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Da Silveira et al.

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(54) **SCALABLE ESTIMATION RING**

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H04L 25/02	(2006.01)
H04B 17/12	(2015.01)
H04B 17/14	(2015.01)

(Continued)

(52) **U.S. Cl.**

CPC ***H04L 25/0212*** (2013.01); ***H04B 17/12*** (2015.01); ***H04B 17/14*** (2015.01); ***H04L 25/0204*** (2013.01); ***H04L 25/024*** (2013.01); ***H04L 25/0224*** (2013.01); ***H04L 25/0228*** (2013.01); *H04B 17/373* (2015.01); *H04W 88/08* (2013.01)

(58) **Field of Classification Search**

CPC H01Q 1/246; H04B 7/06; H04B 17/12

USPC 455/562.1, 522; 370/336, 335, 328, 370/204; 375/218, 232, 260, 222, 341, 233, 375/267, 145

See application file for complete search history.

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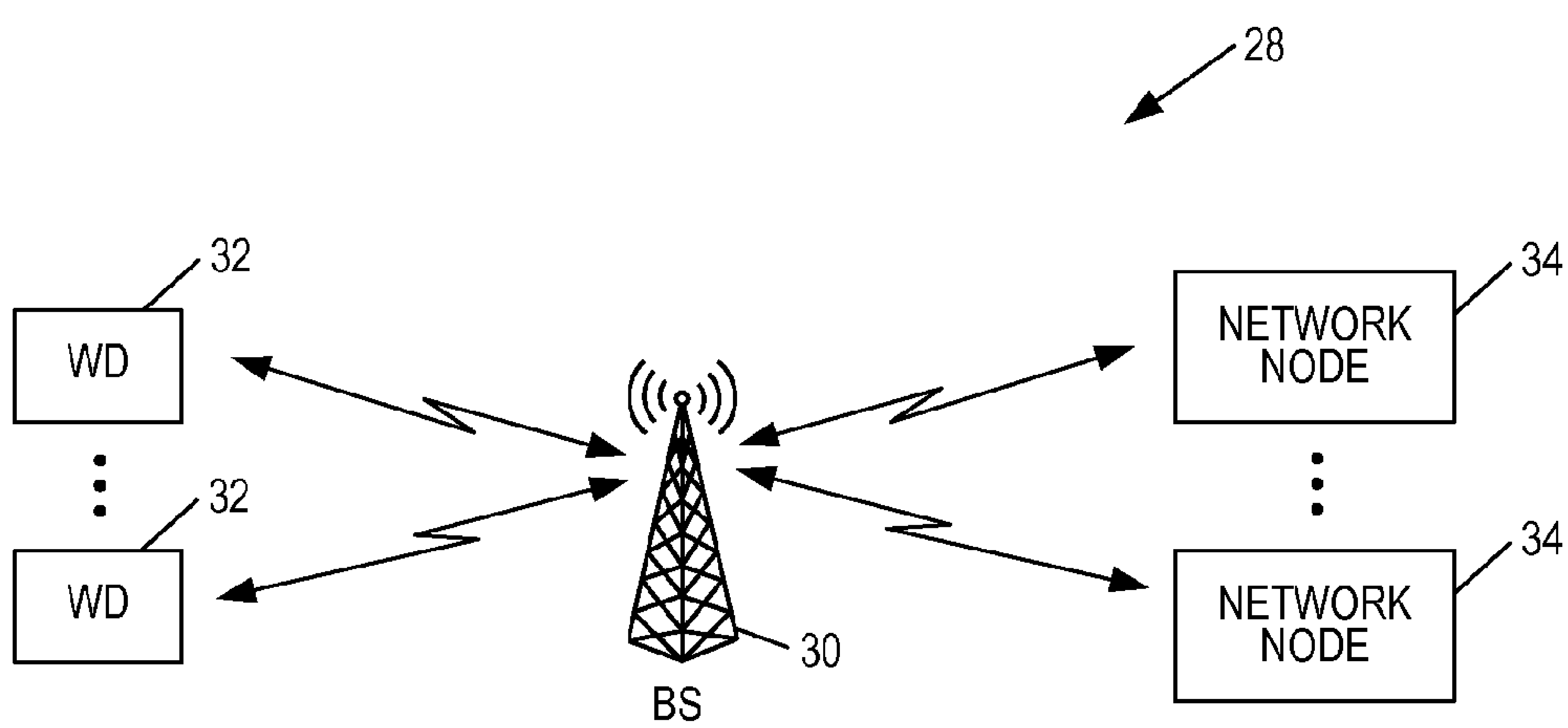
(74) *Attorney, Agent, or Firm* — Withrow & Terranova, PLLC

(57) **ABSTRACT**

Systems and methods are disclosed for estimating impulse responses of multiple channels, e.g., multiple antenna sub-array paths of a base station, in a distributed manner. In one embodiment, a method of operation of a Scalable Estimation Ring (SER) processing component in a SER that operates to estimate impulse responses of corresponding channels is provided. In one embodiment, the method includes, during a first iteration of the SER, receiving a feedback signal for the SER processing component and computing an initial estimate of an impulse response of a corresponding channel based on the feedback signal, removing a contribution of the corresponding channel from the feedback signal based on the initial estimate of the impulse response of the corresponding channel to thereby provide a feedback signal for a next SER processing component in the SER, and outputting the feedback signal for the next SER processing component in the SER.

8 Claims, 11 Drawing Sheets



(51) **Int. Cl.**

H04W 88/08	(2009.01)
H04B 17/373	(2015.01)

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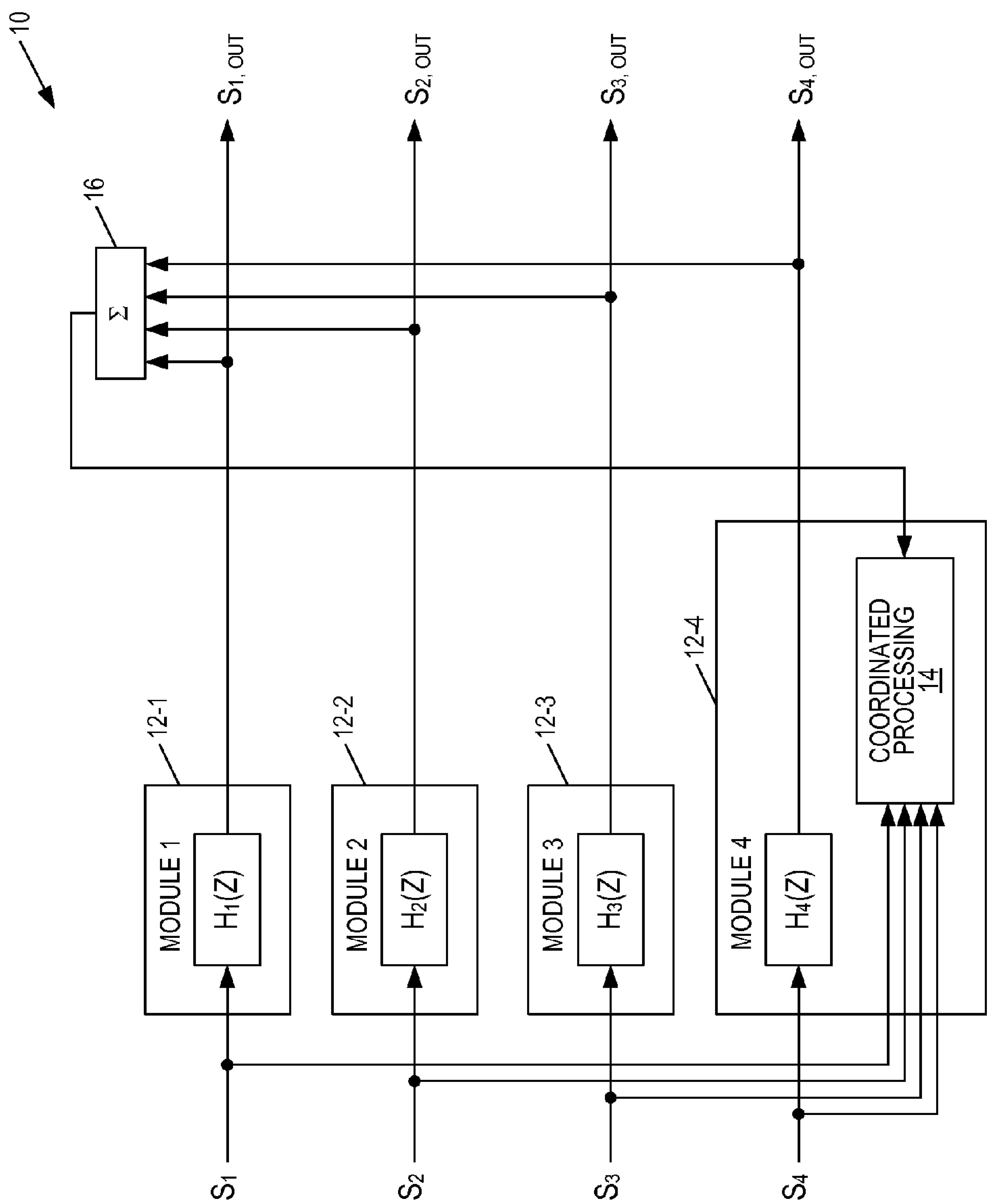

10
16
Σ
$S_{1,\,OUT}$
$S_{2,\,OUT}$
$S_{3,\,OUT}$
$S_{4,\,OUT}$
12-1
12-2
12-3
12-4
MODULE 1
MODULE 2
MODULE 3
MODULE 4
$H_1(Z)$
$H_2(Z)$
$H_3(Z)$
$H_4(Z)$
COORDINATED PROCESSING 14
S_1
S_2
S_3
S_4

FIG. 1

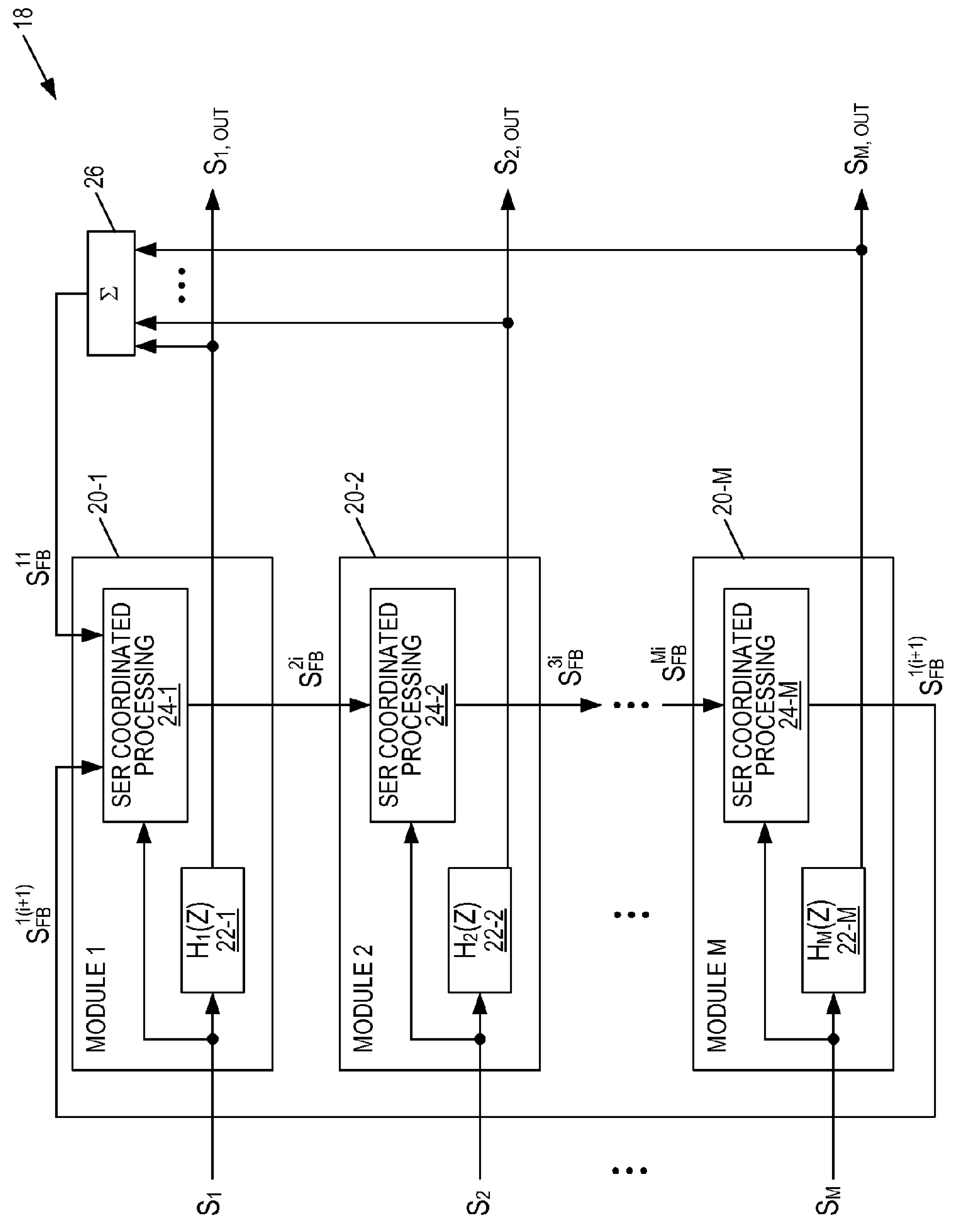

18
26
Σ
$S_{1,OUT}$
$S_{2,OUT}$
$S_{M,OUT}$
S_{FB}^{11}
$S_{FB}^{1(i+1)}$
20-1
20-2
20-M
MODULE 1
MODULE 2
MODULE M
SER COORDINATED PROCESSING 24-1
SER COORDINATED PROCESSING 24-2
SER COORDINATED PROCESSING 24-M
$H_1(Z)$ 22-1
$H_2(Z)$ 22-2
$H_M(Z)$ 22-M
S_{FB}^{2i}
S_{FB}^{3i}
S_{FB}^{Mi}
S_1
S_2
S_M

FIG. 2

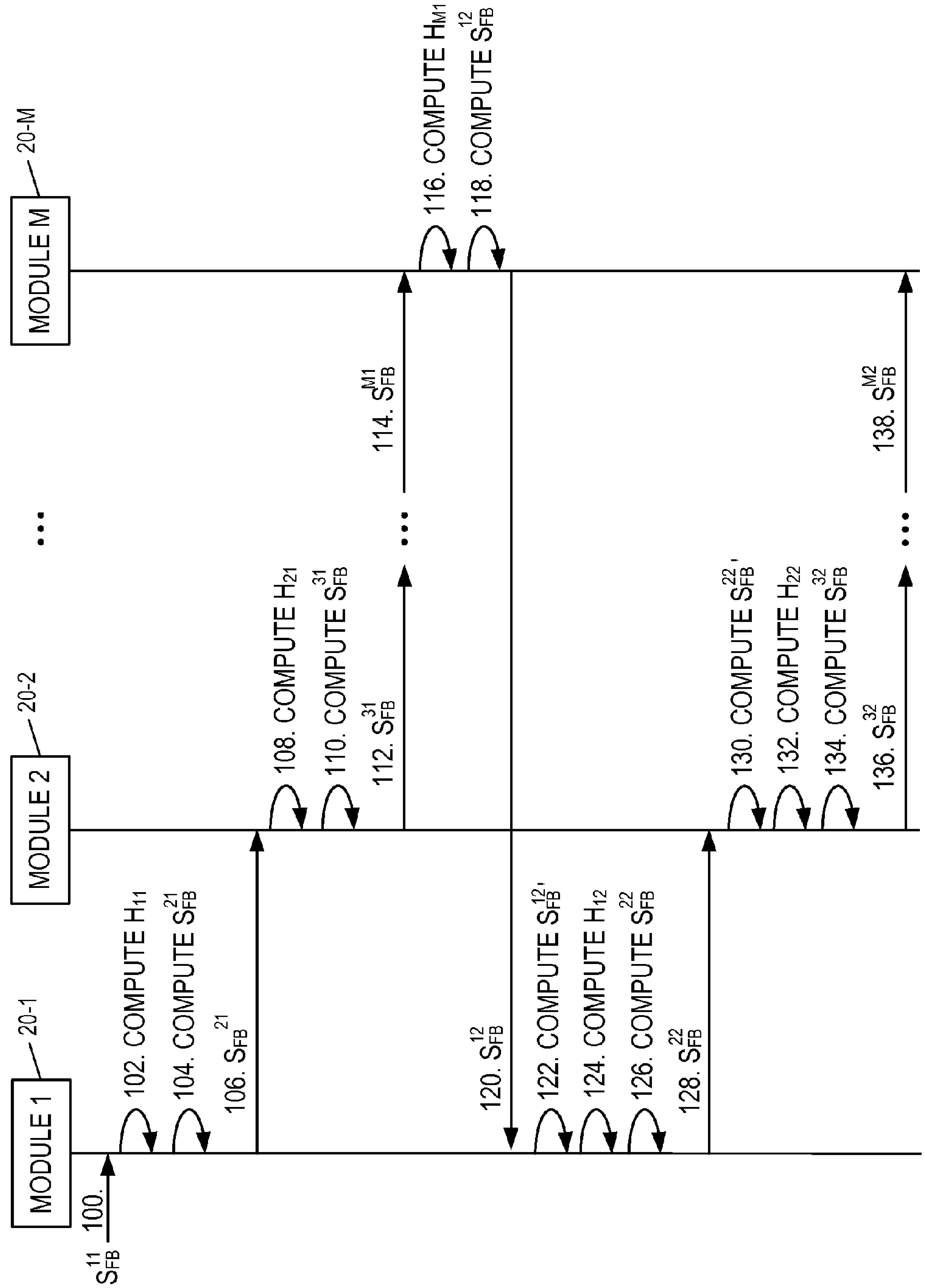

MODULE 1
20-1
MODULE 2
20-2
MODULE M
20-M
100. S_{FB}^{11}
102. COMPUTE H_{11}
104. COMPUTE S_{FB}^{21}
106. S_{FB}^{21}
108. COMPUTE H_{21}
110. COMPUTE S_{FB}^{31}
112. S_{FB}^{31}
114. S_{FB}^{M1}
116. COMPUTE H_{M1}
118. COMPUTE S_{FB}^{12}
120. S_{FB}^{12}
122. COMPUTE $S_{FB}^{12}{}'$
124. COMPUTE H_{12}
126. COMPUTE S_{FB}^{22}
128. S_{FB}^{22}
130. COMPUTE $S_{FB}^{22}{}'$
132. COMPUTE H_{22}
134. COMPUTE S_{FB}^{32}
136. S_{FB}^{32}
138. S_{FB}^{M2}

FIG. 3A

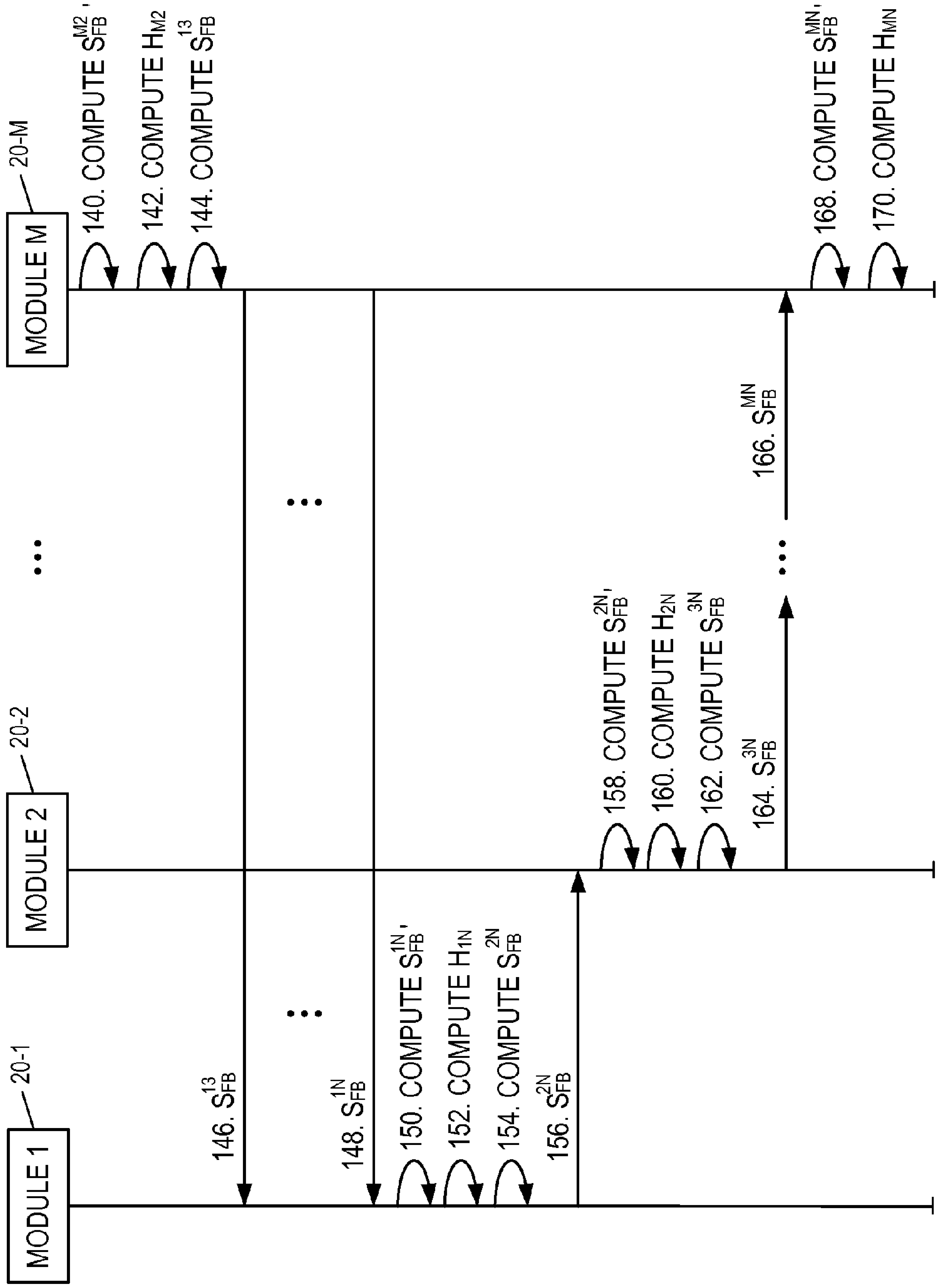

MODULE 1
20-1
MODULE 2
20-2
MODULE M
20-M
140. COMPUTE S_{FB}^{M2}'
142. COMPUTE H_{M2}
144. COMPUTE S_{FB}^{13}
146. S_{FB}^{13}
148. S_{FB}^{1N}
150. COMPUTE S_{FB}^{1N}'
152. COMPUTE H_{1N}
154. COMPUTE S_{FB}^{2N}
156. S_{FB}^{2N}
158. COMPUTE S_{FB}^{2N}'
160. COMPUTE H_{2N}
162. COMPUTE S_{FB}^{3N}
164. S_{FB}^{3N}
166. S_{FB}^{MN}
168. COMPUTE S_{FB}^{MN}'
170. COMPUTE H_{MN}

FIG. 3B

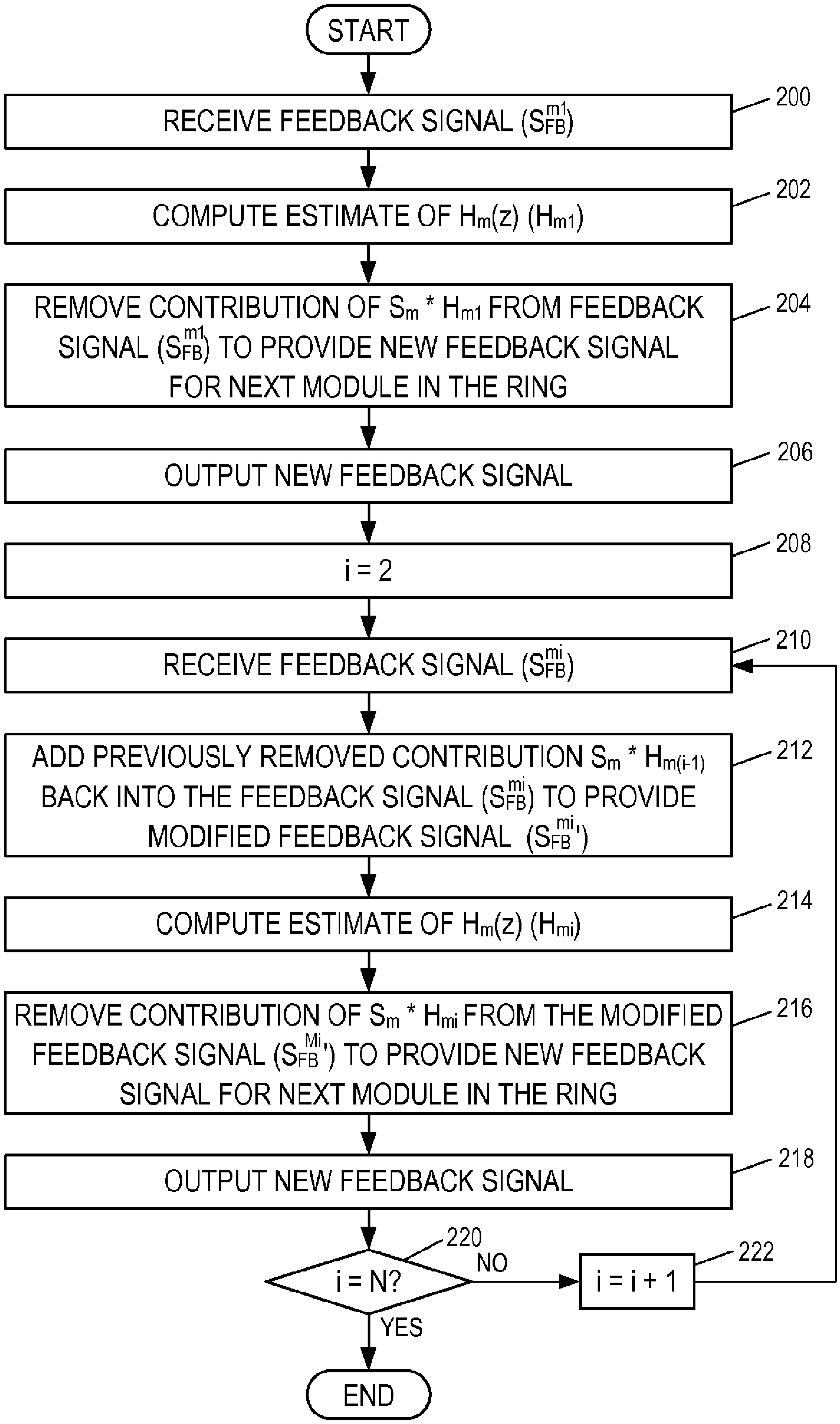

START
RECEIVE FEEDBACK SIGNAL (S_{FB}^{m1})
200
COMPUTE ESTIMATE OF $H_m(z)$ (H_{m1})
202
REMOVE CONTRIBUTION OF $S_m * H_{m1}$ FROM FEEDBACK SIGNAL (S_{FB}^{m1}) TO PROVIDE NEW FEEDBACK SIGNAL FOR NEXT MODULE IN THE RING
204
OUTPUT NEW FEEDBACK SIGNAL
206
i = 2
208
RECEIVE FEEDBACK SIGNAL (S_{FB}^{mi})
210
ADD PREVIOUSLY REMOVED CONTRIBUTION $S_m * H_{m(i-1)}$ BACK INTO THE FEEDBACK SIGNAL (S_{FB}^{mi}) TO PROVIDE MODIFIED FEEDBACK SIGNAL ($S_{FB}^{mi}{}'$)
212
COMPUTE ESTIMATE OF $H_m(z)$ (H_{mi})
214
REMOVE CONTRIBUTION OF $S_m * H_{mi}$ FROM THE MODIFIED FEEDBACK SIGNAL ($S_{FB}^{Mi}{}'$) TO PROVIDE NEW FEEDBACK SIGNAL FOR NEXT MODULE IN THE RING
216
OUTPUT NEW FEEDBACK SIGNAL
218
i = N?
220
NO
i = i + 1
222
YES
END

FIG. 4

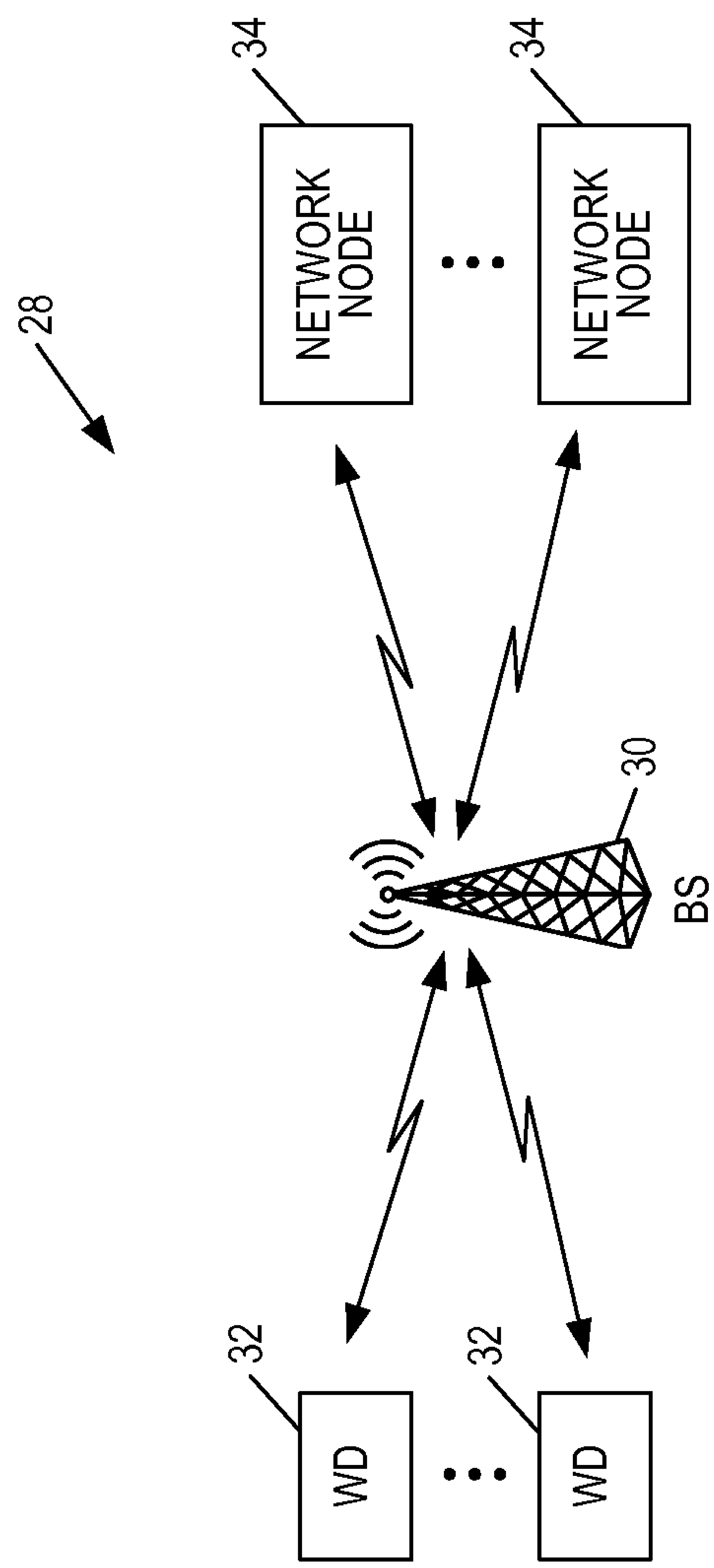


FIG. 5

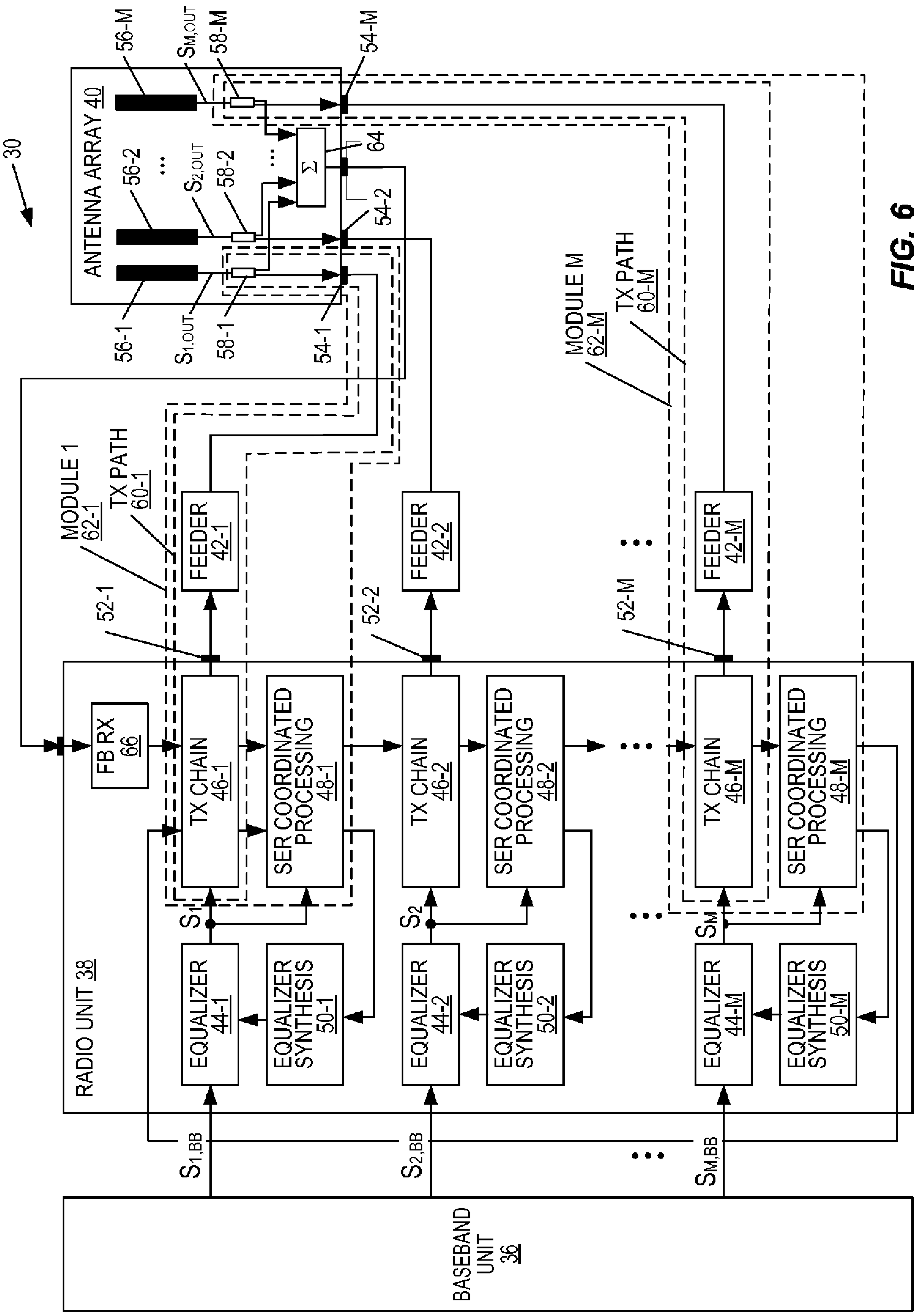

30
ANTENNA ARRAY 40
56-1
56-2
56-M
$S_{1,OUT}$
$S_{2,OUT}$
$S_{M,OUT}$
58-1
58-2
58-M
54-1
54-2
54-M
Σ
64
MODULE 1 62-1
TX PATH 60-1
MODULE M 62-M
TX PATH 60-M
FEEDER 42-1
FEEDER 42-2
FEEDER 42-M
52-1
52-2
52-M
RADIO UNIT 38
FB RX 66
TX CHAIN 46-1
TX CHAIN 46-2
TX CHAIN 46-M
SER COORDINATED PROCESSING 48-1
SER COORDINATED PROCESSING 48-2
SER COORDINATED PROCESSING 48-M
S_1
S_2
S_M
EQUALIZER 44-1
EQUALIZER 44-2
EQUALIZER 44-M
EQUALIZER SYNTHESIS 50-1
EQUALIZER SYNTHESIS 50-2
EQUALIZER SYNTHESIS 50-M
$S_{1,BB}$
$S_{2,BB}$
$S_{M,BB}$
BASEBAND UNIT 36

FIG. 6

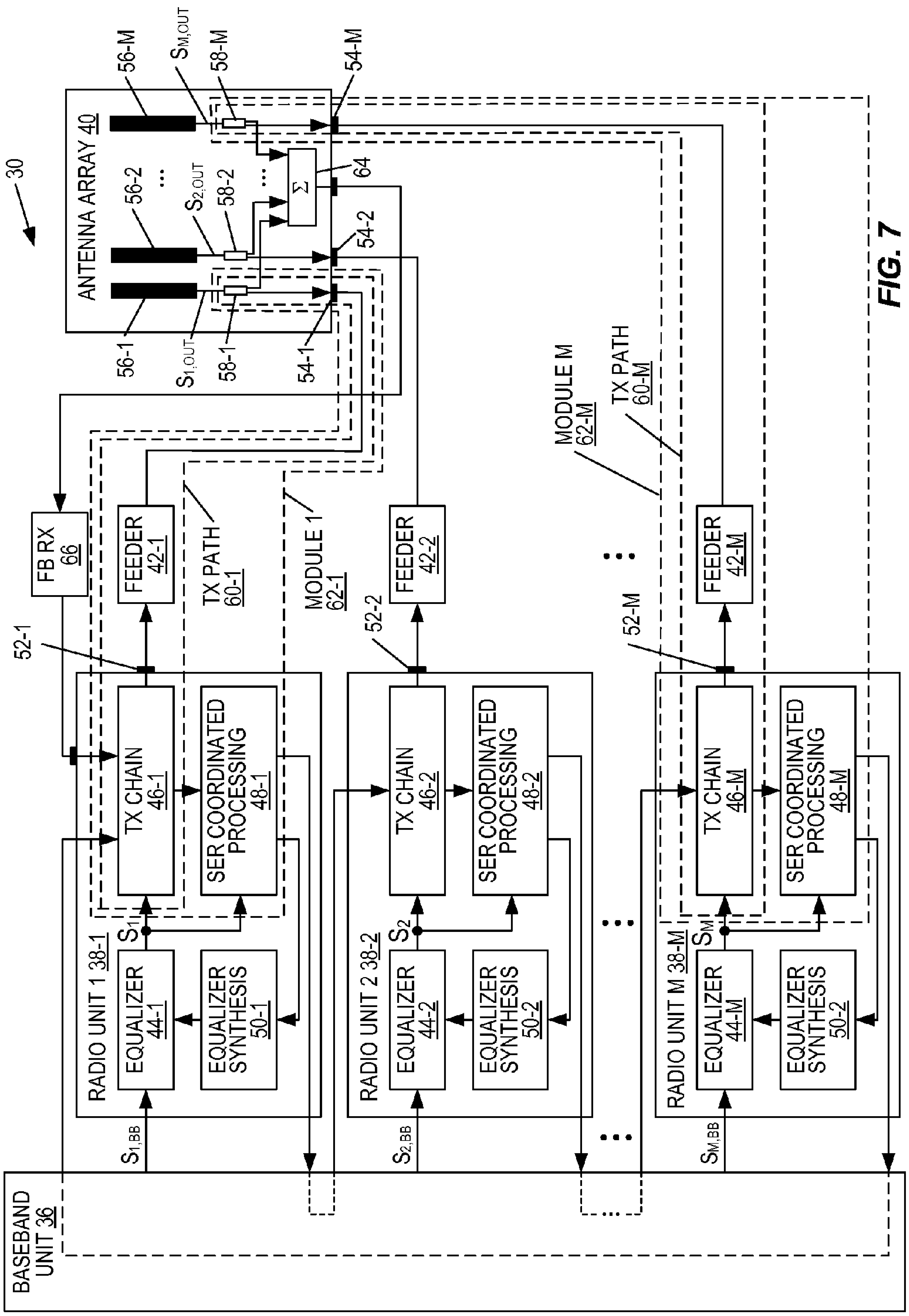

30
ANTENNA ARRAY 40
56-M
$S_{M,OUT}$
58-M
54-M
56-2
$S_{2,OUT}$
58-2
64
Σ
54-2
56-1
$S_{1,OUT}$
58-1
54-1
MODULE M 62-M
TX PATH 60-M
FB RX 66
FEEDER 42-1
TX PATH 60-1
MODULE 1 62-1
FEEDER 42-2
FEEDER 42-M
52-1
52-2
52-M
TX CHAIN 46-1
SER COORDINATED PROCESSING 48-1
TX CHAIN 46-2
SER COORDINATED PROCESSING 48-2
TX CHAIN 46-M
SER COORDINATED PROCESSING 48-M
S_1
S_2
S_M
RADIO UNIT 1 38-1
EQUALIZER 44-1
EQUALIZER SYNTHESIS 50-1
RADIO UNIT 2 38-2
EQUALIZER 44-2
EQUALIZER SYNTHESIS 50-2
RADIO UNIT M 38-M
EQUALIZER 44-M
EQUALIZER SYNTHESIS 50-2
$S_{1,BB}$
$S_{2,BB}$
$S_{M,BB}$
BASEBAND UNIT 36

FIG. 7

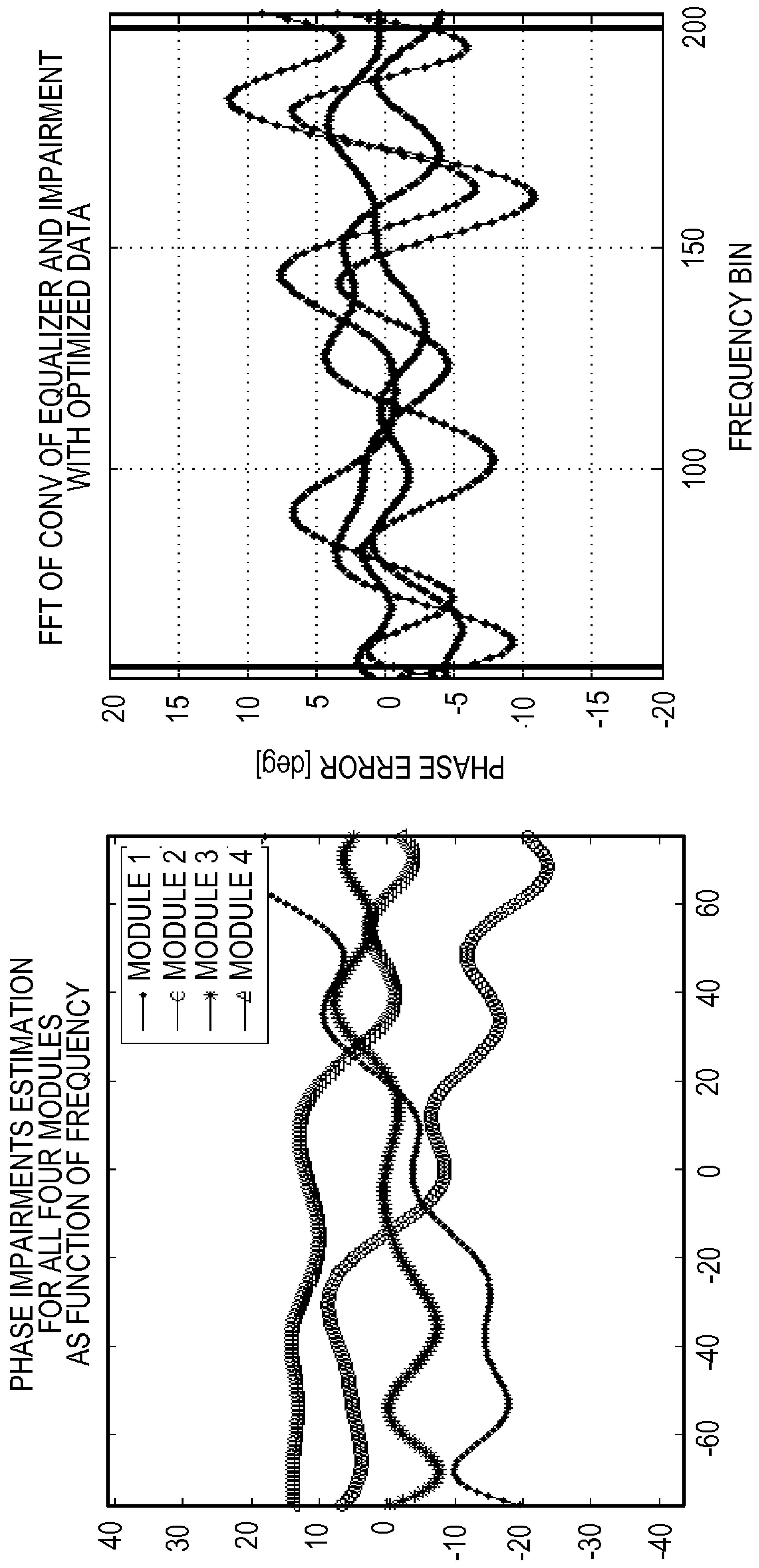

PHASE IMPAIRMENTS ESTIMATION
FOR ALL FOUR MODULES
AS FUNCTION OF FREQUENCY
MODULE 1
MODULE 2
MODULE 3
MODULE 4
40
30
20
10
0
-10
-20
-30
-40
-60
-40
-20
0
20
40
60
FFT OF CONV OF EQUALIZER AND IMPAIRMENT
WITH OPTIMIZED DATA
PHASE ERROR [deg]
20
15
10
5
0
-5
-10
-15
-20
100
150
200
FREQUENCY BIN

FIG. 8

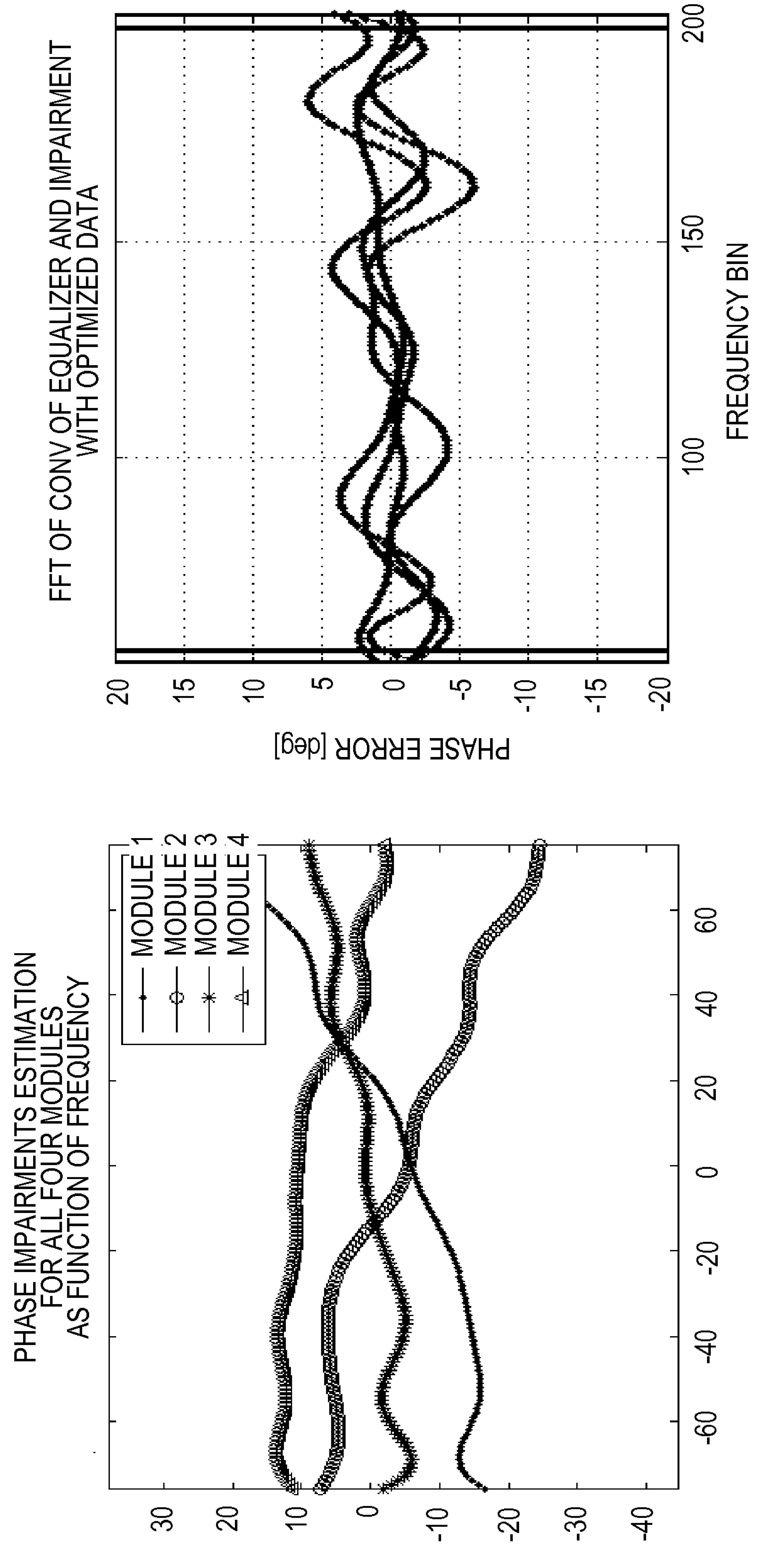
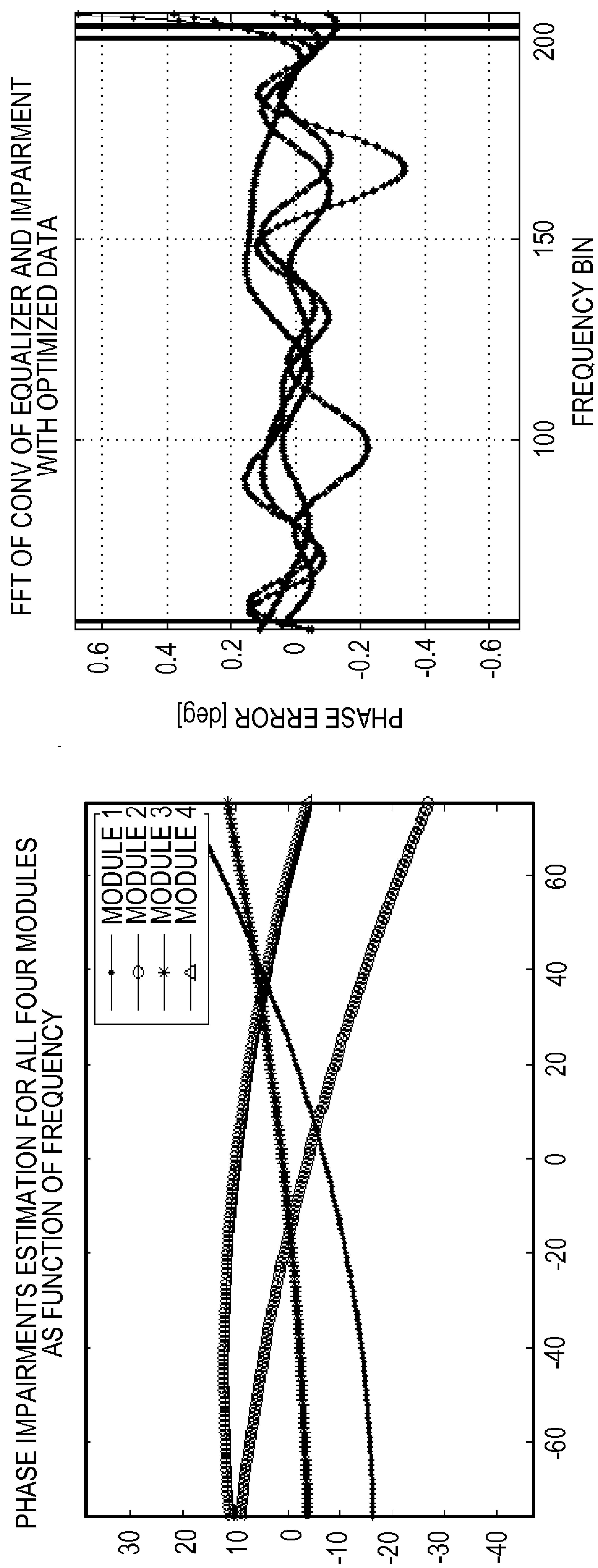

FFT OF CONV OF EQUALIZER AND IMPAIRMENT
WITH OPTIMIZED DATA
PHASE ERROR [deg]
FREQUENCY BIN
20
15
10
5
0
-5
-10
-15
-20
100
150
200
PHASE IMPAIRMENTS ESTIMATION
FOR ALL FOUR MODULES
AS FUNCTION OF FREQUENCY
MODULE 1
MODULE 2
MODULE 3
MODULE 4
30
20
10
0
-10
-20
-30
-40
-60
-40
-20
0
20
40
60

FIG. 9



PHASE IMPAIRMENTS ESTIMATION FOR ALL FOUR MODULES
AS FUNCTION OF FREQUENCY
MODULE 1
MODULE 2
MODULE 3
MODULE 4
FFT OF CONV OF EQUALIZER AND IMPAIRMENT
WITH OPTIMIZED DATA
PHASE ERROR [deg]
FREQUENCY BIN

FIG. 10

SCALABLE ESTIMATION RING

FIELD OF THE DISCLOSURE

The present disclosure relates to antenna calibration and, in particular, to antenna calibration in a base station of a wireless, or cellular, network.

BACKGROUND

Base stations having antenna arrays have been widely used in cellular networks for directional signal transmission and reception with an increased gain compared to an omni-directional antenna. The increased gain translates into a higher cell density and data throughput. An antenna array needs to be calibrated across its sub-array paths to remove any linear phase and/or amplitude distortions (hereafter simply referred to as phase distortion) in these paths. If the transmission beam pattern is out of phase or otherwise phase-distorted, the signal transmitted by the base station at normal transmission power may not be correctly received and decoded by a wireless device, e.g., a user terminal. To compensate for the phase distortions, the base station may transmit data at a higher power level; however, increasing the transmission power acts as a load to the system, causing a reduction to the power that can be allocated to other wireless devices. In addition, the signal transmitted at higher power may interfere with other terminals, causing a reduction in signal quality.

Calibration of the antenna array is typically performed by careful coordination of radio signals transmitted by the sub-arrays of an antenna array. Coordination of the radio signals transmitted by the sub-arrays requires signal correction or compensation, which in turn requires estimation of impulse responses of the sub-array paths (i.e., transmit or receive paths). Estimation of the impulse responses of the sub-array paths is normally done using centralized processing in a radio unit where the correction and compensation is done. In this regard, commonly owned and assigned U.S. patent application Ser. No. 13/894,826, entitled METHOD AND APPARATUS FOR ANTENNA ARRAY CALIBRATION USING TRAFFIC SIGNALS, which was filed May 13, 2013, discloses systems and methods for calibrating an antenna array using a centralized architecture.

Base stations for advanced 4th Generation (4G) and 5th Generation (5G) wireless, or cellular, networks require many radio units and many antennas. Further, it is important for base stations in these 4G and 5G wireless networks to be scalable and modular in order for the base stations to be cost effective and manageable. One issue with a centralized approach for estimating the impulse responses of the sub-array paths in such a base station is that a complexity of the centralized approach increases as the number of radio units (or sub-array paths) increases. This increases the cost and complexity of the base station.

As such, there is a need for systems and methods for estimating impulse responses of sub-arrays paths in a base station having an antenna array that enhance scalability and modularity of the base station without increasing the complexity of the base station.

SUMMARY

Systems and methods are disclosed for estimating impulse responses of multiple channels, e.g., multiple sub-array paths of a base station having an antenna array including multiple antenna sub-arrays, in a distributed manner. By estimating the impulse responses of the channels in a distributed manner, the use of a centralized impulse response estimation architecture is avoided, which in turn reduces complexity and increases modularity.

In one embodiment, a method of operation of a Scalable Estimation Ring (SER) processing component in a SER including multiple SER processing components that operate to estimate impulse responses of corresponding channels is provided. In one embodiment, the method of operation of the SER processing component includes, during a first iteration of the SER, receiving a feedback signal for the SER processing component and computing an initial estimate of an impulse response of a corresponding channel based on the feedback signal for the SER processing component. The method further includes removing a contribution of the corresponding channel from the feedback signal for the SER processing component based on the initial estimate of the impulse response of the corresponding channel to thereby provide a feedback signal for a next SER processing component in the SER. The method also includes outputting the feedback signal for the next SER processing component in the SER. By removing the contribution of the corresponding channel from the feedback signal for the SER processing component to provide the feedback signal for the next SER processing component, the feedback signal for the next SER processing component is less noisy, which in turn results in better impulse response estimation.

In one embodiment, the method of operation of the SER processing component further includes, during a second iteration of the SER, receiving a new feedback signal output by a preceding SER processing component in the SER and adding the contribution of the corresponding channel previously removed from the feedback signal for the SER processing component based on the initial estimate of the impulse response of the corresponding channel into the new feedback signal to thereby provide a modified new feedback signal. The method of operation of the SER processing component during the second iteration further includes computing a new estimate of the impulse response of the corresponding channel based on the modified new feedback signal and removing a contribution of the corresponding channel from the modified new feedback signal based on the new estimate of the impulse response of the corresponding channel to thereby provide a new feedback signal for the next SER processing component in the SER. The method also includes, for the second iteration of the SER, outputting the new feedback signal for the next SER processing component in the SER.

In one embodiment, the SER processing component is a first SER processing component in the SER, and receiving the feedback signal for the SER processing component includes receiving a combined feedback signal, where the combined feedback signal is a summation of output signals of the channels in response to corresponding input signals.

In one embodiment, the channels are transmit paths of a base station of a cellular communications network, where the base station has an antenna array that includes multiple antenna sub-arrays. Each transmit path is connected to a corresponding antenna sub-array. In one embodiment, each transmit path includes a transmit chain, a feeder having a first end connected to an output of the transmit chain and a second end, and a coupler configured to connect the second end of the feeder to a corresponding sub-array. Further, in one embodiment, the transmit chains of the transmit paths are implemented in a single radio unit. In another embodiment, the transmit paths of at least two of the transmit paths are implemented in different radio units. In another embodiment, the transmit chains of the transmit paths are implemented in different radio units.

In one embodiment, the channels are receive paths of a base station of a cellular communications network, where the base station has an antenna array including multiple antenna sub-arrays. Each receive path is connected to a corresponding one of the plurality of antenna sub-arrays.

In one embodiment, for each SER processing component in the SER, removing the contribution of the corresponding channel from the feedback signal for the next SER processing component based on the initial estimate includes subtracting a convolution of a corresponding input signal and the initial estimate of the impulse response of the corresponding channel from the feedback signal for the next SER processing component. In one embodiment, for each SER processing component in the SER, adding the contribution of the corresponding channel previously removed from the combined feedback signal based on the initial estimate into the new feedback signal includes adding the convolution of the corresponding input signal and the initial estimate of the impulse response of the corresponding channel to the new feedback signal to thereby provide the modified new feedback signal, and removing the contribution of the corresponding channel from the modified new feedback signal based on the new estimate for the SER processing component includes subtracting a convolution of the corresponding input signal and the new estimate of the impulse response of the corresponding channel from the modified new feedback signal.

In one embodiment, outputting the feedback signal includes outputting the feedback signal to a baseband unit for distribution to the next SER processing component in the SER. In another embodiment, outputting the feedback signal includes outputting the feedback signal directly to the next SER processing component in the SER.

In one embodiment, a SER processing component that operates according to any of the embodiments above is provided.

In one embodiment, a method of operation of a SER including multiple SER processing components to estimate impulse responses of corresponding channels is provided. In one embodiment, the method includes performing an initial iteration of the SER. Performing the initial iteration of the SER includes, for each SER processing component in the SER: receiving a feedback signal for the SER processing component, computing an initial estimate of an impulse response of a corresponding channel based on the feedback signal for the SER processing component, removing a contribution of the corresponding channel from the feedback signal for the SER processing component based on the initial estimate of the impulse response of the corresponding channel to thereby provide a feedback signal for a next SER processing component in the SER, and outputting the feedback signal for the next SER processing component in the SER.

In one embodiment, for a first SER processing component in the SER, the feedback signal for the initial iteration is a combined feedback signal that is a summation of output signals of the channels in response to corresponding input signals. Further, in one embodiment, for each additional SER processing component in the SER, the feedback signal for the initial iteration is the feedback signal output by a preceding SER processing component in the SER for the initial iteration.

In one embodiment, the method of operation of the SER further includes performing a second iteration of the SER. Performing the second iteration of the SER includes, for each SER processing component in the SER, receiving a new feedback signal output by a preceding SER processing component in the SER, adding the contribution of the corresponding channel removed in the initial iteration of the SER into the new feedback signal to thereby provide a modified new feedback signal, computing a new estimate of the impulse response of the corresponding channel based on the modified new feedback signal, removing a contribution of the corresponding channel from the modified new feedback signal based on the new estimate of the impulse response of the corresponding channel to thereby provide a new feedback signal for the next SER processing component in the SER, and outputting the new feedback signal for the next SER processing component in the SER.

In one embodiment, a SER that operates according to any of the embodiments above is provided.

In one embodiment, a base station for a wireless network that performs calibration of an antenna array to remove distortion incurred by multiple transmit paths in the base station is provided. The antenna array of the base station includes multiple sub-arrays each connected to a corresponding one of the transmit paths. In one embodiment, the base station includes a feedback receiver and a SER. The feedback receiver is configured to receive a combined radio frequency feedback signal and output a combined feedback signal, the combined radio frequency feedback signal being a summation of output signals of the transmit paths in response to corresponding input signals. The SER is configured to estimate impulse responses of the transmit paths based on the combined feedback signal in a distributed manner. The SER includes multiple SER processing components each operating to estimate the impulse response of a corresponding one of the transmit paths.

In one embodiment, each transmit path includes a transmit chain, a feeder having a first end connected to an output of the transmit chain and a second end, and a coupler configured to connect the second end of the feeder to a corresponding sub-array. Further, in one embodiment, the transmit chains of the transmit paths are implemented in a single radio unit. In another embodiment, the transmit chains of the transmit paths are implemented in different radio units. In another embodiment, the transmit chains of at least two of the transmit paths are implemented in different radio units.

In one embodiment, in order to estimate the impulse responses of the transmit paths, for an initial iteration of the SER, each SER processing component in the SER is configured to receive a feedback signal for the SER processing component, compute an initial estimate of the impulse response of a corresponding transmit path based on the feedback signal for the SER processing component, remove a contribution of the corresponding transmit path from the feedback signal for the SER processing component based on the initial estimate of the impulse response of the corresponding transmit path to thereby provide a feedback signal for a next SER processing component in the SER, and output the feedback signal for the next SER processing component in the SER.

In one embodiment, for a first SER processing component in the SER, the feedback signal for the initial iteration is the combined feedback signal from the feedback receiver. Further, in one embodiment, for each additional SER processing component in the SER, the feedback signal for the initial iteration is the feedback signal output by a preceding SER processing component in the SER for the initial iteration.

In one embodiment, in order to estimate the impulse responses of the transmit paths, for a second iteration of the SER, each SER processing component in the SER is configured to receive a new feedback signal output by a preceding SER processing component in the SER, add the contribution of the corresponding transmit path removed in the initial iteration of the SER into the new feedback signal to thereby provide a modified new feedback signal, compute a new estimate of the impulse response of the corresponding transmit path based on the modified new feedback signal, remove a contribution of the corresponding transmit path from the modified new feedback signal based on the new estimate of the impulse response of the corresponding transmit path to thereby provide a new feedback signal for the next SER processing component in the SER, and output the new feedback signal for the next SER processing component in the SER.

Those skilled in the art will appreciate the scope of the present disclosure and realize additional aspects thereof after reading the following detailed description of the embodiments in association with the accompanying drawing figures.

BRIEF DESCRIPTION OF THE DRAWING FIGURES

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 the principles of the disclosure.

FIG. **1** illustrates a centralized architecture for estimating impulse responses of channels formed by multiple modules;

FIG. **2** illustrates a system implementing a distributed architecture for estimating impulse responses of channels formed by multiple modules according to one embodiment of the present disclosure;

FIGS. **3**A and **3**B illustrate the operation of the system of FIG. **2**, and in particular the Scalable Estimation Ring (SER) of the system of FIG. **2**, to estimate the impulse responses of the channels according to one embodiment of the present disclosure;

FIG. **4** is a flow chart that illustrates the operation of the m-th SER coordinated processing component in the SER of FIG. **2** according to one embodiment of the present disclosure;

FIG. **5** illustrates a cellular network including a base station that includes a SER according to one embodiment of the present disclosure;

FIG. **6** illustrates the base station of FIG. **5** in more detail according to one embodiment of the present disclosure;

FIG. **7** illustrates the base station of FIG. **5** according to another embodiment of the present disclosure; and

FIGS. **8** through **10** illustrate example simulation results.

DETAILED DESCRIPTION

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 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 and the accompanying claims.

Systems and methods are disclosed for estimating impulse responses of multiple channels, e.g., multiple sub-array paths of a base station having an antenna array including multiple antenna sub-arrays, in a distributed manner. Before discussing embodiments of the present disclosure, a brief description of a centralized architecture for estimating impulse responses of multiple channels is beneficial. In this regard, FIG. **1** illustrates a centralized architecture **10** that includes multiple modules **12-1** through **12-4** (generally referred to herein collectively as modules **12** or individually as module **12**) that define channels having corresponding impulse responses $H_1(z)$ through $H_4(z)$. In the centralized architecture **10**, one of the modules **12**, which in this example is the module **12-4**, includes a coordinated processing component **14** that estimates the impulse responses $H_1(z)$ through $H_4(z)$ in a coordinated, or joint, manner. More specifically, the modules **12-1** through **12-4** receive input signals S_1 through S_4 and produce output signals $S_{1,OUT}$ through $S_{4,OUT}$, respectively. The coordinated processing component **14** estimates the impulse responses $H_1(z)$ through $H_4(z)$ based on the input signals S_1 through S_4 (as reference signals) and a combined feedback signal output by a summation component **16**. The combined feedback signal is a summation of the output signals $S_{1,OUT}$ through $S_{4,OUT}$.

One issue with the centralized architecture **10** of FIG. **1** is that many interconnects are required for the module **12-4** including the coordinated processing component **14**. In particular, as the number of modules **12** increases, the number of interconnects required for the module **12-4** also increases. Since the module **12-4** must have a limited number of interconnects, the number of modules **12** is also limited. Another issue is that, if the modules **12** are to be interchangeable, each of the modules **12** must include the coordinated processing component **14** even though the coordinated processing component **14** of only one of the modules **12**, which again in this example is the module **12-4**, is used. This significantly increases the complexity and cost of the modules **12**.

Systems and methods disclosed herein utilize a distributed architecture for estimating impulse responses of multiple channels. The distributed architecture decreases complexity and improves modularity as compared to a centralized architecture such as that of FIG. **1**. In this regard, FIG. **2** illustrates a system **18** implementing a distributed architecture including multiple modules **20-1** through **20**-M (generally referred to herein collectively as modules **20** and individually as module **20**) according to one embodiment of the present disclosure. The modules **20** include a number of hardware components that form corresponding channels **22-1** through **22**-M (generally referred to herein collectively as channels **22** and individually as a channel **22**). The channels **22-1** through **22**-M have corresponding impulse responses $H_1(z)$ through $H_M(z)$ (hereafter referred to as H_1 through H_M) that transform input signals S_1 through S_M into output signals $S_{1,OUT}$ through $S_{M,OUT}$, respectively. As discussed below, in one embodiment, the channels **22** are sub-array paths (e.g., transmit paths or receive paths) of a base station for a cellular network, where the base station includes an antenna array including multiple sub-arrays and each sub-array path is connected to a corresponding, or different, sub-array. However, the concepts disclosed herein may also be applied to other types of systems where impulse responses for multiple channels are desired to be estimated based on a combined feedback signal.

The modules **20-1** through **20**-M include Scalable Estimation Ring (SER) coordinated processing components **24-1** through **24**-M, respectively, that form a SER. The SER coordinated processing components **24-1** through **24**-M are generally referred to herein collectively as SER coordinated processing components **24** and individually as SER coordinated processing component **24**. The SER coordinated processing components **24** forming the SER operate to estimate the impulse responses H_1 through H_M of the channels **22** in a distributed manner. In particular, the SER coordinated processing component **24-1** estimates the impulse response H_1 of the corresponding channel **22-1**, the SER coordinated processing component **24-2** estimates the impulse response H_2 of the corresponding channel **22-2**, etc.

As described below in detail, multiple iterations of the SER are performed to estimate the impulse responses H_1 through H_M of the channels **22-1** through **22-M** based on a combined feedback signal S_{FB}^{11}. A summation component **26** operates to sum the output signals $S_{1,OUT}$ through $S_{M,OUT}$ to provide the combined feedback signal S_{FB}^{11}. During a first iteration of the SER, the SER performs a sequential procedure by which the SER coordinated processing components **24-1** through **24-M** sequentially estimate the impulse responses H_1 through H_M of the corresponding channels **22-1** through **22-M** and remove, or subtract, the contributions of the corresponding channels **22-1** through **22-M** from the combined feedback signal S_{FB}^{11} based on the estimates of the impulse responses H_1 through H_M, respectively. In this manner, as feedback signals are propagated through the SER for the first iteration, the SER coordinated processing component **24** of each module **20** has a better signal to noise ratio because a portion of the noise in the combined feedback signal S_{FB}^{11} as seen by the SER coordinated processing component **24** of that module **20** has been removed by the SER coordinated processing component **24** of the previous module **20**. At the end of the first iteration, the contributions of all of the channels **22-1** through **22-M** have been removed from the combined feedback signal S_{FB}^{11} based on initial estimates of the impulse responses H_1 through H_M to thereby provide a feedback signal S_{FB}^{12} (i.e., $S_{FB}^{1(i+1)}$ where i=1 for the first iteration) returned to the SER coordinated processing component **24-1** for the second iteration of the SER.

During the second iteration of the SER, the SER performs a sequential procedure by which each SER coordinated processing component **24-**m (where $m \in \{1, 2, \ldots, M\}$) operates to: (a) add the contribution of the corresponding channel **22-**m removed during the first iteration based on the initial estimate of the corresponding impulse response H_m back into the feedback signal S_{FB}^{m2} received by the SER coordinated processing component **24-**m to provide a modified feedback signal $S_{FB}^{m2\prime}$, (b) compute a new estimate H_{m2} of the impulse response H_m of the corresponding channel **22-**m based on the modified feedback signal $S_{FB}^{m2\prime}$ and the input signal S_m, and (c) remove a contribution of the corresponding channel **22-**m from the modified feedback signal $S_{FB}^{m2\prime}$ based on the new estimate H_{m2} of the corresponding impulse response H_m to thereby provide a new feedback signal for a next SER coordinated processing component **24** in the SER. The process can continue in this manner to perform one or more additional iterations of the SER to, e.g., achieve a desired accuracy for the estimates of the impulse responses H_1 through H_M.

FIGS. **3**A and **3**B illustrate the operation of the system **18** of FIG. **2**, and in particular the SER, to estimate the impulse responses H_1 through H_M of the channels **22-1** through **22-M**, respectively, according to one embodiment of the present disclosure. For an initial or first iteration of the SER, the SER coordinated processing component **24-1** receives the combined feedback signal S_{FB}^{11} (step **100**). The combined feedback signal S_{FB}^{11} can be defined as:

$$S_{FB}^{11} = \sum_{m=1}^{M} S_m * H_m + \text{noise}$$

where * denotes convolution. The SER coordinated processing component **24-1** of the module **20-1** then computes an estimate of the impulse response H_1 of the channel **22-1** for the first iteration, which is referred to as the estimate H_{11} of the impulse response H_1 of the channel **22-1**, based on the combined feedback signal S_{FB}^{11} and the input signal S_1 (step **102**). During the first iteration, since $S_2*H_2, \ldots, S_M*H_M$ are completely unknown to the module **20-1** and have not yet been removed by the SER coordinated processing components **24-2** through **24-M**, respectively, the estimate H_{11} of the impulse response H_1 of the channel **22-1** is generally a less than ideal estimate. However, as discussed below, the estimate is improved by using additional iterations of the SER. The estimate H_{11} is computed as a de-convolution of time-aligned versions the combined feedback signal S_{FB}^{11} and the input signal S_1. More specifically, this de-convolution may be computed as, for example, dividing the combined feedback signal S_{FB}^{11} by the input signal S_1 in the frequency domain after time-alignment.

The SER coordinated processing component **24-1** of the module **20-1** then removes a contribution of the channel **22-1** from the combined feedback signal S_{FB}^{11} to thereby provide a feedback signal S_{FB}^{21} the next SER coordinated processing component **24** in the SER, which is the SER coordinated processing component **24-2** (step **104**). More specifically, the SER coordinated processing component **24-1** removes the contribution of the channel **22-1** to provide the feedback signal S_{FB}^{21} to the equation:

$$S_{FB}^{21} = S_{FB}^{11} - (S_1 * H_{11}).$$

The SER coordinated processing component **24-1** of the module **20-1** then outputs the feedback signal S_{FB}^{21} the SER coordinated processing component **24-2** of the module **20-2** (step **106**). In this embodiment, the SER coordinated processing component **24-1** of the module **20-1** outputs the feedback signal S_{FB}^{21} directly to the SER coordinated processing component **24-2** of the module **20-2**. However, in another embodiment, the SER coordinated processing component **24-1** of the module **20-1** outputs the feedback signal S_{FB}^{21} the SER coordinated processing component **24-2** of the module **20-2** via one or more other components (e.g., a controller or a baseband unit).

Likewise, upon receiving the feedback signal S_{FB}^{21}, the SER coordinated processing component **24-2** of the module **20-2** then computes an estimate of the impulse response H_2 of the channel **22-2** for the first iteration, which is referred to as the estimate H_{21} of the impulse response H_2 of the channel **22-2**, based on the feedback signal S_{FB}^{21} the input signal S_2 (step **108**). During the first iteration, since $S_3*H_3, \ldots, S_M*H_M$ are completely unknown to the module **20-2** and have not yet been removed by the SER coordinated processing components **24-3** through **24-M**, respectively, the estimate H_{21} of the impulse response H_2 of the channel **22-2** is generally a less than ideal estimate. However, as discussed blow, the estimate is improved by using additional iterations of the SER. Further, since S_1*H_{11} has been removed, the estimate H_{21} of the impulse response H_2 of the channel **22-2** is less noisy than the estimate H_{11} of the impulse response H_1 of the channel **22-1**. The estimate H_{21} is computed as a de-convolution of time-aligned versions the feedback signal S_{FB}^{21} and the input signal S_2. More specifically, this de-convolution may be computed as, for example, dividing the feedback signal S_{FB}^{21} by the input signal S_2 in the frequency domain after time-alignment.

The SER coordinated processing component **24-2** of the module **20-2** then removes a contribution of the channel **22-2** from the feedback signal S_{FB}^{21} to thereby provide a feedback signal S_{FB}^{31} for the next SER coordinated processing component **24** in the SER, which is the SER coordinated processing component **24-3** (not shown) (step **110**). More specifically, the SER coordinated processing component **24-2** removes the contribution of the channel **22-2** to provide the feedback signal S_{FB}^{31} according to the equation:

$$S_{FB}^{31}=S_{FB}^{21}-(S_2*H_{21}).$$

The SER coordinated processing component **24-2** of the module **20-2** then outputs the feedback signal S_{FB}^{31} (for the SER coordinated processing component **24-3** of the module **20-3**, which are not shown) (step **112**). Note that the module **20-3** is the last module **20**-M in the case M=3. In this embodiment, the SER coordinated processing component **24-2** of the module **20-2** outputs the feedback signal S_{FB}^{31} directly to the SER coordinated processing component **24-3** of the module **20-3**. However, in another embodiment, the SER coordinated processing component **24-2** of the module **20-2** outputs the feedback signal S_{FB}^{31} to the SER coordinated processing component **24-3** of the module **20-3** via one or more other components (e.g., a controller or a baseband unit).

The first iteration of the SER continues in this manner until the SER coordinated processing component **24**-M receives a feedback signal S_{FB}^{M1} from its preceding SER coordinated processing component **24**-(M−1) in the SER (step **114**). Upon receiving the feedback signal S_{FB}^{M1}, the SER coordinated processing component **24**-M of the module **20**-M computes an estimate of the impulse response H_M of the channel **22**-M for the first iteration, which is referred to as the estimate H_{M1} of the impulse response H_M of the channel **22**-M, based on the feedback signal S_{FB}^{M1} and the input signal S_M (step **116**). Since the estimated contributions $S_1H*H_{11}, \ldots, S_{(M-1)}*H_{(M-1)1}$ of the channels **22-1** through **22**-(M−1) have been removed, the estimate H_{M1} of the impulse response H_M of the channel **22**-M is less noisy than the other estimates H_{11} through $H_{(M-1),1}$ of the impulse responses H_1 through $H_{(M-1)}$ of the channels **22-1** through **22**-(M−1), respectively. The estimate H_{M1} is computed as a de-convolution of time-aligned versions of the feedback signal S_{FB}^{M1} and the input signal S_M. More specifically, this de-convolution may be computed as, for example, dividing the feedback signal S_{FB}^{M1} by the input signal S_M in the frequency domain after time-alignment.

The SER coordinated processing component **24**-M of the module **20**-M then removes a contribution of the channel **22**-M from the feedback signal S_{FB}^{M1} to thereby provide a feedback signal S_{FB}^{12} for the next SER coordinated processing component **24** in the SER, which is the SER coordinated processing component **24-1** (i.e., the feedback signal S_{FB}^{12} is the feedback signal for the SER coordinated processing component **24-1** for a second iteration of the SER) (step **118**). More specifically, the SER coordinated processing component **24**-M removes the contribution of the channel **22**-M to provide the feedback signal S_{FB}^{12} according to the equation:

$$S_{FB}^{12}=S_{FB}^{M1}-(S_M*H_{M1}).$$

The SER coordinated processing component **24**-M of the module **20**-M then outputs the feedback signal S_{FB}^{12} for the SER coordinated processing component **24-1** of the module **20-1** (step **120**). In this embodiment, the SER coordinated processing component **24**-M of the module **20**-M outputs the feedback signal S_{FB}^{12} directly to the SER coordinated processing component **24-1** of the module **20-1**. However, in another embodiment, the SER coordinated processing component **24**-M of the module **20**-M outputs the feedback signal S_{FB}^{12} to the SER coordinated processing component **24-1** of the module **20-1** via one or more other components (e.g., a controller or a baseband unit). At this point, the first iteration of the SER is complete.

Next, a second iteration of the SER is performed. In the second iteration of the SER, the SER coordinated processing component **24-1** of the module **20-1** first adds the contribution of the channel **22-1** removed in the previous iteration of the SER back into the feedback signal S_{FB}^{12} to thereby provide a modified feedback signal $S_{FB}^{12\prime}$ (step **122**). More specifically, the feedback signal S_{FB}^{12} can be expressed as:

$$S_{FB}^{12}=\sum_{m=1}^{M}S_m*(H_m-H_{m1})+\text{noise}.$$

The SER coordinated processing component **24-1** can then add the contribution of the channel **22-1** removed in the previous iteration of the SER (i.e., S_1*H_{11}) back into the feedback signal S_{FB}^{12} to thereby provide the modified feedback signal $S_{FB}^{12\prime}$ according to:

$$\begin{aligned} S_{FB}^{12\prime} &= S_{FB}^{12}+S_1*H_{11} \\ &= S_1*H_1+\sum_{m=2}^{M}S_m*(H_m-H_{m1})+\text{noise} \end{aligned}$$

The SER coordinated processing component **24-1** of the module **20-1** then computes a new estimate H_{12} of the impulse response H_1 of the channel **22-1** for the second iteration, which is referred to as the estimate H_{12} of the impulse response H_1 of the channel **22-1**, based on the modified feedback signal $S_{FB}^{12\prime}$ and the input signal S_1 (step **124**). Since the estimated contributions $S_2*H_{21}, \ldots, S_M*H_{M1}$ of the channels **22-2** through **22**-M were removed in the initial iteration, the estimate H_{12} of the impulse response H_1 of the channel **22-1** for the second iteration is less noisy (i.e., improved) than the estimate H_{11} of the impulse response H_1 of the channel **22-1** for the first iteration. The estimate H_{12} is computed as a de-convolution of time-aligned versions of the modified feedback signal $S_{FB}^{12\prime}$ and the input signal S_1. More specifically, this de-convolution may be computed as, for example, dividing the modified feedback signal $S_{FB}^{12\prime}$ by the input signal S_1 in the frequency domain after time-alignment.

The SER coordinated processing component **24-1** of the module **20-1** then removes a contribution of the channel **22-1** from the modified feedback signal $S_{FB}^{12\prime}$ to thereby provide a feedback signal S_{FB}^{22} for the next SER coordinated processing component **24** in the SER, which is the SER coordinated processing component **24-2** (step **126**). More specifically, the SER coordinated processing component **24-1** removes the contribution of the channel **22-1** to provide the feedback signal S_{FB}^{22} according to the equation:

$$S_{FB}^{22}=S_{FB}^{12\prime}-(S_1*H_{12}).$$

The SER coordinated processing component **24-1** of the module **20-1** then outputs the feedback signal S_{FB}^{22} for the SER coordinated processing component **24-2** of the module **20-2** (step **128**). In this embodiment, the SER coordinated processing component **24-1** of the module **20-1** outputs the feedback signal S_{FB}^{22} directly to the SER coordinated processing component **24-2** of the module **20-2**. However, in another embodiment, the SER coordinated processing component **24-1** of the module **20-1** outputs the feedback signal S_{FB}^{22} to the SER coordinated processing component **24-2** of the module **20-2** via one or more other components (e.g., a controller or a baseband unit).

Likewise, upon receiving the feedback signal $S_{FB}^{22'}$ the SER coordinated processing component **24-2** of the module **20-2** adds the contribution of the channel **22-2** removed in the previous iteration of the SER back into the feedback signal S_{FB}^{22} to thereby provide a modified feedback signal $S_{FB}^{22'}$ (step **130**). More specifically, the feedback signal S_{FB}^{22} can be expressed as:

$$S_{FB}^{22} = S_1 * (H_1 - H_{12}) + \sum_{m=2}^{M} S_m * (H_m - H_{m1}) + \text{noise}.$$

The SER coordinated processing component **24-2** can then add the contribution of the channel **22-2** removed in the previous iteration of the SER (i.e., $S_2 * H_{21}$) back into the feedback signal S_{FB}^{22} to thereby provide the modified feedback signal $S_{FB}^{22'}$ according to:

$$\begin{aligned} S_{FB}^{22'} &= S_{FB}^{22} + S_2 * H_{21} \\ &= S_1 * (H_1 - H_{12}) + S_2 * H_2 + \sum_{m=3}^{M} S_m * (H_m - H_{m1}) + \text{noise} \end{aligned}$$

The SER coordinated processing component **24-2** of the module **20-2** then computes a new estimate of the impulse response H_2 of the channel **22-2** for the second iteration, which is referred to as the estimate H_{22} of the impulse response H_2 of the channel **22-2**, based on the modified feedback signal $S_{FB}^{22'}$ and the input signal S_2 (step **132**). Since the estimated contribution $S_1 * H_{12}$ of the channel **22-1** has already been removed in the second iteration and the estimated contributions $S_3 * H_{31}, \ldots, S_M * H_{M1}$ of the channels **22-3** through **22-M** were removed in the initial iteration, the estimate H_{22} of the impulse response H_2 of the channel **22-2** for the second iteration is less noisy (i.e., improved) than the estimate H_{21} of the impulse response H_2 of the channel **22-2** for the first iteration. The estimate H_{22} is computed as a de-convolution of time-aligned versions of the modified feedback signal $S_{FB}^{22'}$ and the input signal S_2. More specifically, this de-convolution may be computed as, for example, dividing the modified feedback signal $S_{FB}^{22'}$ by the input signal S_2 in the frequency domain after time-alignment.

The SER coordinated processing component **24-2** of the module **20-2** then removes a contribution of the channel **22-2** from the modified feedback signal $S_{FB}^{22'}$ to thereby provide a feedback signal S_{FB}^{32} for the next SER coordinated processing component **24** in the SER, which is the SER coordinated processing component **24-3** (step **134**). More specifically, the SER coordinated processing component **24-2** removes the contribution of the channel **22-2** to provide the feedback signal S_{FB}^{32} according to the equation:

$$S_{FB}^{32} = S_{FB}^{22'} - (S_2 * H_{22}).$$

The SER coordinated processing component **24-2** of the module **20-2** then outputs the feedback signal S_{FB}^{32} for the SER coordinated processing component **24-3** of the module **20-3** (not shown) (step **136**). In this embodiment, the SER coordinated processing component **24-2** of the module **20-2** outputs the feedback signal S_{FB}^{32} directly to the SER coordinated processing component **24-3** of the module **20-3** (again, not shown). However, in another embodiment, the SER coordinated processing component **24-2** of the module **20-2** outputs the feedback signal S_{FB}^{32} to the SER coordinated processing component **24-3** of the module **20-3** via one or more other components (e.g., a controller or a baseband unit).

The second iteration of the SER continues in this manner until the final SER coordinated processing component **24**-M of the final module **20**-M receives a feedback signal S_{FB}^{M2} from its preceding SER coordinated processing component **24**-(M−1) in the SER (step **138**). Upon receiving the feedback signal S_{FB}^{M2}, the SER coordinated processing component **24**-M of the module **20**-M adds the contribution of the channel **22**-M removed in the previous iteration of the SER back into the feedback signal S_{FB}^{M2} to thereby provide a modified feedback signal $S_{FB}^{M2'}$ (step **140**). More specifically, the feedback signal S_{FB}^{M2} can be expressed as:

$$S_{FB}^{M2} = \sum_{m=1}^{M-1} S_m * (H_m - H_{m2}) + S_M * (H_m - H_{M1}) + \text{noise}.$$

The SER coordinated processing component **24**-M can then add the contribution of the channel **22**-M removed in the previous iteration of the SER (i.e., $S_M * H_{M1}$) back into the feedback signal S_{FB}^{M2} to thereby provide the modified feedback signal $S_{FB}^{M2'}$ according to:

$$S_{FB}^{M2'} = \sum_{m=1}^{M-1} S_m * (H_m - H_{m2}) + S_M * H_M + \text{noise}.$$

The SER coordinated processing component **24**-M of the module **20**-M then computes a new estimate of the impulse response H_M of the channel **22**-M for the second iteration, which is referred to as the estimate H_{M2} of the impulse response H_M of the channel **22**-M, based on the modified feedback signal $S_{FB}^{M2'}$ and the input signal S_M (step **142**). Since the new (and improved) estimated contributions $S_1 H * H_{12}, \ldots, S_{(M-1)} * H_{(M-1)2}$ of the channels **22-1** through **22**-(M−1) for the second iteration have been removed, the estimate H_{M2} of the impulse response H_M of the channel **22**-M is improved. The estimate H_{M2} is computed as a de-convolution of time-aligned versions of the modified feedback signal $S_{FB}^{M2'}$ and the input signal S_M. More specifically, this de-convolution may be computed as, for example, dividing the modified feedback signal $S_{FB}^{M2'}$ by the input signal S_M in the frequency domain after time-alignment.

The SER coordinated processing component **24**-M of the module **20**-M then removes a contribution of the channel **22**-M from the modified feedback signal $S_{FB}^{M2'}$ to thereby provide a feedback signal S_{FB}^{13} for the next SER coordinated processing component **24** in the SER, which is the SER coordinated processing component **24-1** (step **144**). In this case, the feedback signal S_{FB}^{13} is a feedback signal for the SER coordinated processing component **24-1** of the module **20-1** for a third iteration of the SER. More specifically, the SER coordinated processing component **24**-M removes the contribution of the channel **22**-M to provide the feedback signal S_{FB}^{13} according to the equation:

$$S_{FB}^{13} = S_{FB}^{M2'} - (S_M * H_{M2}).$$

The SER coordinated processing component **24**-M of the module **20**-M then outputs the feedback signal S_{FB}^{13} for the SER coordinated processing component **24-1** of the module **20-1** (step **146**). In this embodiment, the SER coordinated processing component **24**-M of the module **20**-M outputs the feedback signal S_{FB}^{13} directly to the SER coordinated processing component **24**-M of the module **20**-M. However, in another embodiment, the SER coordinated processing component **24**-M of the module **20**-M outputs the feedback signal S_{FB}^{13} to the SER coordinated processing component **24-1** of the module **20-1** via one or more other components (e.g., a controller or a baseband unit).

Iterations of the SER continue in this manner until a final iteration of the SER is reached. Note that the desired number of iterations is, in one embodiment, greater than or equal to 2. In another embodiment, the number of iterations is greater than or equal to 8. Note that the number of iterations performed is, in one embodiment, a tradeoff between accuracy and time.

In the final iteration, the SER coordinated processing component **24-1** of the module **20-1** receives a feedback signal S_{FB}^{1N} from the SER coordinated processing component **24**-M of the module **20**-M, where N is the number of iterations performed by the SER (step **148**). Upon receiving the feedback signal S_{FB}^{1N}, the SER coordinated processing component **24-1** of the module **20-1** adds the contribution of the channel **22-1** removed in the previous iteration (i.e., the (N−1)th iteration) of the SER back into the feedback signal S_{FB}^{1N} to thereby provide a modified feedback signal $S_{FB}^{1N'}$ (step **150**). More specifically, the feedback signal S_{FB}^{1N} can be expressed as:

$$S_{FB}^{1N} = \sum_{m=1}^{M} S_m * (H_m - H_{m(N-1)}) + \text{noise}.$$

The SER coordinated processing component **24-1** can then add the contribution of the channel **22-1** removed in the previous iteration of the SER (i.e., $S_1 * H_{1(N-1)}$) back into the feedback signal S_{FB}^{1N} to thereby provide the modified feedback signal $S_{FB}^{1N'}$ according to:

$$\begin{aligned} S_{FB}^{1N'} &= S_{FB}^{1N} + S_1 * H_{1(N-1)} \\ &= S_1 * H_1 + \sum_{m=2}^{M} S_m * (H_m - H_{m(N-1)}) + \text{noise} \end{aligned}$$

The SER coordinated processing component **24-1** of the module **20-1** then computes a new estimate of the impulse response H_1 of the channel **22-1** for the Nth iteration, which is referred to as the estimate H_{1N} of the impulse response H_1 of the channel **22-1**, based on the modified feedback signal $S_{FB}^{1N'}$ and the input signal S_1 (step **152**). The estimate H_{1N} is computed as a de-convolution of time-aligned versions of the modified feedback signal $S_{FB}^{1N'}$ and the input signal S_1. More specifically, this de-convolution may be computed as, for example, dividing the modified feedback signal $S_{FB}^{1N'}$ by the input signal S_1 in the frequency domain after time-alignment.

The SER coordinated processing component **24-1** of the module **20-1** then removes a contribution of the channel **22-1** from the modified feedback signal $S_{FB}^{1N'}$ to thereby provide a feedback signal S_{FB}^{2N} for the next SER coordinated processing component **24** in the SER, which is the SER coordinated processing component **24-2** (step **154**). More specifically, the SER coordinated processing component **24-1** removes the contribution of the channel **22-1** to provide the feedback signal S_{FB}^{2N} according to the equation:

$$S_{FB}^{2N} = S_{FB}^{1N'} - (S_1 * H_{1N}).$$

The SER coordinated processing component **24-1** of the module **20-1** then outputs the feedback signal S_{FB}^{2N} for the SER coordinated processing component **24-2** of the module **20-2** (step **156**). In this embodiment, the SER coordinated processing component **24-1** of the module **20-1** outputs the feedback signal S_{FB}^{2N} directly to the SER coordinated processing component **24-2** of the module **20-2**. However, in another embodiment, the SER coordinated processing component **24-1** of the module **20-1** outputs the feedback signal S_{FB}^{2N} to the SER coordinated processing component **24-2** of the module **20-2** via one or more other components (e.g., a controller or a baseband unit).

Likewise, upon receiving the feedback signal S_{FB}^{2N}, the SER coordinated processing component **24-2** of the module **20-2** adds the contribution of the channel **22-2** removed in the previous iteration (i.e., the (N−1)th iteration) of the SER back into the feedback signal S_{FB}^{2N} to thereby provide a modified feedback signal $S_{FB}^{2N'}$ (step **158**). More specifically, the feedback signal S_{FB}^{2N} can be expressed as:

$$S_{FB}^{2N} = S_1 * (H_1 - H_{1N}) + \sum_{m=2}^{M} S_m * (H_m - H_{m(N-1)}) + \text{noise}.$$

The SER coordinated processing component **24-2** can then add the contribution of the channel **22-2** removed in the previous iteration of the SER (i.e., $S_2 * H_{2(N-1)}$) back into the feedback signal S_{FB}^{2N} to thereby provide the modified feedback signal $S_{FB}^{2N'}$ according to:

$$\begin{aligned} S_{FB}^{2N'} &= S_{FB}^{2N} + S_2 * H_{2(N-1)} \\ &= S_1 * (H_1 - H_{1N}) + S_2 * H_2 + \sum_{m=3}^{M} S_m * (H_m - H_{m(N-1)}) + \text{noise} \end{aligned}$$

The SER coordinated processing component **24-2** of the module **20-2** then computes a new estimate of the impulse response H_2 of the channel **22-2** for the Nth iteration, which is referred to as the estimate H_{2N} of the impulse response H_2 of the channel **22-2**, based on the modified feedback signal $S_{FB}^{2N'}$ and the input signal S_2 (step **160**). The estimate H_{2N} is computed as a de-convolution of time-aligned versions of the modified feedback signal $S_{FB}^{2N'}$ and the input signal S_2. More specifically, this de-convolution may be computed as, for example, dividing the modified feedback signal $S_{FB}^{2N'}$ by the input signal S_2 in the frequency domain after time-alignment.

The SER coordinated processing component **24-2** of the module **20-2** then removes a contribution of the channel **22-2** from the modified feedback signal $S_{FB}^{2N'}$ to thereby provide a feedback signal S_{FB}^{3N} for the next SER coordinated processing component **24** in the SER, which is the SER coordinated processing component **24-3** (step **162**). More specifically, the SER coordinated processing component **24-2** removes the contribution of the channel **22-2** to provide the feedback signal S_{FB}^{3N} according to the equation:

$$S_{FB}^{3N} = S_{FB}^{2N'} - (S_2 * H_{2N}).$$

The SER coordinated processing component **24-2** of the module **20-2** then outputs the feedback signal S_{FB}^{3N} for the SER coordinated processing component **24-3** of the module **20-3** (not shown) (step **164**). In this embodiment, the SER coordinated processing component **24-2** of the module **20-2** outputs the feedback signal S_{FB}^{3N} directly to the SER coordinated processing component **24-3** of the module **20-3** (again, not shown). However, in another embodiment, the SER coordinated processing component **24-2** of the module **20-2** outputs the feedback signal S_{FB}^{3N} to the SER coordinated processing component **24-3** of the module **20-3** via one or more other components (e.g., a controller or a baseband unit).

The Nth (or final) iteration of the SER continues in this manner until the final SER coordinated processing component **24**-M of the final module **20**-M receives a feedback signal S_{FB}^{MN} from its preceding SER coordinated processing component **24**-(M−1) in the SER (step **166**). Upon receiving the feedback signal S_{FB}^{MN}, the SER coordinated processing component **24**-M of the module **20**-M adds the contribution of the channel **22**-M removed in the previous iteration (i.e., the (N−1)th iteration) of the SER back into the feedback signal S_{FB}^{MN} to thereby provide a modified feedback signal $S_{FB}^{MN'}$ (step **168**). More specifically, the feedback signal S_{FB}^{MN} can be expressed as:

$$S_{FB}^{MN} = \sum_{m=1}^{M-1} S_m * (H_m - H_{mN}) + S_M * (H_M - H_{M(N-1)}) + \text{noise}.$$

The SER coordinated processing component **24**-M can then add the contribution of the channel **22**-M removed in the previous iteration of the SER (i.e., $S_M*H_{M(N-1)}$) back into the feedback signal S_{FB}^{MN} to thereby provide the modified feedback signal $S_{FB}^{MN'}$ according to:

$$S_{FB}^{MN'} = \sum_{m=1}^{M-1} S_m * (H_m - H_{mN}) + S_M * H_M + \text{noise}.$$

The SER coordinated processing component **24**-M of the module **20**-M then computes a new estimate of the impulse response H_M of the channel **22**-M for the Nth iteration, which is referred to as the estimate H_{MN} of the impulse response H_M of the channel **22**-M, based on the modified feedback signal $S_{FB}^{MN'}$, and the input signal S_M (step **170**). The estimate H_{MN} is computed as a de-convolution of time-aligned versions of the modified feedback signal $S_{FB}^{MN'}$ and the input signal S_M. More specifically, this de-convolution may be computed as, for example, dividing the modified feedback signal $S_{FB}^{MN'}$ by the input signal S_M in the frequency domain after time-alignment.

At this point, the process is complete. The estimates H_{1N} through H_{MN} are the final estimates of the impulse responses H_1 through H_M of the channels **22-1** through **22**-M, respectively. The final estimates of the impulse responses H_1 through H_M of the channels **22-1** through **22**-M can then be used to correct or compensate for linear distortions (i.e., to equalize) the channels **22-1** through **22**-M. Notably, during operation, the process of FIGS. **3**A and **3**B may be repeated as desired in order to update the final estimates of the impulse responses H_1 through H_M of the channels **22-1** through **22**-M over time in order to account for changes in the impulse responses H_1 through H_M of the channels **22-1** through **22**-M.

FIG. **4** is a flow chart that illustrates the operation of the m-th SER coordinated processing component **24**-*m* of FIG. **2** according to one embodiment of the present disclosure. The operation of the SER coordinated processing component **24**-*m* in this embodiment is the same as described above with respect to FIG. **3**. As such, some details are not repeated. As illustrated, for the first or initial iteration of the SER, the SER coordinated processing component **24**-*m* receives the feedback signal S_{FB}^{m1} (step **200**). The SER coordinated processing component **24**-*m* then computes the estimate H_{m1} of the impulse response H_m of the corresponding channel **22**-*m* for the first iteration of the SER based on the feedback signal S_{FB}^{m1} and the corresponding input signal S_m (step **202**). The SER coordinated processing component **24**-*m* then removes the contribution of the corresponding channel S_m (i.e., S_m*H_{m1}) from the feedback signal S_{FB}^{m1} to provide the feedback signal for the next SER coordinated processing component **24** in the SER (step **204**). The SER coordinated processing component **24**-*m* then outputs the feedback signal for the next SER coordinated processing component **24** in the SER (step **206**).

In this embodiment, the SER coordinated processing component **24**-*m* then sets an iteration counter i to 2 (step **208**). Next, the SER coordinated processing component **24**-*m* receives the feedback signal S_{FB}^{mi} for the i-th iteration of the SER from the preceding SER coordinated processing component **24** in the SER (step **210**). The SER coordinated processing component **24**-*m* then adds the contribution (i.e., $S_m*H_{m(i-1)}$) of the channel **22**-*m* removed during the previous iteration (i.e., iteration i−1) back into the feedback signal S_{FB}^{mi} to thereby provide a modified feedback signal $S_{FB}^{mi'}$ (step **212**). The SER coordinated processing component **24**-*m* then computes the new estimate H_{mi} for the impulse response H_m of the channel **22**-*m* based on the modified feedback signal $S_{FB}^{mi'}$ and the corresponding input signal S_m (step **214**). Next, the SER coordinated processing component **24**-*m* removes the contribution (i.e., S_m*H_{mi}) of the channel **22**-*m* from the modified feedback signal $S_{FB}^{mi'}$ to thereby provide a new feedback signal for the next SER coordinated processing component **24** in the SER (step **216**). The SER coordinated processing component **24**-*m* then outputs the new feedback signal to the next SER coordinated processing component **24** (step **218**).

The SER coordinated processing component **24**-*m* then determines whether the desired number of iterations of the SER have been performed (i.e., determines whether i=N, where N is the desired number of iterations of the SER) (step **220**). If not, the iteration counter i is incremented (step **222**), and the process returns to step **210** and is repeated. Once the desired number (N) of iterations have been performed, the final estimate H_{mN} of the impulse response H_m of the corresponding channel **22**-*m* has been computed, and the process ends. It should be noted that while the first and subsequent iterations of the SER are illustrated separately in the flow chart of FIG. **4**, the present disclosure is not limited thereto. In another embodiment, the first iteration may be performed just like the other iterations but where the previously removed contribution that is added back into the feedback signal for the first iteration is **0**.

While the SER described above can be used in any suitable system, in one embodiment, the SER is used to estimate sub-array paths (e.g., transmit or receive paths) in a base station having an antenna array including multiple sub-arrays. In this regard, FIG. **5** illustrates a cellular network **28** including a base station **30** that transmits radio signals to and receives radio signals from a number of wireless devices **32** and, in some embodiments, transmits radio signals to and receives radio signals from a number of network nodes **34** (e.g., other base stations using a wireless backhaul network). The base station **30** includes an antenna array including multiple sub-arrays. Radio signals are provided to or received from the sub-arrays by corresponding channels, which are defined by corresponding sub-array paths. In one embodiment, the sub-array paths are more particularly transmit paths through which radio signals are provided to the sub-arrays for transmission. However, in another embodiment, the sub-array paths are receive paths through which radio signals received by the sub-arrays are processed. In this embodiment, the base station **30** includes a SER ring that operates to estimate impulse responses of the sub-array paths in a distributed manner.

FIG. **6** illustrates the base station **30** in more detail according to one embodiment of the present disclosure. As illustrated, the base station **30** includes a baseband unit **36**, a radio unit **38**, an antenna array **40**, and feeders **42-1** through **42**-M (generally referred to herein collectively as feeders **42** and individually as a feeder **42**) connected as shown. The radio unit **38** includes multiple (M) branches formed by equalizers **44-1** through **44**-M and transmit chains **46-1** through **46**-M. In addition, the radio unit **38** includes a SER formed by SER coordinated processing components **48-1** through **48**-M, and equalizer synthesis components **50-1** through **50**-M that operate to configure the equalizers **44-1** through **44**-M based on estimates from the corresponding SER coordinated processing components **48-1** through **48**-M.

The radio unit **38** also includes connectors **52-1** through **52**-M by which outputs of the transmit chains **46-1** through **46**-M are connected to first ends of the feeders **42-1** through **42**-M, respectively. The feeders **42-1** through **42**-M are cables that interconnect the radio unit **38** and the antenna array **40**. Second ends of the feeders **42-1** through **42**-M are connected to corresponding connectors **54-1** through **54**-M of the antenna array **40**. Within the antenna array **40**, multiple sub-arrays **56-1** through **56**-M are connected to the feeders **42-1** through **42**-M, respectively, via corresponding couplers **58-1** through **58**-M and the connectors **54-1** through **54**-M.

In this embodiment, the transmit chain **46-1**, the connector **52-1**, the feeder **42-1**, the connector **54-1**, and the coupler **58-1** form a transmit path **60-1** having a corresponding impulse response H_1 by which an input signal S_1 of the transmit chain **46-1** is transformed to provide an output signal $S_{1,OUT}$ to the corresponding sub-array **56-1**. Together, the transmit path **60-1** and the SER coordinated processing component **48-1** form a first module **62-1**. Likewise, the transmit chain **46-2**, the connector **52-2**, the feeder **42-2**, the connector **54-2**, and the coupler **58-2** form a transmit path having a corresponding impulse response H_2 by which an input signal S_2 of the transmit chain **46-2** is transformed to provide an output signal $S_{2,OUT}$ to the corresponding sub-array **56-2**. Together, the transmit path and the SER coordinated processing component **48-2** form a second module. In the same manner, the transmit chain **46**-M, the connector **52**-M, the feeder **42**-M, the connector **54**-M, and the coupler **58**-M form a transmit path **60**-M having a corresponding impulse response H_M by which an input signal S_M of the transmit chain **46**-M is transformed to provide an output signal $S_{M,OUT}$ to the corresponding sub-array **56**-M. Together, the transmit path **60**-M and the SER coordinated processing component **48**-M form an Mth module **62**-M.

In operation, the baseband unit **36** outputs baseband input signals $S_{1,BB}$ through $S_{M,BB}$, which are baseband representations of radio signals to be transmitted by the base station **30**. The equalizers **44-1** through **44**-M process the baseband input signals $S_{1,BB}$ through $S_{M,BB}$ to compensate or correct for the impulse responses H_1 through H_M of the transmit paths **60-1** through **60**-M, as estimated by the SER, and thereby provide the input signals S_1 through S_M of the transmit chains **46-1** through **46**-M. In particular, the equalizer synthesis components **50-1** through **50**-M configure the equalizers **44-1** through **44**-M to apply an inverse of the estimated impulse responses of the transmit paths **60-1** through **60**-M, respectively. Notably, while not illustrated, the baseband input signals $S_{1,BB}$ through $S_{M,BB}$ may be conditioned by corresponding conditioning component(s) prior to equalization if the baseband input signals $S_{1,BB}$ through $S_{M,BB}$ are correlated. In other words, the input signals S_1 through S_M should be uncorrelated. If they are not, then conditioning may be performed in order to remove the correlation between the input signals S_1 through S_M. While not essential, the interested reader can refer to U.S. patent application Ser. No. 13/894,826 for a discussion on one example conditioning process.

The input signals S_1 through S_M are then processed by the transmit chains **46-1** through **46**-M (e.g., upconversion, amplification, filtering, etc.). The resulting radio signals are then provided to the corresponding antenna sub-arrays **56-1** through **56**-M via the connectors **52-1** through **52**-M, the feeders **42-1** through **42**-M, the connectors **54-1** through **54**-M, and the couplers **58-1** through **58**-M. Significant non-linearities in the transmit paths **60-1** through **60**-M (e.g., non-linearities of power amplifiers in the transmit chains **46-1** through **46**-M) are typically taken care of by non-linear predistortion techniques. To calibrate and compensate for the linear impairment of phase and/or amplitude in the transmit paths **60-1** through **60**-M, the SER operates to estimate the impulse responses H_1 through H_M of the transmit paths **60-1** through **60**-M in the manner described above. The estimates of the impulse responses H_1 through H_M are then used by the equalizer synthesis components **50-1** through **50**-M to set the equalizers **44-1** through **44**-M to apply an inverse of the estimated impulse responses H_1 through H_M, respectively, and thereby correct, or compensate, for the linear impairment of phase and/or amplitude in the transmit paths **60-1** through **60**-M.

In order to estimate the impulse responses H_1 through H_M, the SER operates in the manner described above. Specifically, for an initial or first iteration of the SER, the SER coordinated processing component **48-1** receives a combined feedback signal S_{FB}^{11} from a summation component **64** in the antenna array **40** via a feedback receiver **66**. The summation component **64** operates to sum the output signals $S_{1,OUT}$ through $S_{M,OUT}$. The feedback receiver **66** operates to receive (e.g., downconvert and digitize) the combined feedback signal S_{FB}^{11}. The SER coordinated processing component **48-1** then computes an estimate of the impulse response H_1 of the transmit path **60-1** for the first iteration, which is referred to as the estimate H_{11} of the impulse response H_1 of the transmit path **60-1**, based on the combined feedback signal S_{FB}^{11} and the input signal S_1. The SER coordinated processing component **48-1** then removes a contribution (i.e., S_1*H_{11}) of the transmit path **60-1** from the combined feedback signal S_{FB}^{11} to thereby provide a feedback signal S_{FB}^{21} for the next SER coordinated processing component **48** in the SER, which is the SER coordinated processing component **48-2**. The SER coordinated processing component **48-1** then outputs the feedback signal S_{FB}^{21} for the SER coordinated processing component **48-2**.

Likewise, upon receiving the feedback signal S_{FB}^{21}, the SER coordinated processing component **48-2** computes an estimate of the impulse response H_2 of the transmit path **60-2** (i.e., the transmit path formed by the transmit chain **46-2**, the connector **52-2**, the feeder **42-2**, the connector **54-2**, and the coupler **58-2**) for the first iteration, which is referred to as the estimate H_{21} of the impulse response H_2 of the transmit path **60-2**, based on the feedback signal S_{FB}^{21} and the input signal S_2. The SER coordinated processing component **48-2** then removes a contribution (i.e., S_2*H_{21}) of the transmit path **60-2** from the feedback signal S_{FB}^{21} to thereby provide a feedback signal S_{FB}^{31} for the next SER coordinated processing component **48** in the SER, which is the SER coordinated processing component **48-3** (not shown). The SER coordinated processing component **48-2** then outputs the feedback signal S_{FB}^{31}.

The first iteration of the SER continues in this manner until the SER coordinated processing component **48**-M receives a feedback signal S_{FB}^{M1} from its preceding SER coordinated processing component **48**-(M−1) in the SER. Upon receiving the feedback signal S_{FB}^{M1}, the SER coordinated processing component **48**-M computes an estimate of the impulse response H_M of the transmit path **60**-M for the first iteration, which is referred to as the estimate H_{M1} of the impulse response H_M of the transmit path **60**-M, based on the feedback signal S_{FB}^{M1} and the input signal S_M. The SER coordinated processing component **48**-M then removes a contribution (i.e., S_M*H_{M1}) of the transmit path **60**-M from the feedback signal S_{FB}^{M1} to thereby provide a feedback signal Sa for the next SER coordinated processing component **48** in the SER, which is the SER coordinated processing component **48-1** (i.e., the feedback signal S_{FB}^{12} is the feedback signal for the SER coordinated processing component **48-1** for a second iteration of the SER). The SER coordinated processing component **48**-M then outputs the feedback signal S_{FB}^{12} to the SER coordinated processing component **48-1** for the second iteration of the SER.

Next, a second iteration of the SER is performed. In the second iteration of the SER, the SER coordinated processing component **48-1** first adds the contribution (i.e., S_1*H_{11}) of the transmit path **60-1** removed in the previous iteration of the SER back into the feedback signal S_{FB}^{12} to thereby provide a modified feedback signal $S_{FB}^{12\prime}$. The SER coordinated processing component **48-1** then computes a new estimate of the impulse response H_1 of the transmit path **60-1** for the second iteration, which is referred to as the estimate H_{12} of the impulse response H_1 of the transmit path **60-1**, based on the modified feedback signal $S_{FB}^{12\prime}$ and the input signal S_1. The SER coordinated processing component **48-1** then removes a contribution (i.e., S_1*H_{12}) of the transmit path **60-1** from the modified feedback signal $S_{FB}^{12\prime}$ to thereby provide a feedback signal S_{FB}^{22} for the next SER coordinated processing component **48** in the SER, which is the SER coordinated processing component **48-2**. The SER coordinated processing component **48-1** then outputs the feedback signal S_{FB}^{22} for the SER coordinated processing component **48-2**.

Likewise, upon receiving the feedback signal S_{FB}^{22}, the SER coordinated processing component **48-2** adds the contribution (i.e., S_2*H_{21}) of the transmit path **60-2** removed in the previous iteration of the SER back into the feedback signal S_{FB}^{22} to thereby provide a modified feedback signal $S_{FB}^{22\prime}$. The SER coordinated processing component **48-2** then computes a new estimate of the impulse response H_2 of the transmit path **60-2** for the second iteration, which is referred to as the estimate H_{22} of the impulse response H_2 of the transmit path **60-2**, based on the modified feedback signal $S_{FB}^{22\prime}$ and the input signal S_2. The SER coordinated processing component **48-2** then removes a contribution (i.e., S_2*H_{22}) of the transmit path **60-2** from the modified feedback signal $S_{FB}^{22\prime}$ to thereby provide a feedback signal S_{FB}^{32} for the next SER coordinated processing component **48** in the SER, which is the SER coordinated processing component **48-3**. The SER coordinated processing component **48-2** then outputs the feedback signal S_{FB}^{32} for the SER coordinated processing component **48-3**.

The second iteration of the SER continues in this manner until the final SER coordinated processing component **48**-M receives a feedback signal S_{FB}^{M2} from its preceding SER coordinated processing component **48**-(M−1) in the SER. Upon receiving the feedback signal S_{FB}^{M2}, the SER coordinated processing component **48**-M adds the contribution (i.e., S_M*H_{M1}) of the transmit path **60**-M removed in the previous iteration of the SER back into the feedback signal S_{FB}^{M2} to thereby provide a modified feedback signal $S_{FB}^{M2\prime}$. The SER coordinated processing component **48**-M then computes a new estimate of the impulse response H_M of the transmit path **60**-M for the second iteration, which is referred to as the estimate H_{M2} of the impulse response H_M of the transmit path **60**-M, based on the modified feedback signal $S_{FB}^{M2\prime}$ and the input signal S_M. The SER coordinated processing component **48**-M then removes a contribution (i.e., S_M*H_{M2}) of the transmit path **60**-M from the modified feedback signal $S_{FB}^{M2\prime}$ to thereby provide a feedback signal S_{FB}^{13} for the next SER coordinated processing component **48** in the SER, which is the SER coordinated processing component **48-1**. The SER coordinated processing component **48**-M then outputs the feedback signal S_{FB}^{13} for the SER coordinated processing component **48-1**.

Iterations of the SER continue in this manner until a final iteration of the SER is reached. Note that the desired number of iterations is, in one embodiment, greater than or equal to 2. In another embodiment, the number of iterations is greater than or equal to 8. Note that the number of iterations performed is, in one embodiment, a tradeoff between accuracy and time.

In the final iteration, the SER coordinated processing component **48-1** receives a feedback signal S_{FB}^{1N} from the SER coordinated processing component **48**-M, where N is the number of iterations performed by the SER. Upon receiving the feedback signal sit the SER coordinated processing component **48-1** adds the contribution (i.e., $S_1H*_{1(N-1)}$) of the transmit path **60-1** removed in the previous iteration (i.e., the (N−1)th iteration) of the SER back into the feedback signal S_{FB}^{1N} to thereby provide a modified feedback signal $S_{FB}^{1N\prime}$. The SER coordinated processing component **48-1** then computes a new estimate of the impulse response H_1 of the transmit path **60-1** for the Nth iteration, which is referred to as the estimate H_{1N} of the impulse response H_1 of the transmit path **60-1**, based on the modified feedback signal $S_{FB}^{1N\prime}$ and the input signal S_1. The SER coordinated processing component **48-1** then removes a contribution (i.e., S_1*H_{1N}) of the transmit path **60-1** from the modified feedback signal $S_{FB}^{1N\prime}$ to thereby provide a feedback signal S_{FB}^{2N} for the next SER coordinated processing component **48** in the SER, which is the SER coordinated processing component **48-2**. The SER coordinated processing component **48-1** then outputs the feedback signal S_{FB}^{2N} for the SER coordinated processing component **48-2**.

Likewise, upon receiving the feedback signal S_{FB}^{2N}, the SER coordinated processing component **48-2** adds the contribution (i.e., $S_2*H_{2(N-1)}$) of the transmit path **60-2** removed in the previous iteration (i.e., the (N−1)th iteration) of the SER back into the feedback signal S_{FB}^{2N} to thereby provide a modified feedback signal $S_{FB}^{2N\prime}$. The SER coordinated processing component **48-2** then computes a new estimate of the impulse response H_2 of the transmit path **60-2** for the Nth iteration, which is referred to as the estimate H_{2N} of the impulse response H_2 of the transmit path **60-2**, based on the modified feedback signal Sir and the input signal S_2. The SER coordinated processing component **48-2** then removes a contribution (i.e., S_2*H_{2N}) of the transmit path **60-2** from the modified feedback signal $S_{FB}^{2N\prime}$ to thereby provide a feedback signal S_{FB}^{3N} for the next SER coordinated processing component **48** in the SER, which is the SER coordinated processing component **48-3**. The SER coordinated processing component **48-2** then outputs the feedback signal S_{FB}^{3N} for the SER coordinated processing component **48-3**.

The Nth (or final) iteration of the SER continues in this manner until the final SER coordinated processing component **48**-M receives a feedback signal S_{FB}^{MN} from its preceding SER coordinated processing component **48**-(M−1) in the SER. Upon receiving the feedback signal S_{FB}^{MN}, the SER coordinated processing component **48**-M adds the contribution (i.e., $S_M*H_{M(N-1)}$) of the transmit path **60**-M removed in the previous iteration (i.e., the (N−1)th iteration) of the SER back into the feedback signal S_{FB}^{MN} to thereby provide a modified feedback signal $S_{FB}^{MN\dagger}$. The SER coordinated processing component **48**-M then computes a new estimate of the impulse response H_M of the transmit path **60**-M for the Nth iteration, which is referred to as the estimate H_{MN} of the impulse response H_M of the transmit path **60**-M, based on the modified feedback signal $S_{FB}^{MN\dagger}$ and the input signal S_M.

At this point, the process is complete. The estimates H_{1N} through H_{MN} are the final estimates of the impulse responses H_1 through H_M of the transmit paths **60-1** through **60**-M. The final estimates of the impulse responses H_1 through H_M of the transmit paths **60-1** through **60**-M are then used by the equalizer synthesis components **50-1** through **50**-M to configure the equalizers **44-1** through **44**-M to correct or compensate for linear distortions (i.e., to equalize) of the transmit paths **60-1** through **60**-M. Notably, during operation, the estimation process performed by the SER may be repeated as desired in order to update the final estimates of the impulse responses H_1 through H_M of the transmit paths **60-1** through **60**-M over time in order to account for changes in the impulse responses H_1 through H_M of the transmit paths **60-1** through **60**-M.

FIG. **7** illustrates the base station **30** according to another embodiment of the present disclosure. This embodiment is similar to that of FIG. **6** but where the base station **30** includes multiple radio units **38-1** through **38**-M. The transmit chains **46-1** through **46**-M together with the SER coordinated processing components **48-1** through **48**-M are implemented in different radio units **38**. Thus, the transmit chain **46-1** and the SER coordinated processing component **48-1** are implemented in the radio unit **38-1**, the transmit chain **46-2** and the SER coordinated processing component **48-2** are implemented in the radio unit **38-2**, etc. Note that while all of the transmit chains **46-1** through **46**-M and their corresponding SER coordinated processing components **48-1** through **48**-M are implemented in different radio units **38** in this embodiment, in an alternative embodiment, some of the transmit chains **46-1** through **46**-M and their corresponding SER coordinated processing components **46-1** through **46**-M may be implemented in the same radio unit **38**. For example, the transmit chains **46-1** and **46-2** and the corresponding SER coordinated processing components **48-1** and **48-2** may all be implemented in a single radio unit **38**, where the rest of the transmit chains **46-3** through **46**-M and the corresponding SER coordinated processing components **48-3** through **48**-M may be implemented in different radio units **38**.

In this embodiment, the feedback receiver **66** is shown as being implemented external to the radio units **38-1** through **38**-M. However, in another embodiment, the feedback receiver **66** may be implemented in one or all of the radio units **38-1** through **38**-M (e.g., each of the radio units **38-1** through **38**-M may include a feedback receiver such that a SER coordinated processing component **48** of any one of the radio units **38-1** through **38**-M can be utilized as the first SER coordinated processing component in the SER). Also, the feedback signals S_{FB}^{mi} are sent between the SER coordinated processing components **48-1** through **48**-M via the baseband unit **36** in this embodiment. However, the feedback signals S_{FB}^{mi} may alternatively be communicated directly between the different radio units **38-1** through **38**-M.

FIGS. **8** through **10** illustrate simulation results for one example implementation of the SER of FIGS. **6** and **7** where M=4 and N=8. In particular, FIGS. **8** through **10** illustrate the impairment estimation and phase accuracy over frequency after the first iteration of the SER, after the second iteration of the SER, and after the eighth iteration of the SER, respectively. From FIG. **8**, it can be seen that the phase accuracy is relatively poor at ±12 degrees after the first iteration. However, as can be seen from FIG. **10**, the phase accuracy improves to a nearly ideal ±0.3 degrees after only eight iterations of the SER.

The SER coordinated processing components **24** and **48** described above can be implemented in any suitable manner. In one embodiment, each SER coordinated processing component **24**, **48** is implemented in hardware or a combination of hardware and software (e.g., at least one processor executing software that instructs the processor to provide the functionality of the SER coordinated processing component **24**, **48** according to any of the embodiments described herein). In another embodiment, a computer program is provided that includes instructions which, when executed on at least one processor, cause the at least one processor to carry out any of the methods of operation of a SER coordinated processing component **24**, **48** discussed above. In another embodiment, a carrier containing the aforementioned computer program is provided, where the carrier is one of an electronic signal, an optical signal, a radio signal, or a computer readable storage medium (e.g., a non-transitory computer readable medium).

While not being limited by any particularly advantage(s), some embodiments of the SER disclosed herein allow for a simplified configuration for coordinated impulse response estimation processing in modular and scalable systems. In addition, some embodiments allow for processing to be distributed across modules and, therefore, lead to less processing per module compared to a centralized architecture. Still further, the number of interconnects between modules is reduced as compared to a centralized architecture. Due to the ring topology, the SER allows unlimited scalability with reduced cost and complexity.

The following acronyms are used throughout this disclosure.

4G 4^{th} Generation

5G 5^{th} Generation

SER Scalable Estimation Ring

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 and the claims that follow.

What is claimed is:

1. A base station for a wireless network that performs calibration of an antenna array to remove distortion incurred by a plurality of transmit paths in the base station, the antenna array including a plurality of sub-arrays each connected to a corresponding one of the plurality of transmit paths, the base station comprising:

a feedback receiver configured to receive a combined radio frequency feedback signal and output a combined feedback signal, the combined radio frequency feedback signal being a summation of a plurality of output signals of the plurality of transmit paths in response to a plurality of input signals; and

a scalable estimation ring configured to estimate impulse responses of the plurality of transmit paths based on the combined feedback signal in a distributed manner, the scalable estimation ring comprising a plurality of scalable estimation ring coordinated processing components each operating to estimate the impulse response of a corresponding one of the plurality of transmit paths.

2. The base station of claim **1** wherein each transmit path of the plurality of transmit paths comprises a transmit chain, a feeder having a first end connected to an output of the transmit chain and a second end, and a coupler configured to connect the second end of the feeder to a corresponding one of the plurality of sub-arrays.

3. The base station of claim **2** wherein the transmit chains of the plurality of transmit paths are implemented in a single radio unit.

4. The base station of claim **2** wherein the transmit chains of the plurality of transmit paths are implemented in different radio units.

5. The base station of claim **2** wherein the transmit chains of at least two of the plurality of transmit paths are implemented in different radio units.

6. The base station of claim **1** wherein, in order to estimate the impulse responses of the plurality of transmit paths, for an initial iteration of the scalable estimation ring, each scalable estimation ring coordinated processing component of the plurality of scalable estimation ring coordinated processing components in the scalable estimation ring is configured to:

receive a feedback signal for the scalable estimation ring coordinated processing component;

compute an initial estimate of the impulse response of a corresponding transmit path of the plurality of transmit paths based on the feedback signal for the scalable estimation ring coordinated processing component;

remove a contribution of the corresponding transmit path from the feedback signal for the scalable estimation ring coordinated processing component based on the initial estimate of the impulse response of the corresponding transmit path to thereby provide a feedback signal for a next scalable estimation ring coordinated processing component in the scalable estimation ring; and

output the feedback signal for the next scalable estimation ring coordinated processing component in the scalable estimation ring.

7. The base station of claim **6** wherein:

for a first scalable estimation ring coordinated processing component in the scalable estimation ring, the feedback signal for the initial iteration is the combined feedback signal from the feedback receiver; and

for each additional scalable estimation ring coordinated processing component in the scalable estimation ring, the feedback signal for the initial iteration is the feedback signal output by a preceding scalable estimation ring coordinated processing component in the scalable estimation ring for the initial iteration.

8. The base station of claim **7** wherein, in order to estimate the impulse responses of the plurality of transmit paths, for a second iteration of the scalable estimation ring, each scalable estimation ring coordinated processing component of the plurality of scalable estimation ring coordinated processing components in the scalable estimation ring is configured to:

receive a new feedback signal output by a preceding scalable estimation ring coordinated processing component in the scalable estimation ring;

add the contribution of the corresponding transmit path removed in the initial iteration of the scalable estimation ring into the new feedback signal to thereby provide a modified new feedback signal;

compute a new estimate of the impulse response of the corresponding transmit path based on the modified new feedback signal;

remove a contribution of the corresponding transmit path from the modified new feedback signal based on the new estimate of the impulse response of the corresponding transmit path to thereby provide a new feedback signal for the next scalable estimation ring coordinated processing component in the scalable estimation ring; and

output the new feedback signal for the next scalable estimation ring coordinated processing component in the scalable estimation ring.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 9,270,493 B2
APPLICATION NO. : 14/191005
DATED : February 23, 2016
INVENTOR(S) : Da Silveira et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In the Specification

In Column 8, Line 45, delete "S_{FB}^{21}" and insert -- S_{FB}^{21} and --, therefor.

In Column 11, Line 1, delete "$S_{FB}^{22'}$" and insert -- S_{FB}^{22}, --, therefor.

In Column 12, Line 18, delete "(H_m-H_{M1})" and insert -- (H_M-H_{M1}) --, therefor.

In Column 12, Line 39, delete "$S_1H{*}H_{12}, \ldots, S_{(M-1)}{*}H_{(M-1)2}$" and insert -- $S_1 * H_{12}, \ldots, S_{(M-1)} * H_{(M-1)2}$ --, therefor.

In Column 19, Line 17, delete "Sa" and insert -- S_{FB}^{12} --, therefor.

In Column 20, Line 32, delete "sit" and insert -- S_{FB}^{1N}, --, therefor.

In Column 20, Line 61, delete "Sir" and insert -- S_{FB}^{21} --, therefor.

Signed and Sealed this
Twenty-first Day of June, 2016

Michelle K. Lee

Michelle K. Lee
Director of the United States Patent and Trademark Office