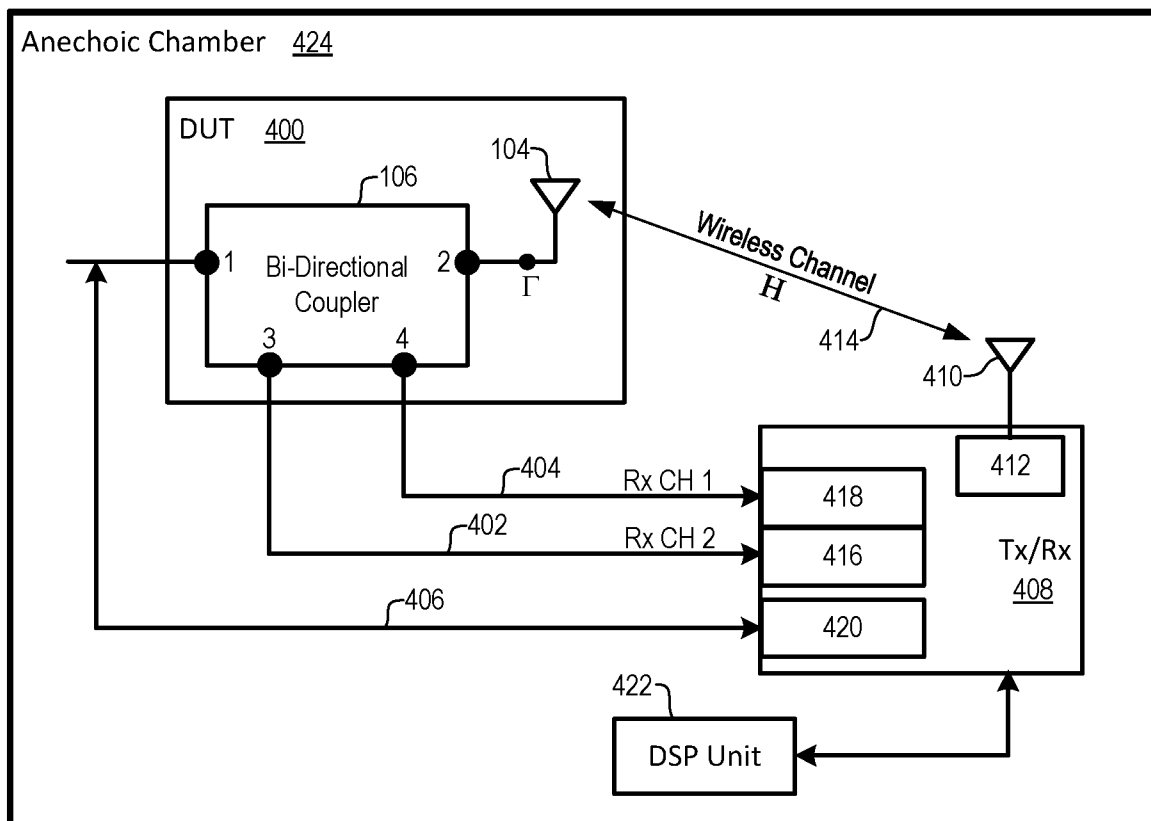
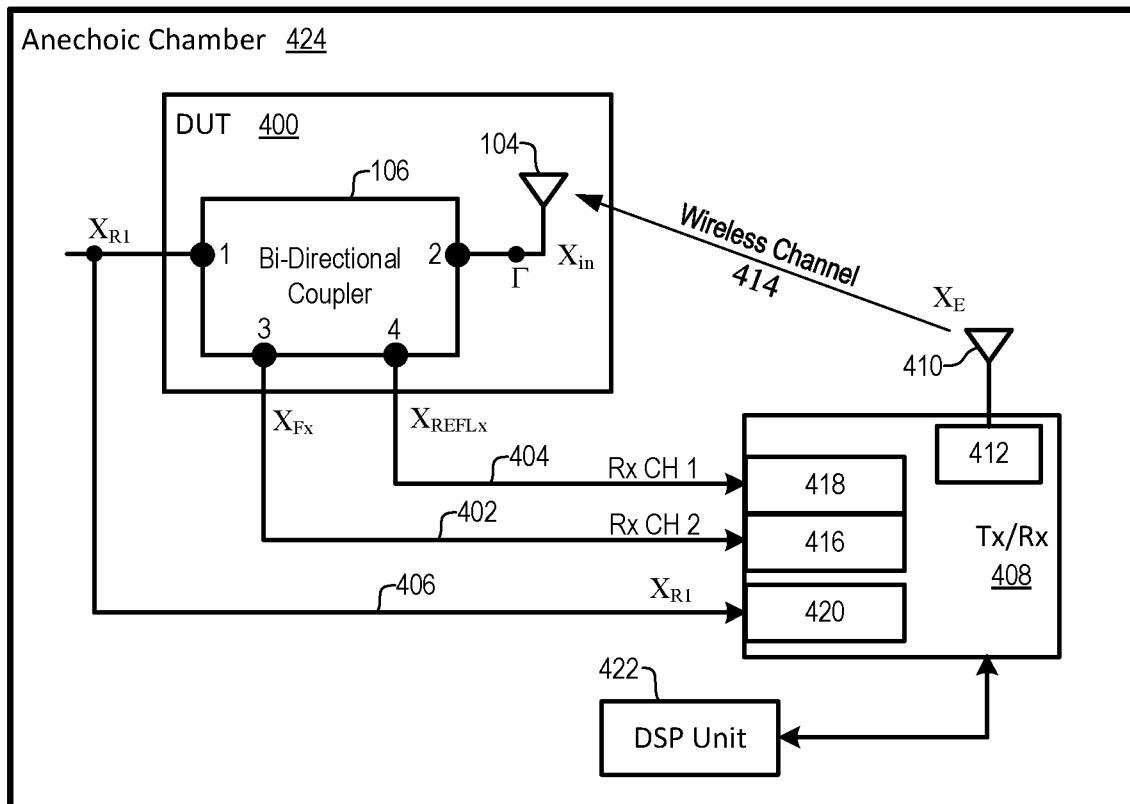


Figure 3

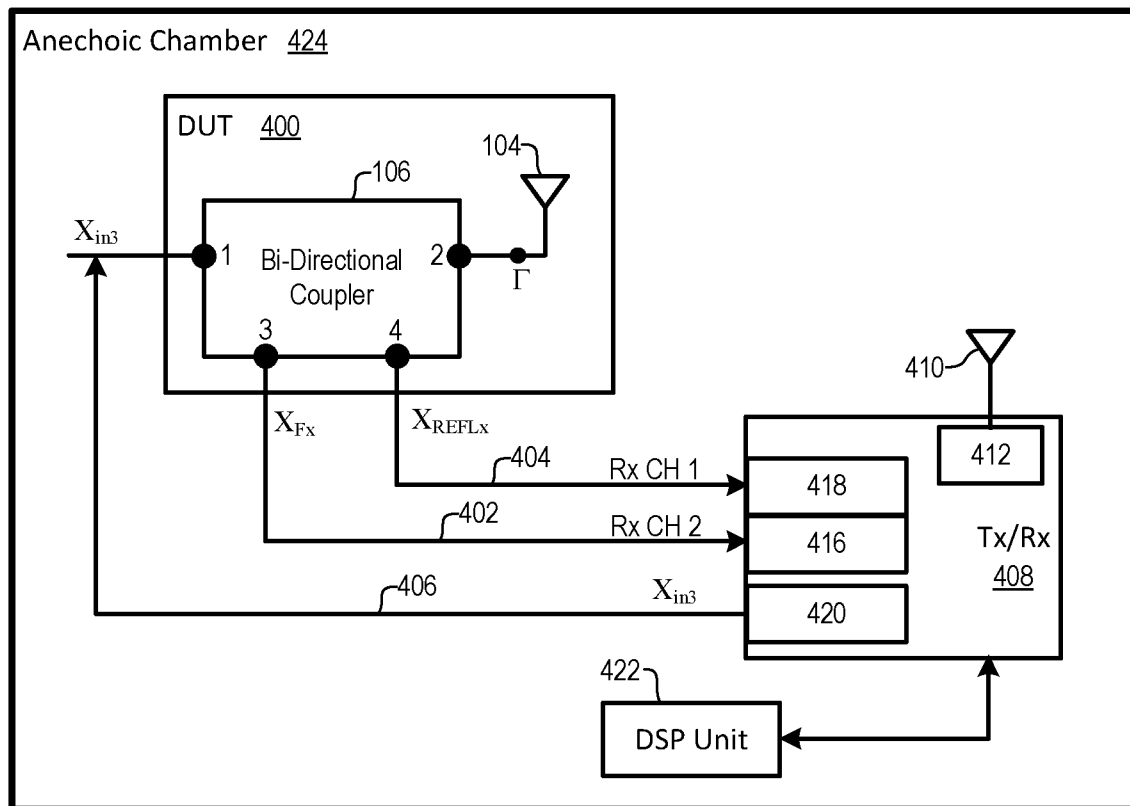
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**Figure 4A****Figure 4B**

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**Figure 5**

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**Figure 6**

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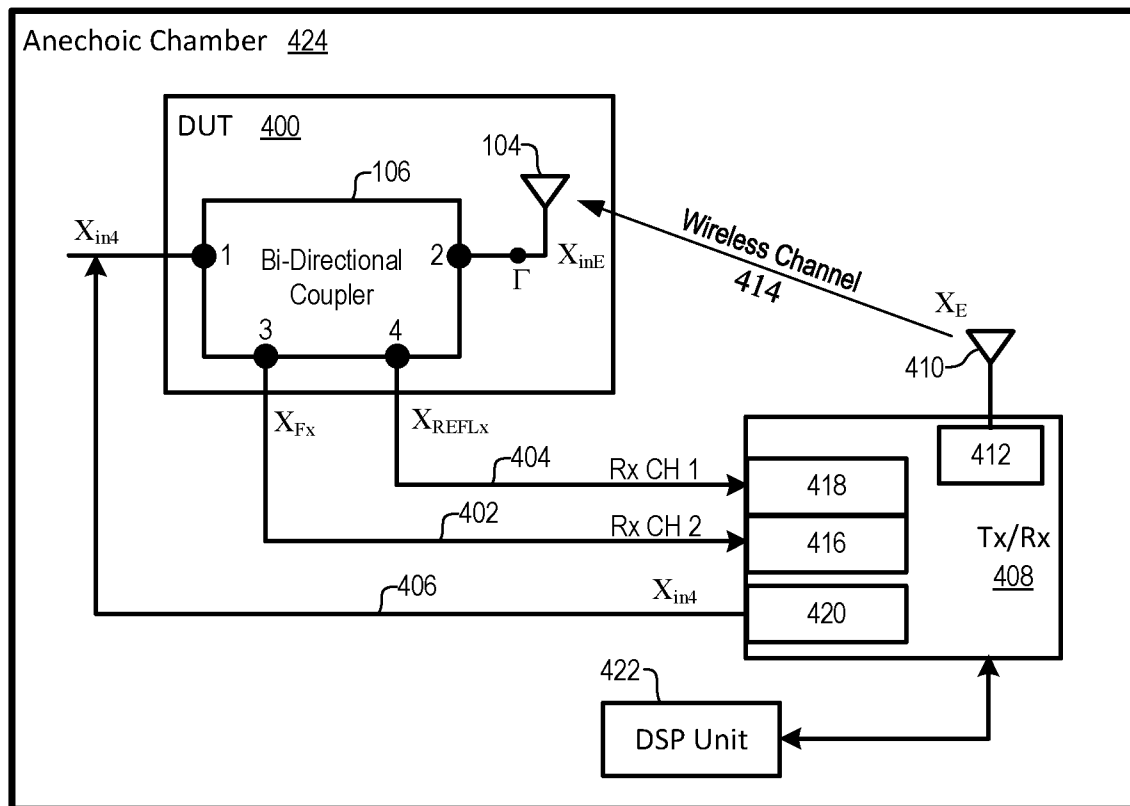
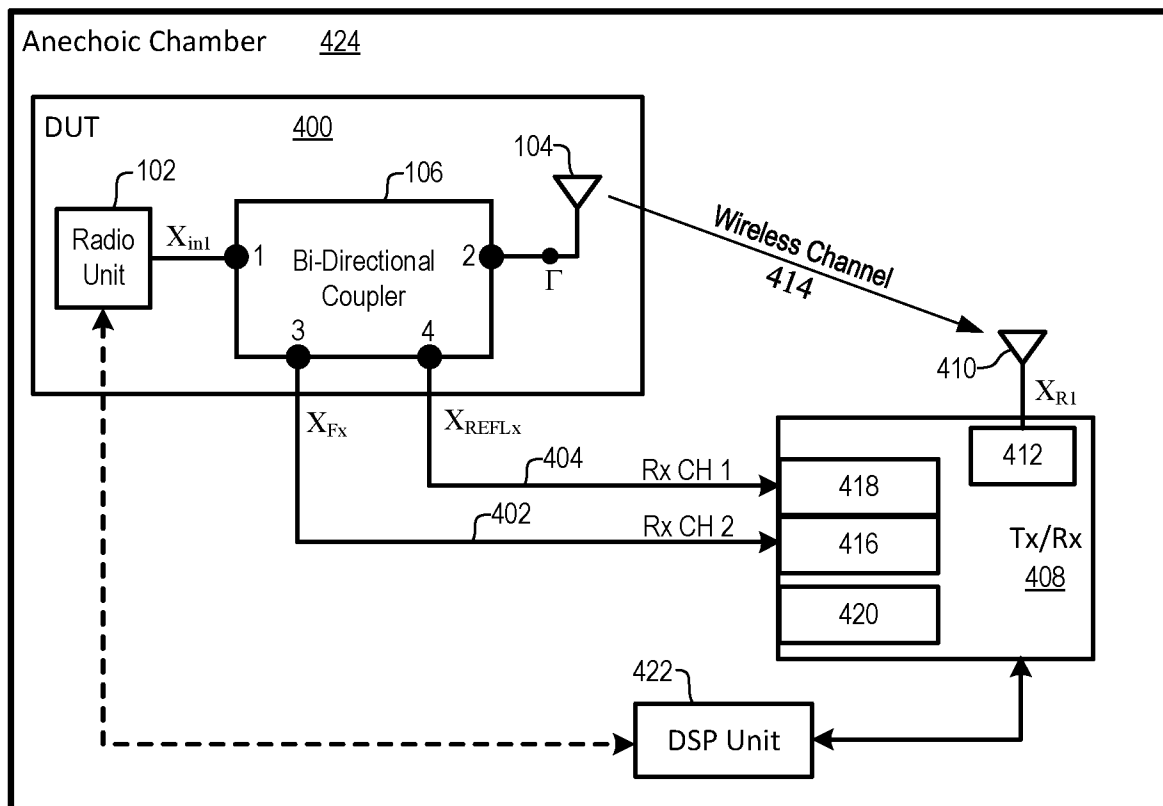


Figure 7

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**Figure 8**

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2019/053402

A. CLASSIFICATION OF SUBJECT MATTER
INV. H04B17/10 H04B17/11 H04B1/04
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H04B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	WO 2017/081522 A1 (ERICSSON TELEFON AB L M [SE]) 18 May 2017 (2017-05-18) figure 3 page 3, line 16 - page 7, line 25 page 13, line 5 - page 14, line 13 page 16, line 14 - page 20, line 17 page 23, line 28 - page 25, line 2 -----	1,2,10, 11 3-9, 12-18
X A	US 2015/355251 A1 (PASCOLINI MATTIA [US]) 10 December 2015 (2015-12-10) paragraph [0066] - paragraph [0070] ----- -/-	1,2,10, 11 3-9, 12-18



Further documents are listed in the continuation of Box C.



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Date of the actual completion of the international search

20 January 2020

Date of mailing of the international search report

27/01/2020

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INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2019/053402

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	US 2017/026020 A1 (SOLOMKO VALENTYN [DE] ET AL) 26 January 2017 (2017-01-26) paragraph [0020] - paragraph [0024] paragraph [0026] - paragraph [0027] paragraph [0039] - paragraph [0041] paragraph [0051] - paragraph [0052] -----	1,2,10, 11 3-9, 12-18
X A	WO 2019/069119 A1 (ERICSSON TELEFON AB L M [SE]) 11 April 2019 (2019-04-11) paragraph [0035] - paragraph [0038] paragraph [0067] - paragraph [0068] -----	1,2,10, 11 3-9, 12-18

INTERNATIONAL SEARCH REPORT

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