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**Ray et al.**

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(54) **SYSTEMS AND METHODS FOR  
PARALLELIZING AND PIPELINING A  
TUNABLE BLIND SOURCE SEPARATION  
FILTER**

(71) Applicants: **THE BOEING COMPANY**, Chicago,  
IL (US); **HRL LABORATORIES**,  
Malibu, CA (US)

(72) Inventors: **Gary Alan Ray**, Issaquah, WA (US);  
**Peter Petre**, Oak Park, CA (US);  
**Charles E. Martin**, Thousand Okas,  
CA (US); **Shankar R. Rao**, Agoura  
Hills, CA (US)

(73) Assignees: **THE BOEING COMPANY**, Chicago,  
IL (US); **HRL LABORATORIES**,  
Malibu, CA (US)

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(2013.01)

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G01S 7/021  
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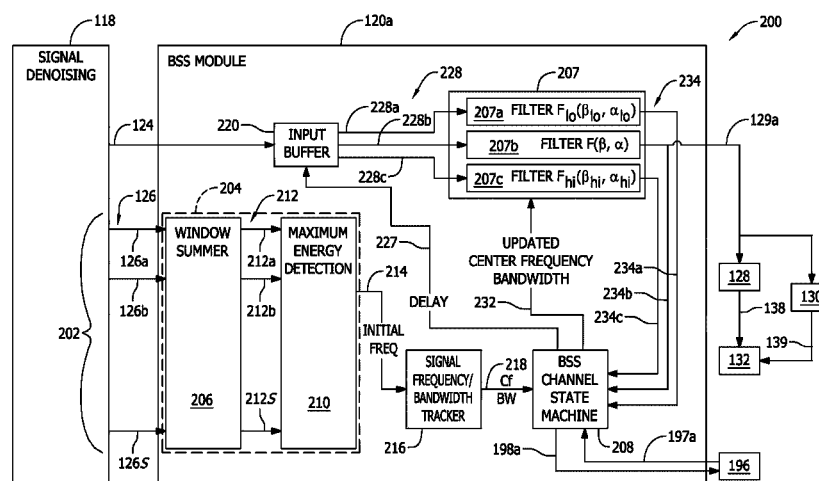
*Primary Examiner* — Aristocratis Fotakis

(74) *Attorney, Agent, or Firm* — Armstrong Teasdale LLP

(57) **ABSTRACT**

A method of processing a plurality of time-varying signals  
received at a sensor communicatively coupled to a signal  
data processor to identify at least one parameter of at least  
one of the plurality of time-varying signals is provided. The  
method includes receiving, at a plurality of blind source  
separation (BSS) modules of the signal data processor,  
signals derived from the plurality of time-varying signals,  
each BSS module of the plurality of BSS modules including  
a filtering subsystem having a pipelined architecture and a  
parallelized architecture. The method also includes gener-  
ating a plurality of blind source separated signals, and  
transmitting at least one pulse descriptor word (PDW)  
parameter vector signal to a computing device of the signal  
data processor. The method further includes identifying the  
at least one parameter from the at least one PDW parameter  
vector signal, and outputting the at least one parameter from  
the signal data processor.

**20 Claims, 12 Drawing Sheets**



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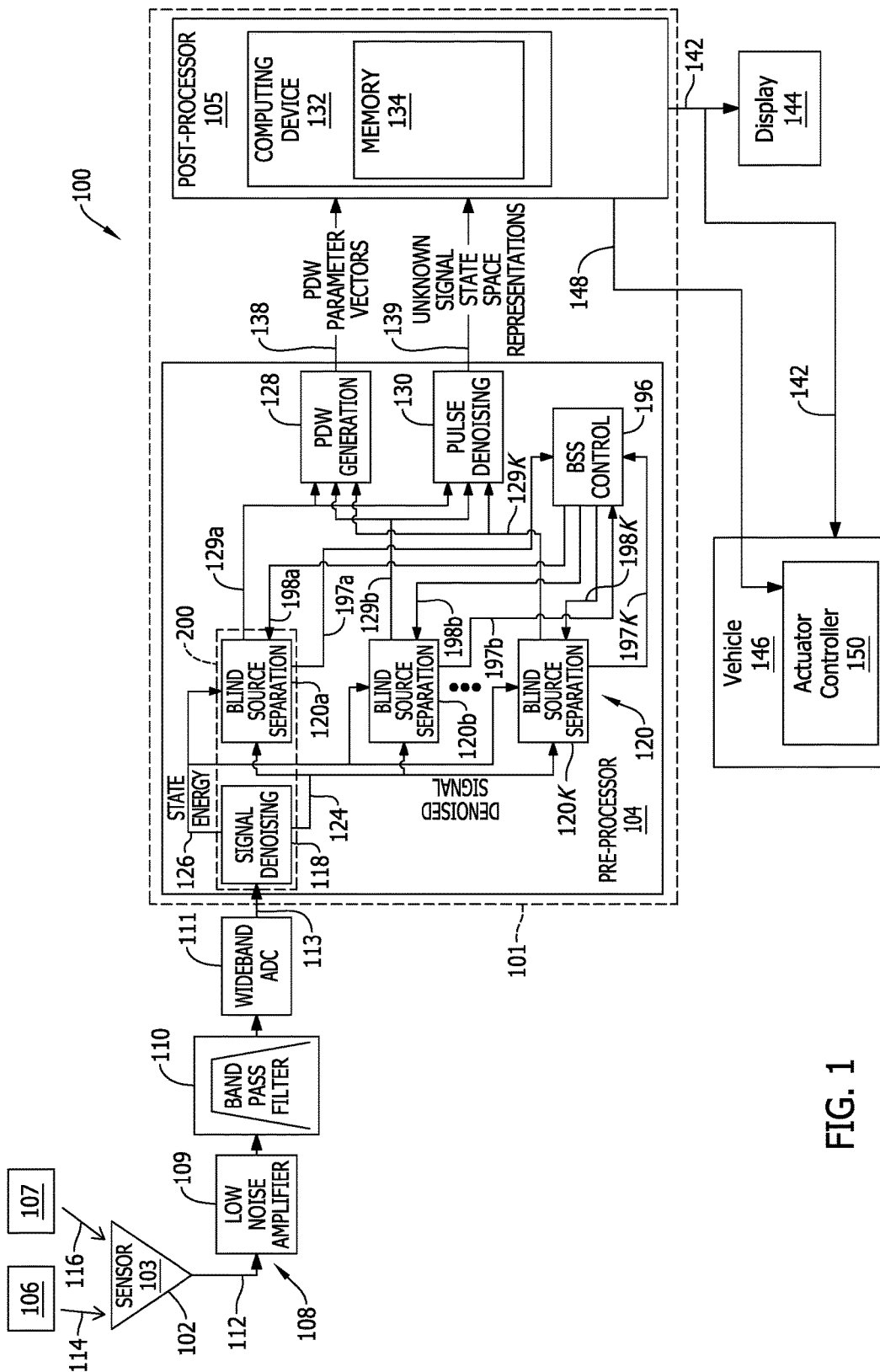


FIG. 1

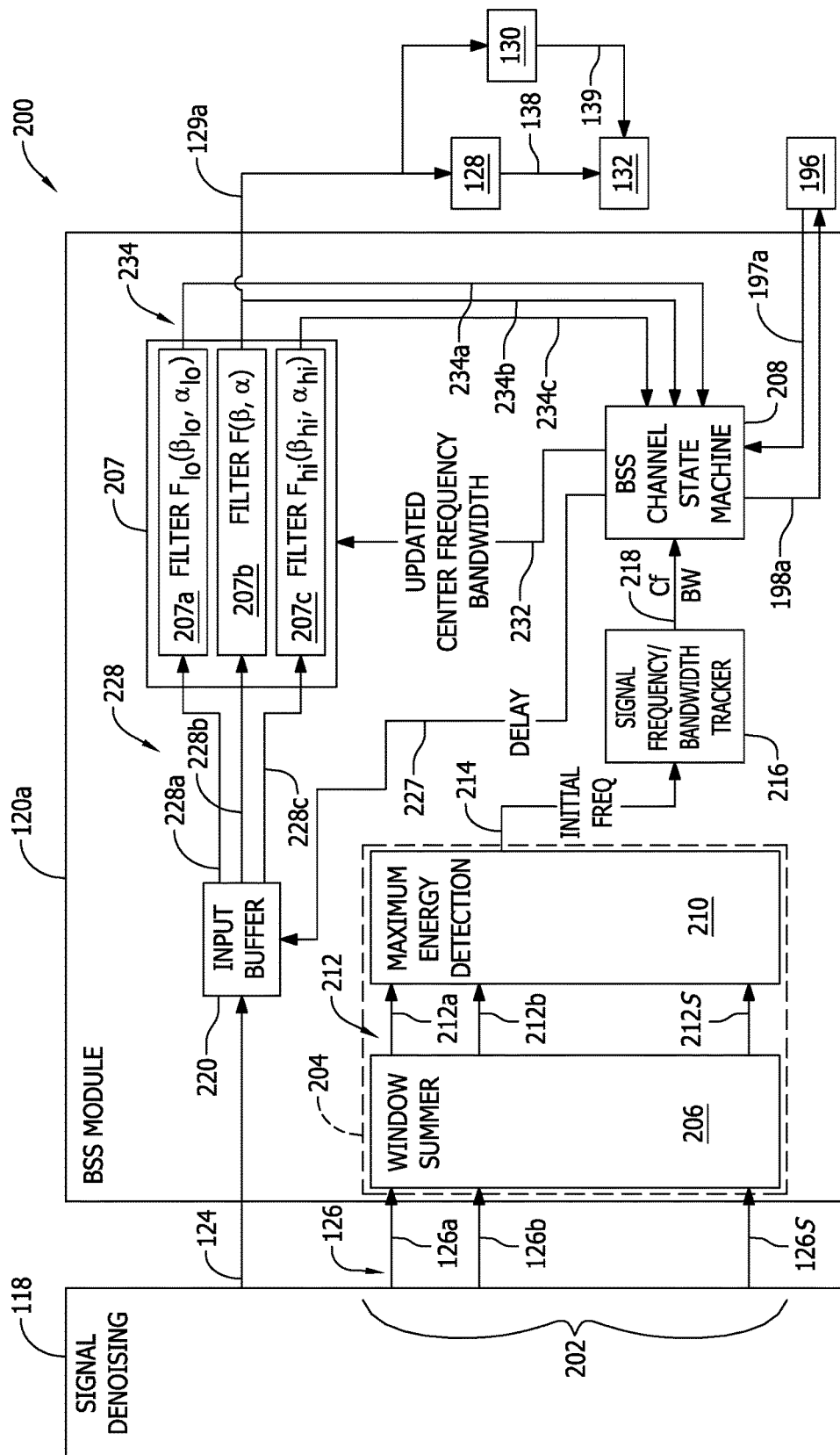


FIG. 2

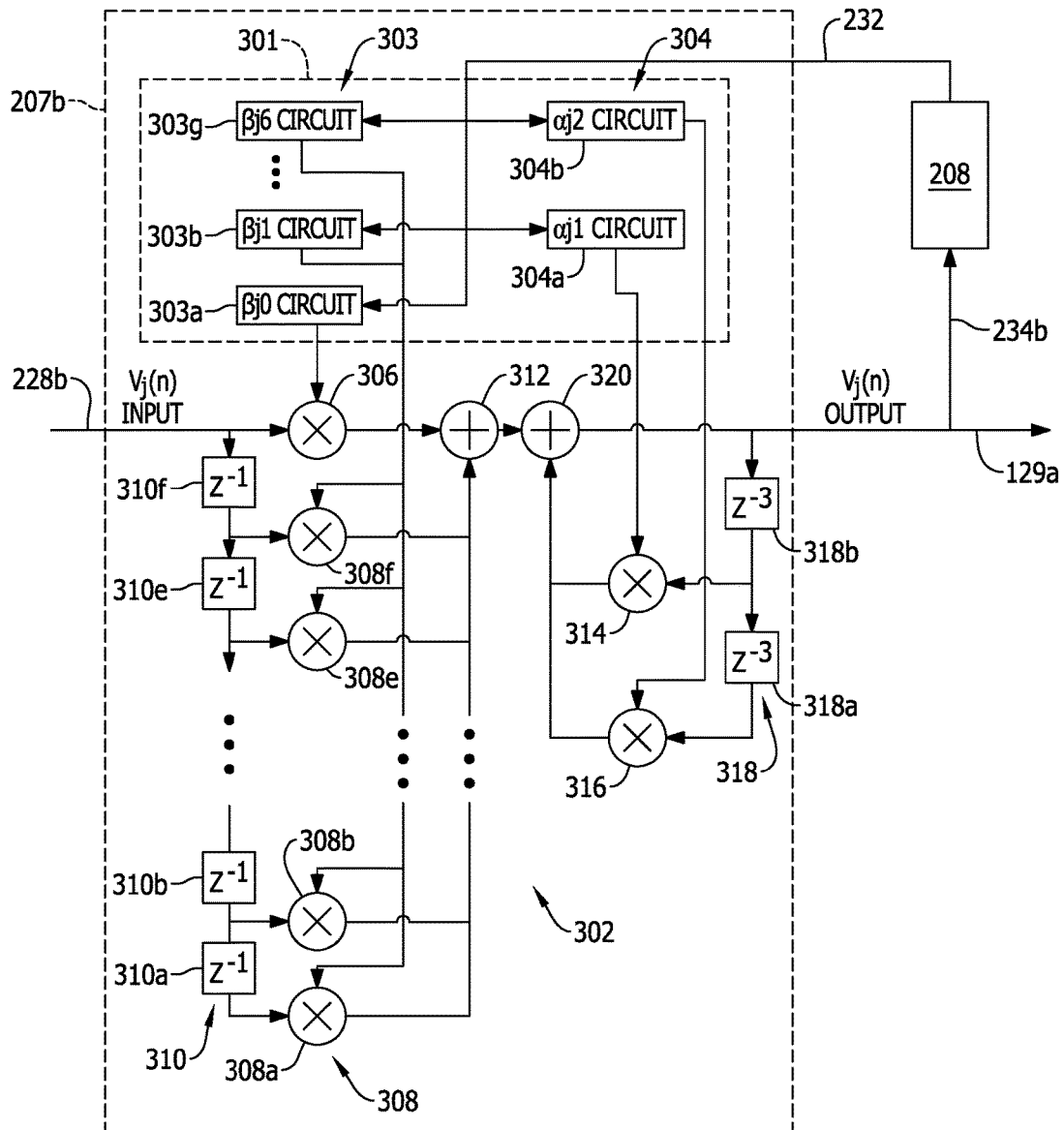


FIG. 3

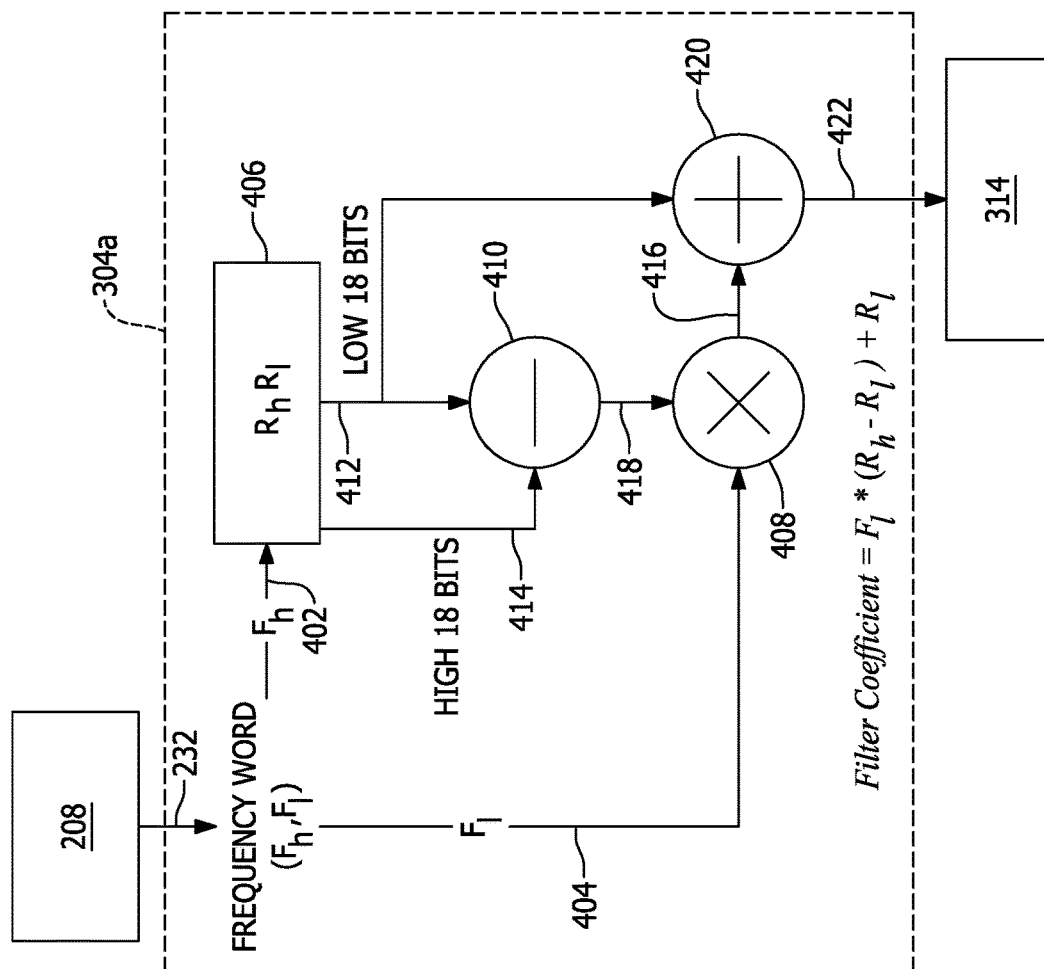


FIG. 4

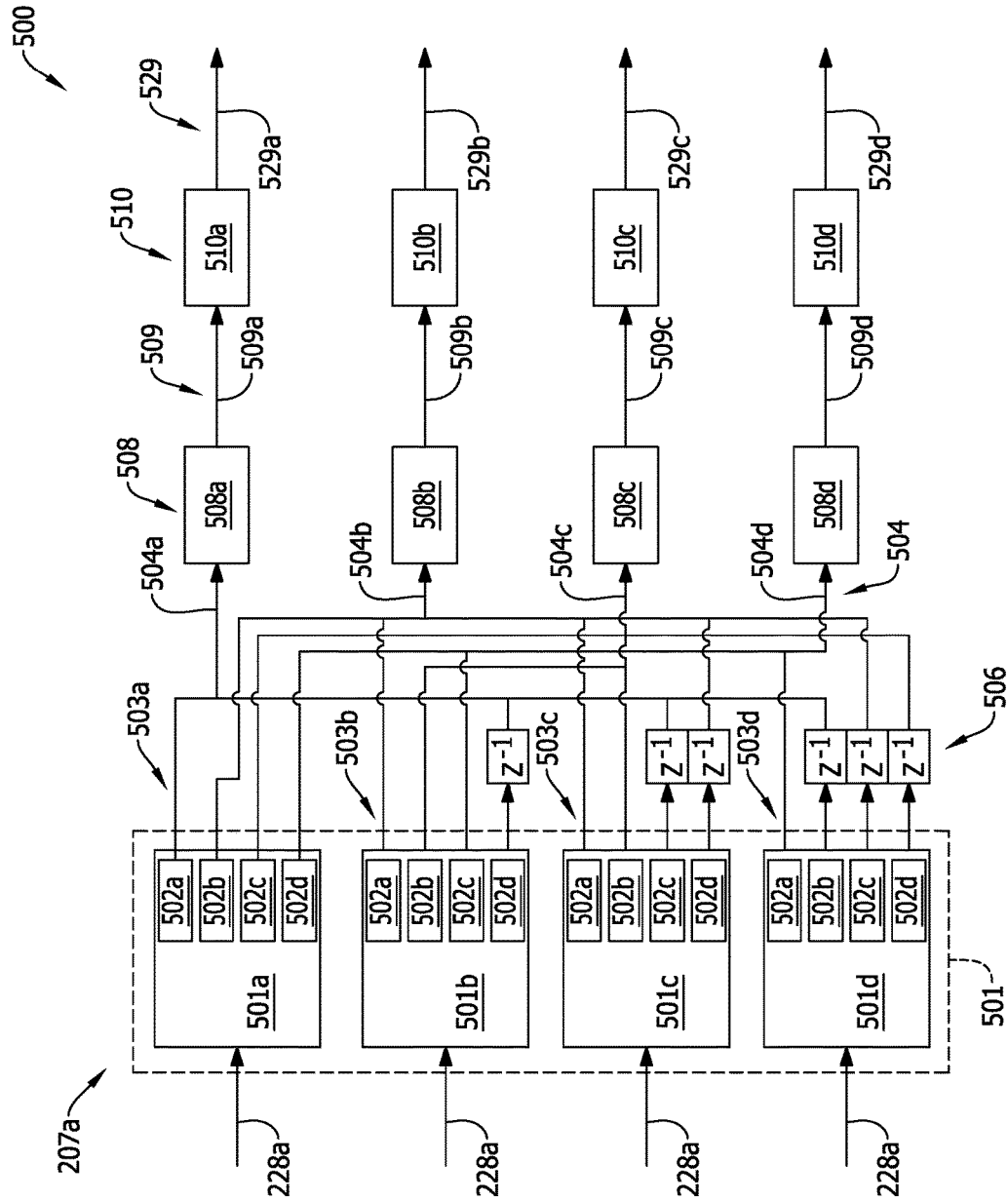


FIG. 5

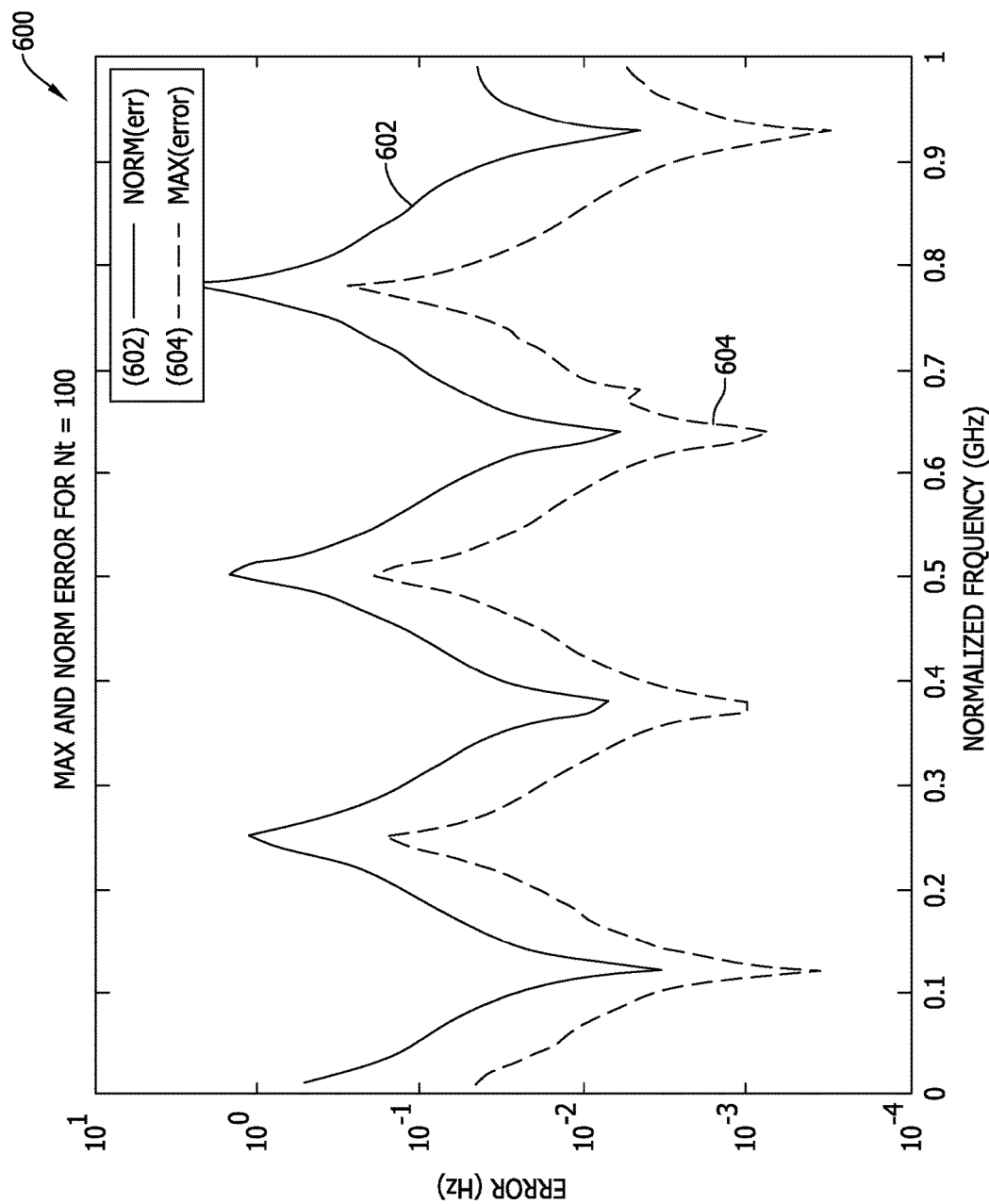


FIG. 6



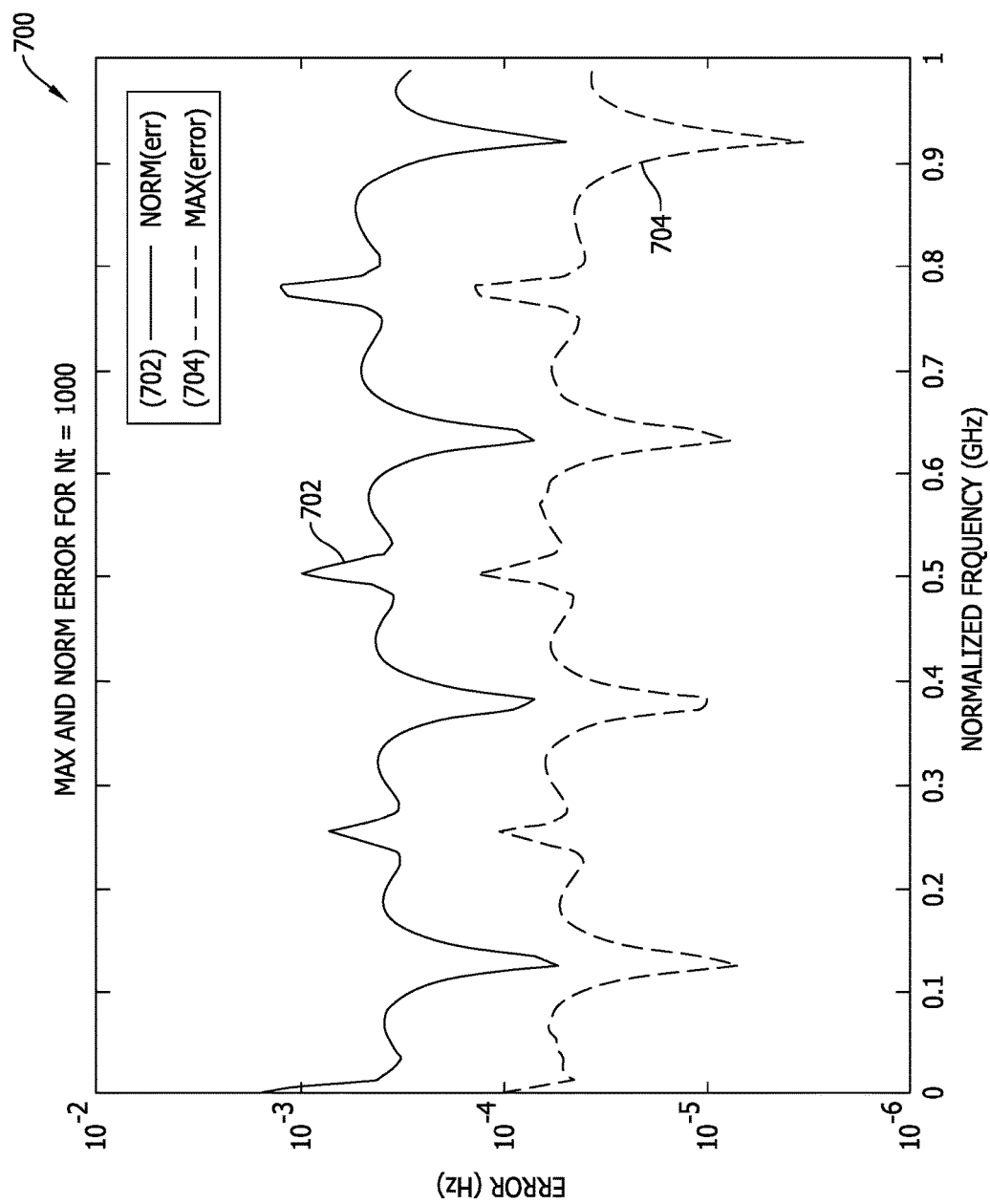


FIG. 7

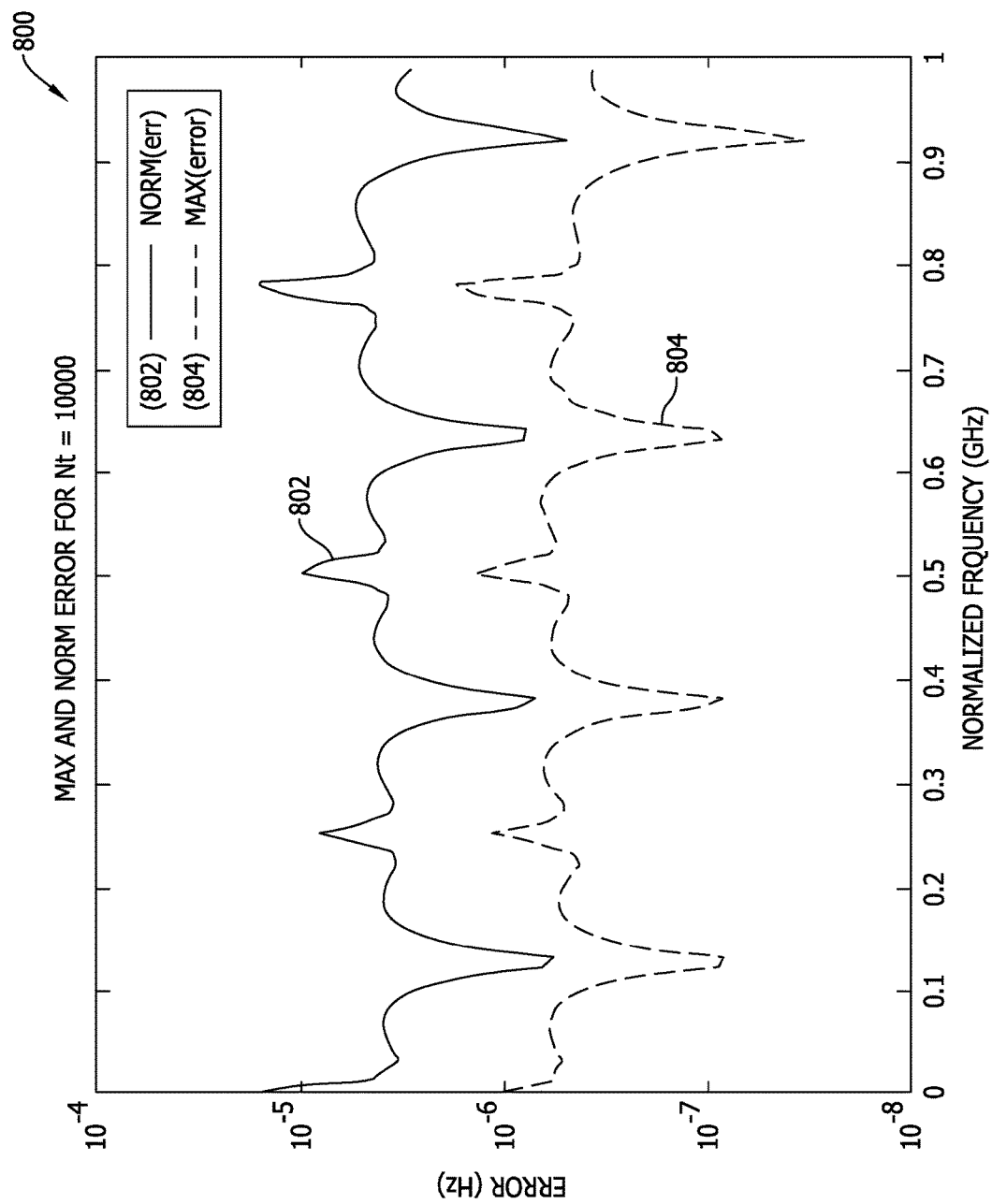


FIG. 8

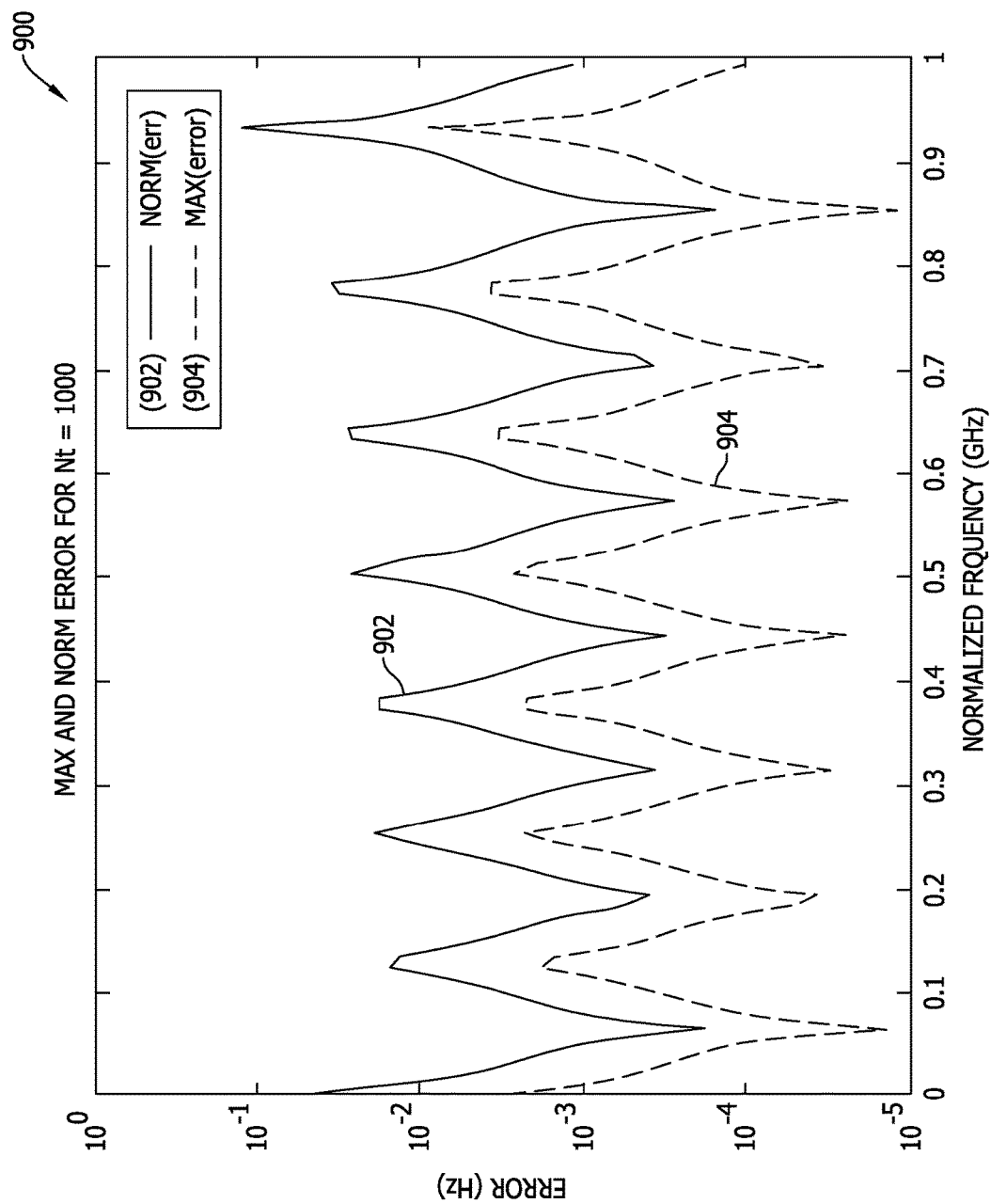


FIG. 9

**FIG. 10**

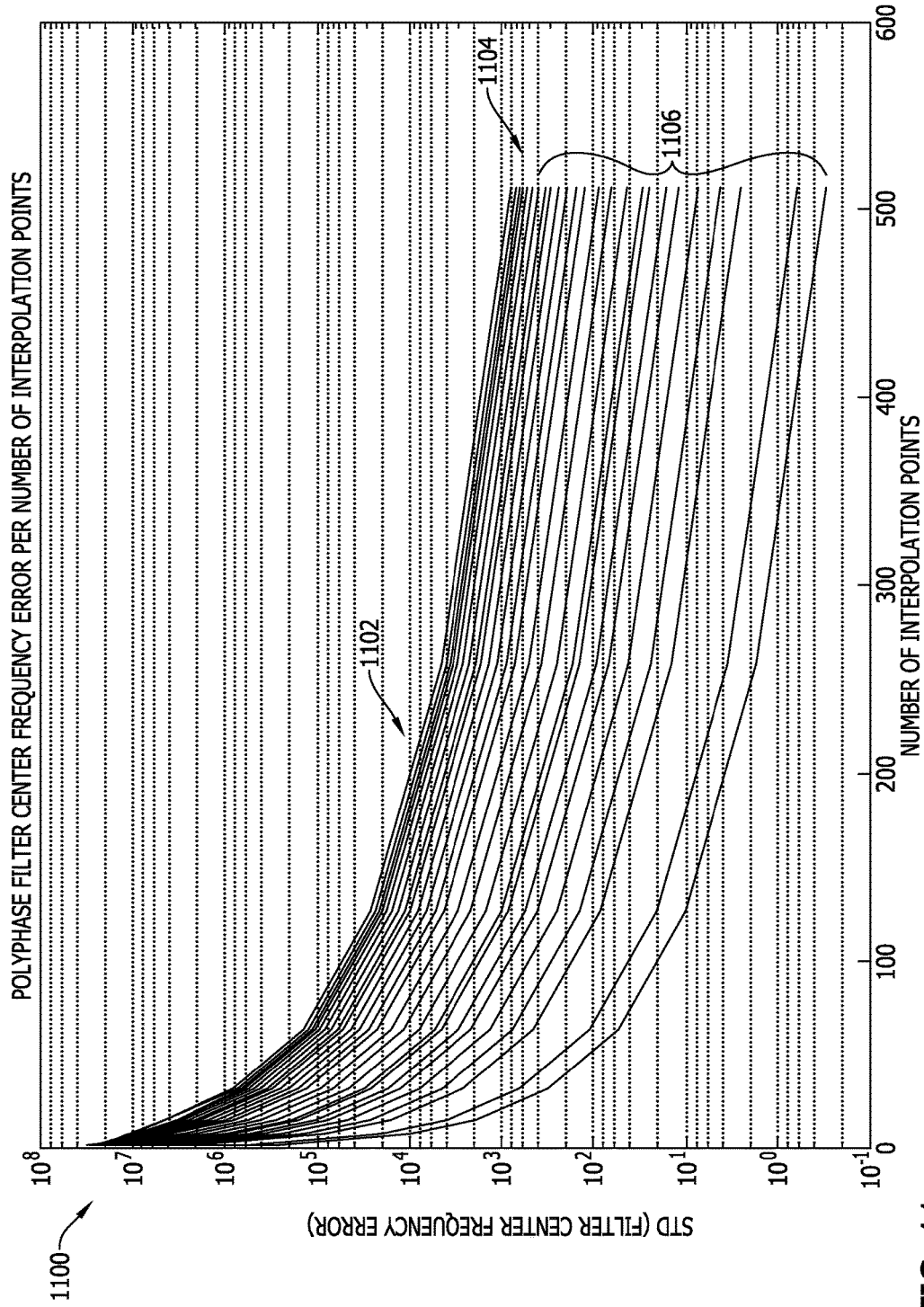


FIG. 11

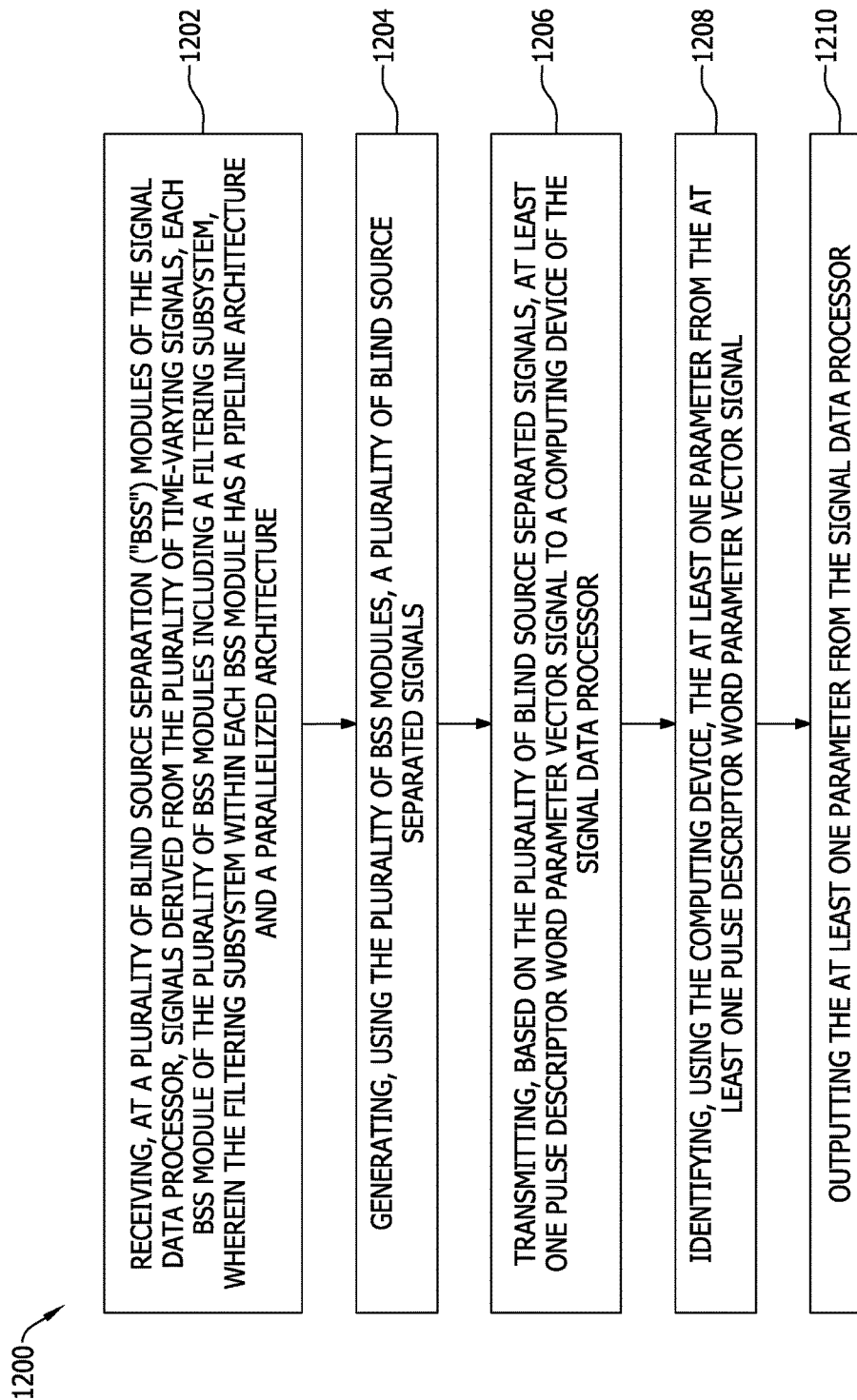


FIG. 12

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# SYSTEMS AND METHODS FOR PARALLELIZING AND PIPELINING A TUNABLE BLIND SOURCE SEPARATION FILTER

STATEMENT REGARDING FEDERALLY  
SPONSORED RESEARCH & DEVELOPMENT

This invention was made with Government support under N00014-12-C-0027 awarded by the Department of Defense. The government has certain rights in this invention.

## BACKGROUND

The field of the disclosure relates generally to separating and identifying signals of interest from a plurality of mixed signals, and, more specifically, to systems and methods for parallelizing and pipelining a tunable blind source separation filter.

In at least some known signal processing systems, a plurality of mixed signals (e.g., radar signals) are received by a sensor communicatively coupled to a blind source separation filter. Using signal processing techniques, the blind source separation filter attempts to accurately separate and identify signals of interest from the plurality of mixed signals. To improve performance, at least some known blind source separation filters use pipelining and parallelizing techniques. However, pipelining and parallelizing filters typically require determining new filter coefficients for each tuned frequency, and utilizing relatively large look-up tables that require intensive memory and computational resources. Additionally, in at least some known systems, excessive hardware latencies (e.g., due to clock cycles) encountered during continuous generation, classification, and tracking may cause potential signals of interest to be misclassified or to not be included in signal tracking. Also, in at least some known signal filter tuning systems and methods, pipelining and parallelizing signal filtering requires substantially different circuit and hardware versions for use on various platforms.

## BRIEF DESCRIPTION

In one aspect, a method of processing a plurality of time-varying signals received at a sensor communicatively coupled to a signal data processor to identify at least one parameter of at least one of the plurality of time-varying signals is provided. The method includes receiving, at a plurality of blind source separation (BSS) modules of the signal data processor, signals derived from the plurality of time-varying signals, each BSS module of the plurality of BSS modules including a filtering subsystem, where the filtering subsystem within each BSS module has a pipelined architecture and a parallelized architecture. The method also includes generating, using the plurality of BSS modules, a plurality of blind source separated signals, and transmitting, based on the plurality of blind source separated signals, at least one pulse descriptor word (PDW) parameter vector signal to a computing device of the signal data processor. The method further includes identifying, using the computing device, the at least one parameter from the at least one PDW parameter vector signal, and outputting the at least one parameter from the signal data processor.

In another aspect, a system for processing a plurality of time-varying signals to identify at least one parameter of at least one of the plurality of time-varying signals is provided. The system includes a sensor configured to receive the

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plurality of time-varying signals, and a signal data processor communicatively coupled to the sensor. The signal data processor includes a plurality of BSS modules, where each BSS module of the plurality of BSS modules includes a filtering subsystem. The filtering subsystem has a pipelined architecture and a parallelized architecture. The signal data processor is configured to receive, at the plurality of BSS modules, signals derived from the plurality of time-varying signals, and generate, using the plurality of BSS modules, a plurality of blind source separated signals. The signal data processor is also configured to transmit, based on the plurality of blind source separated signals, at least one PDW parameter vector signal to a computing device of the signal data processor. The signal data processor is further configured to identify, using the computing device, the at least one parameter from the at least one PDW parameter vector signal, and output the at least one parameter from the signal data processor.

In yet another aspect, a signal data processor for processing a plurality of time-varying signals to identify at least one parameter of at least one of the plurality of time-varying signals is provided. The signal data processor includes a plurality of BSS modules, where each BSS module of the plurality of BSS modules includes a filtering subsystem. The filtering subsystem has a pipelined architecture and a parallelized architecture. The signal data processor is configured to receive, at the plurality of BSS modules, signals derived from the plurality of time-varying signals, and generate, using the plurality of BSS modules, a plurality of blind source separated signals. The signal data processor is also configured to transmit, based on the plurality of blind source separated signals, at least one PDW parameter vector signal to a computing device of the signal data processor. The signal data processor is further configured to identify, using the computing device, the at least one parameter from the at least one PDW parameter vector signal, and output the at least one parameter from the signal data processor.

## BRIEF DESCRIPTION OF THE DRAWINGS

These and other features, aspects, and advantages of the present disclosure will become better understood when the following detailed description is read with reference to the accompanying drawings in which like characters represent like parts throughout the drawings, wherein:

FIG. 1 is a schematic diagram of an exemplary signal processing system for generating pulse descriptor words (PDWs) using blind source separation (BSS).

FIG. 2 is a schematic diagram of an exemplary BSS channel that forms a portion of the signal processing system shown in FIG. 1.

FIG. 3 is a schematic diagram of a pipelined architecture of an exemplary filter module that may be used with the filtering subsystem shown in FIG. 2.

FIG. 4 is a detailed view of an exemplary filter circuit that may be used with the filter module shown in FIG. 3.

FIG. 5 is a schematic diagram of a parallelized architecture of an exemplary filter module that may be used with the filtering subsystem shown in FIG. 2.

FIG. 6 is an exemplary plot of frequency tracking error (hertz, Hz) versus known normalized frequencies (GHz) in the parallelized filter architecture shown in FIG. 5 with  $N_t=100$  for  $P=4$ , and  $M=4$ .

FIG. 7 is an exemplary plot of frequency tracking error (Hz) versus known normalized frequencies (GHz) in the parallelized filter architecture shown in FIG. 5 with  $N_t=1000$  for  $P=4$ , and  $M=4$ .

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FIG. 8 is an exemplary plot of frequency tracking error (Hz) versus known normalized frequencies (GHz) in the parallelized filter architecture shown in FIG. 5 with  $N_t=10000$  for  $P=4$ , and  $M=4$ .

FIG. 9 is an exemplary plot of frequency tracking error (Hz) versus known normalized frequencies (GHz) in the parallelized filter architecture shown in FIG. 5 with  $N_t=1000$  for  $P=8$ .

FIG. 10 is a graphical representation of operation of the signal processing system 100 shown in FIG. 1 depicting power spectral density (PSD) versus frequency for a double precision filter and a pipelined parallel fixed point filter with center frequencies of 875.0 megahertz (MHz).

FIG. 11 is a graphical representation of operation of the parallelized filter architecture shown in FIG. 5 depicting error (Hz) of a polyphase system function-determined filter center frequency versus number of interpolation points for 28 different filter coefficients.

FIG. 12 is a flowchart of an exemplary method of processing a plurality of time-varying signals that may be used with signal processing system shown in FIG. 1.

Unless otherwise indicated, the drawings provided herein are meant to illustrate features of implementations of this disclosure. These features are believed to be applicable in a wide variety of systems comprising one or more implementations of this disclosure. As such, the drawings are not meant to include all conventional features known by those of ordinary skill in the art to be required for the practice of the implementations disclosed herein.

#### DETAILED DESCRIPTION

In the following specification and the claims, reference will be made to a number of terms, which shall be defined to have the following meanings.

The singular forms “a”, “an”, and “the” include plural references unless the context clearly dictates otherwise.

“Optional” or “optionally” means that the subsequently described event or circumstance may or may not occur, and that the description includes instances where the event occurs and instances where it does not.

Approximating language, as used herein throughout the specification and claims, may be applied to modify any quantitative representation that could permissibly vary without resulting in a change in the basic function to which it is related. Accordingly, a value modified by a term or terms, such as “about”, “approximately”, and “substantially”, are not to be limited to the precise value specified. In at least some instances, the approximating language may correspond to the precision of an instrument for measuring the value. Here and throughout the specification and claims, range limitations may be combined and/or interchanged, and such ranges are identified and include all the sub-ranges contained therein unless context or language indicates otherwise.

As used herein, the terms “processor” and “computer” and related terms, e.g., “processing device”, “computing device”, and “controller” are not limited to just those integrated circuits referred to in the art as a computer, but broadly refers to a microcontroller, a microcomputer, a programmable logic controller (PLC), an application specific integrated circuit (ASIC), and other programmable circuits, and these terms are used interchangeably herein. In the implementations described herein, memory may include, but is not limited to, a computer-readable medium, such as a random access memory (RAM), and a computer-readable non-volatile medium, such as flash memory. Alternatively, a

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floppy disk, a compact disc-read only memory (CD-ROM), a magneto-optical disk (MOD), and/or a digital versatile disc (DVD) may also be used. Also, in the implementations described herein, additional input channels may be, but are not limited to, computer peripherals associated with an operator interface such as a mouse and a keyboard. Alternatively, other computer peripherals may also be used that may include, for example, but not be limited to, a scanner. Furthermore, in the exemplary embodiment, additional output channels may include, but not be limited to, an operator interface monitor.

Furthermore, as used herein, the term “real-time” refers to at least one of the time of occurrence of the associated events, the time of measurement and collection of predetermined data, the time to process the data, and the time of a system response to the events and the environment. In the implementations described herein, these activities and events occur substantially instantaneously.

The systems and methods described herein are directed to a signal processing system. The signal processing system detects a plurality of mixed signals (e.g., radar signals) using a sensor. A signal data processor communicatively coupled to the sensor uses blind source separation (BSS) and other signal processing techniques to separate and identify one or more signals of interest from the plurality of mixed signals. For example, signal parameters (e.g., frequency, amplitude, etc.) of each signal of interest are identified. The identified signals of interest are output from the signal data processor. For example, the identified signals may be output to a human machine interface for display, and/or may be output to a vehicle to facilitate controlling operation of the vehicle based on the identified signals.

The signal data processor uses filter coefficients to separate and identify signals of interest. In the system and methods described herein, parallelizing and pipelining techniques are used to promptly update filter coefficients of a tunable blind source separation filter (e.g., with a hardware latency of as low as one clock cycle). The implementations described herein also facilitate continuous filter tuning and accurate signal parameter tracking through linear interpolation from a significantly smaller lookup table relative to known systems and methods. The implementations described herein further enable continuous generation, classification, and tracking of pulsed signal parameters using less memory and computational resources than known systems and methods. The systems and methods for parallelizing and pipelining a tunable blind source separation filter described herein also provide combined parallelization and pipelining of infinite impulse response (IIR) filters with substantially similar circuit and hardware implementations for both FPGA- and ASIC-based designs.

FIG. 1 is a schematic diagram of an exemplary signal processing system 100 for generating pulse descriptor words (PDWs) using BSS. Also known as blind signal separation, BSS is used to separate (e.g., filter) one or more source signals of interest from a plurality of mixed signals. In applications including, without limitation, an underdetermined case (e.g., fewer observed signals than signal sources), BSS facilitates separating and identifying pure signals of interest from an arbitrary set of time-varying signals (e.g., radar pulses from one or more signal emitters) without relying on substantial amounts of known information about the signal emitters, signals of interest, or the signal mixing process.

In the exemplary embodiment, signal processing system 100 includes a signal data processor 101 communicatively coupled to an antenna 102. Antenna 102, in the exemplary



embodiment, is a wide-area sensor **103**. Signal data processor **101** includes a pre-processor **104** and a post-processor **105**. Sensor **103** is configured to receive signals from radar signal emitters **106** and **107**. Although two radar signal emitters **106** and **107** are shown in FIG. 1, those of skill in the art will appreciate that sensor **103** may receive signals from any number of radar signal emitters **106** and **107**.

Sensor **103** is communicatively coupled to pre-processor **104** through a pre-conditioner **108**. In the exemplary embodiment, pre-conditioner **108** includes a low noise amplifier **109**, a band pass filter **110**, and a wideband analog-to-digital converter (ADC) **111**. In operation, pre-conditioner **108** is configured to convert a sensor output signal **112** received from sensor **103** into an incoming signal **113** transmitted to pre-processor **104**. Each incoming signal **113** is derived from a time-varying signal received at sensor **103**. Time-varying signal may include a mix of signals received from radar signal emitters **106** and **107**. For example, time-varying signals may include a first radar signal **114** and a second radar signal **116**.

In the exemplary embodiment, pre-processor **104** includes one or more signal denoising modules **118**, and a plurality of blind source separation (BSS) modules **120**. Each BSS module **120** is coupled to a single signal denoising module **118**, and represents one BSS channel. A total number of BSS channels in signal processing system **100** is expressed as K. Signal denoising module **118** transmits a denoised signal **124** and a state energy signal **126** to each respective BSS module **120** (e.g., **120a**, **120b**, . . . , **120K**) of the plurality of BSS modules **120**. State energy signal **126** represents a quantity (e.g., an analog voltage level) that is proportional to an amplitude of incoming signal **113** at particular sampled time points (e.g., states).

In operation, incoming signal **113** is transmitted from pre-conditioner **108** to signal denoising module **118** where incoming signal **113** undergoes signal denoising and is subsequently transmitted as denoised signal **124** to the each BSS module **120**. For example, first radar signal **114** is initially received at sensor **103** as a pulse having signal characteristics including, without limitation, a frequency and a bandwidth. In this example, a single pulse of first radar signal **114**, after processing by pre-conditioner **108**, is then received at signal denoising module **118** as a mixed signal (e.g., the incoming signal **113** represents a signal pulse of the first radar signal **114** and has various characteristics including, without limitation, noise and information other than the desired information of interest). Signal denoising module **118** denoises the mixed incoming signal **113** prior to transmitting denoised signal **124** having a frequency and a bandwidth (or a regular pattern of frequencies and bandwidths) to the BSS modules **120**. Methods implemented by signal processing system **100** are performed in substantially real time by the devices and systems described above, and as shown and described below in further detail with reference to FIG. 2.

Further, in the exemplary embodiment, pre-processor **104** includes one or more PDW generation modules **128** coupled to each BSS module **120**, and a pulse denoising module **130** coupled to each BSS module **120**. PDW generation module **128** generates PDW parameter vector signals **138** based on blind source separated signals **129** received from each BSS module **120**. Each PDW parameter vector signal **138** contains data representative of characteristics of interest of one of radar signals **114** and **116** derived from a singular pulse of blind source separated signal **129** (e.g., frequency, bandwidth, time of arrival, time of departure, pulse width, pulse amplitude, pulse repetition interval, and/or angle of arrival

(AOA)). Pulse denoising module **130** also generates an unknown signal state space representation signal **139** based on blind source separated signals **129**. Unknown signal state space representation signal **139** contains data representative of additional (e.g., non-PDW-type) characteristics of interest of one of radar signals **114** and **116** from which usable spatial information about one of radar signal emitters **106** and **107** is discernable. PDW parameter vector signals **138** and unknown signal state space representation signals **139** are transmitted to post-processor **105**. Signal denoising module **118**, PDW generation module **128**, and pulse denoising module **130** include suitable signal filtering, signal amplification, signal modulation, signal separation, signal conditioning, and/or ADC circuitry implemented using analog and/or digital electronic circuit components. Also, in the exemplary embodiment, each BSS module **120** transmits a respective blind source separated signal **129** (e.g., **129a**, **129b**, . . . , **129K**) to PDW generation module **128** and to pulse denoising module **130**.

Post-processor **105** includes a computing device **132** that includes a memory **134**. As described above, PDW generation module **128** receives blind source separated signals **129** from each respective BSS module **120**. PDW generation module **128** then utilizes the blind source separated signals **129** to generate a PDW parameter vector signal **138**, which is subsequently transmitted to post-processor **105**. PDW parameter vector signal **138** is received by computing device **132** and stored as computer-readable data in memory **134** including, without limitation, as at least one buffered data set. Pulse denoising module **130** is also configured to receive blind source separated signals **129** from each respective BSS module **120**. Pulse denoising module **130** is further configured to utilize the blind source separated signals **129** to generate the unknown signal state space representation signal **139**, which is subsequently transmitted to post-processor **105**. Unknown signal state space representation signal **139** is received by computing device **132** and stored as computer-readable data in memory **134** including, without limitation, as at least one buffered data set. In the exemplary embodiment, computing device **132** fetches buffered data sets from memory **134** for processing using a computer-based method employing an operating system running software executed from instruction set data also stored in memory **134** (e.g., from one or more computer-readable storage media).

Computing device **132** implements a computer-based method (e.g., from software instructions stored in one or more computer-readable storage media including, without limitation, in memory **134**) to carry out operations based on data contained in at least one of PDW parameter vector signal **138** and unknown signal state space representation signal **139**. Such operations include, without limitation, detecting, processing, quantifying, storing, and displaying (e.g., in human readable data form) various characteristics of at least one radar signal (e.g., signals **114** and **116**) represented as data in at least one of PDW parameter vector signal **138** and unknown signal state space representation signal **139**. For example, PDW parameter vector signal **138** generated by PDW generation module **128** contains a plurality of PDW vector data blocks structured in a vector form, where each PDW vector data block contains one parameter of first radar signal **114**. Parameters (e.g., representative of at least one characteristic of first radar signal **114**) include, without limitation, frequency, bandwidth, time of arrival, time of departure, pulse width, pulse amplitude, pulse repetition interval, and/or AOA. Computing device **132** reads PDW parameter vector signal **138** and carries out at least one

of the aforementioned operations on at least one PDW vector data block of the plurality of PDW vector data blocks. Also, in the exemplary embodiment, computing device **132** reads and separates (e.g., deinterleaves) PDW parameter vector signal **138** into its constituent PDW vector data blocks, and stores fewer PDW vector data blocks in memory **134** than the total number of PDW vector data blocks contained in PDW parameter vector signal **138**. Deinterleaving of PDW parameter vector signal **138** enables determining characteristics of interest of radar signals **114** and/or **116** by computing device **132** to, for example, and without limitation, accurately determine and track spatial information for radar signal emitters **106** and/or **107**. In other implementations, computing device **132** reads and separates all PDW vector data blocks from one another and stores all data contained therein in memory **134**. Computing device **132** performs the aforementioned operations substantially simultaneously (e.g., in real time) upon receipt of radar signals **114** and **116** by sensor **103**.

Resultant data from operations performed by computing device **132** are stored in memory **134**. Further, in the exemplary embodiment, computing device **132** causes post-processor **105** to transmit a data output signal **142** to a human machine interface (HMI) to facilitate at least one of an interaction, a modification, a visualization, at least one further operation, and a viewable recording of information about radar signals **114** and **116** by a user of signal processing system **100**. HMI is, for example, a display **144** which receives data output signal **142** from post-processor **105**. In one example, characteristics (e.g., location characteristics such as grid coordinates in a physical spatial domain) representing a physical location of radar signal emitters **106** and **107**, as determined by signal processing system **100**, are displayed on display **144**, and are updated in substantially in real time. Data output signal **142** is also transmitted from post-processor **105** to at least one device and/or system (e.g., a vehicle **146**) associated with signal processing system **100**. Further, computing device **132** enables post-processor **105** to transmit, in substantially real time, an actuator control signal **148** to an actuator controller **150** included within vehicle **146** to facilitate controlling vehicle **146**. For example, vehicle **146** may be a remotely and/or autonomously operated land vehicle and/or an unmanned aerial vehicle (UAV).

In one mode of operation, at least one of frequency and bandwidth information contained in respective PDW parameter vector signals **138** is displayed on display **144** along with locations of respective radar signal emitters **106** and **107** to facilitate accurate tracking of locations and association with particular radar signal emitters **106** and **107**. In cases where at least one radar signal emitter **106** and **107** is mobile, display **144** is automatically updated in substantially real-time to show the location information of at least one respective mobile radar signal emitter **106** and **107**. Further, computing device **132** also determines at least one of a velocity, an acceleration, a trajectory, and a track (e.g., including present and prior locations) of the at least one respective mobile radar signal emitter **106** and **107**. In another mode of operation, characteristics determined by signal data processor **101** also trigger a variety of substantially real time physical actions in physical devices and systems in communication with signal processing system **100**. For example, characteristics of radar signal emitters **106** and **107**, including frequency and bandwidth determined by signal processing system **100**, are transmitted in substantially real-time as data to actuator controller **150** in vehicle **146** (e.g., to control rudders and flaps of a UAV). If

radar signal emitters **106** and **107** are unauthorized (e.g., hostile, previously undetected, etc.) radar signal emitters determined to be a threat, actuator controller **150** maneuvers vehicle **146** to avoid an area of operation of signal emitters **106** and **107** or engages signal emitters **106** and **107**. As a further example, characteristics of radar signal emitters **106** and **107** determined by signal data processing methods described herein are transmitted in substantially real time in a control signal to at least one of an electronic support measure (ESM) device and an electronic warfare (EW) system associated with signal processing system **100** to direct, for example, a radar jamming signal at radar signal emitters **106** and **107** operating in the surveillable environment of sensor **103** without authorization.

In operation, each BSS module **120** of the plurality of BSS modules **120** in signal processing system **100** implements filtering methods with dynamic updating to enable generating high quality PDWs containing at least one of frequency, center frequency, bandwidth, pulse time, and pulse width information. BSS modules **120** have a pipelined and parallelized architecture, as described herein. Such improved accuracy and resolution of PDWs to track, for example, frequency and bandwidth of radar signals of interest facilitates identifying, determining, and/or analyzing radar signal emitters **106** and **107** from which associated radar signals are emitted. For example, information including, without limitation, information derived from PDWs from radar signal emitters **106** and **107** is displayed on display **144** after being transmitted thereto by post-processor **105** as data output signal **142**, as described above. This improved information enables signal processing system **100** to distinguish first radar signal emitter **106** from second radar signal emitter **107**. Also, for example, different radar signal emitters (e.g., first radar signal emitter **106** and second radar signal emitter **107**) in a surveilled environment of sensor **103** are plotted at respective locations (e.g., grid coordinates) on display **144** (e.g., as a map).

Also, in operation, the plurality of BSS modules **120** separate a plurality of denoised signals **124**. As further shown and described below with reference to FIGS. 2 and 3, each BSS module **120** contains a plurality of tunable filters, where each filter operates based on filter parameters including, without limitation, a center frequency and a bandwidth. Further, in the exemplary embodiment, pre-processor **104** includes a BSS control module **196**, which facilitates controlling each respective BSS module **120** of the plurality of BSS modules **120**. BSS control module **196** receives respective BSS data signals **197** (e.g., **197a**, **197b**, . . . , **197K**) containing BSS-related information including, without limitation, frequency, bandwidth, and state, from each BSS module **120** of the plurality of BSS modules **120**. Based on the BSS-related information contained in BSS data signals **197**, BSS control module **196** also generates and transmits respective BSS control signals **198** (e.g., **198a**, **198b**, . . . , **198K**) back to each respective BSS module **120** to control, for example and without limitation, a timing of receipt of denoised signal **124** and transmission of respective blind source separated signals **129** to at least one of PDW generation module **128** and pulse denoising module **130**. Information contained in BSS data signals **197** and BSS control signals **198** is used by BSS control module **196** to facilitate implementation of a feedback control loop.

FIG. 2 is a schematic diagram of an exemplary BSS channel **200** (e.g., BSS module **120a** receiving denoised signal **124** from signal denoising module **118**) that forms a portion of the signal processing system **100** shown in FIG. 1. As described above, signal denoising module **118** trans-

mits denoised signal 124 and state energy signal 126. Also, in the exemplary embodiment, state energy signal 126 is embodied in a plurality of state energy signals 126. Each state energy signal 126 of the plurality of state energy signals 126 contains information that is representative of the state (e.g., the analog voltage level that is proportional to the amplitude of incoming signal 113 at particular sampled time points) of a respective state output 202 of signal denoising module 118. The plurality of state energy signals 126 are received by a state energy analysis subsystem 204. State energy analysis subsystem 204 determines a center frequency (e.g.,  $f_0$ ) of respective state energy signals 126 of S signals (e.g., 126a, 126b, . . . , 126S) corresponding to S filter states of a filtering subsystem 207. State energy analysis subsystem 204 includes a window summer module 206 configured to determine a total energy within a set of S windows of length  $N_e$  (e.g., one for each state of a BSS channel state machine module 208 of BSS module 120a). BSS channel state machine module 208 coordinates a timing of filtering of denoised signal 124 by filtering subsystem 207. State energy analysis subsystem 204 also includes a maximum energy detection module 210 coupled to window summer module 206. Maximum energy detection module 210 is configured to receive S summed window signals 212 (e.g., 212a, 212b, . . . , 212S) and determine a maximum energy of each summed window signal 212 of the S summed window signals 212. Maximum energy detection module 210 is further configured to determine and transmit an initial frequency signal 214 to a signal frequency and bandwidth tracker module 216 coupled to maximum energy detection module 210.

In an exemplary embodiment, initial frequency signal 214 is representative of the  $f_0$  of the maximum energy of the respective state energy signal 126 corresponding to the associated state of BSS channel 200. Signal frequency and bandwidth tracker module 216 uses initial frequency signal 214 to determine a center frequency ("Cf") and a bandwidth ("BW") of the respective summed window signal 212 corresponding to the maximum energy state of BSS channel 200. Signal frequency and bandwidth tracker module 216 further outputs a Cf and BW signal 218 to BSS channel state machine module 208. BSS channel state machine module 208 is coupled to filtering subsystem 207, signal frequency and bandwidth tracker module 216, an input buffer module 220, and computing device 132. Substantially simultaneously with receipt of Cf and BW signal 218 by BSS channel state machine module 208 from signal frequency and bandwidth tracker module 216, input buffer module 220 delays filtering of denoised signal 124 by filtering subsystem 207 to enable BSS channel state machine 208 to update Cf and BW filter parameters of filtering subsystem 207 (as further described below).

In the exemplary embodiment, filtering subsystem 207 is a tunable filter bank including a plurality of filter modules including, for example, and without limitation, a low filter ("F<sub>lo</sub>") module 207a, a main filter ("F") module 207b, and a high filter ("F<sub>hi</sub>") module 207c. In other implementations (e.g., as shown and described below with reference to FIG. 5), filtering subsystem 207 includes greater than or less than three filter modules. Input buffer module 220 is coupled to and between filtering subsystem 207 and signal denoising module 118, and is configured to transmit a plurality of filter input signals 228 (e.g., 228a, 228b, and 228c) to respective filter modules (e.g., 207a, 207b, and 207c) in filtering subsystem 207. Input buffer module 220 is further configured to receive a delay signal 227 transmitted from a first output of BSS channel state machine module 208. Delay

signal 227 dictates a timing of outputting filter input signal 228 to filtering subsystem 207. From a second output, BSS channel state machine module 208 transmits a center frequency and bandwidth update signal 232 to filtering subsystem 207. Center frequency and bandwidth update signal 232 enables continuous updating of Cf and BW operational parameters and associated filter coefficients  $\alpha$  ("alpha") and  $\beta$  ("beta"), respectively, of each filter module (e.g., 207a, 207b, and 207c) in filtering subsystem 207. Center frequency and bandwidth update signal 232 thus facilitates accurate tracking of denoised signal 124 frequency and bandwidth to yield a continuous and undistorted blind source separated signal 129a output from BSS module 120a and BSS channel 200.

In the exemplary embodiment, filtering subsystem 207 uses digital and/or analog electronic circuitry including, without limitation, circuits instantiated in at least one of a field-programmable gate array (FPGA) and an application-specific integrated circuit (ASIC). Also, in the exemplary embodiment, at least a portion of the methods implemented in BSS channel 200 are instantiated via software on at least one of a general purpose processor (e.g., computing device 132) and a digital signal processor (DSP). Further, in the exemplary embodiment, operational parameters of each filter module (e.g., 207a, 207b, and 207c) in filtering subsystem 207 are stored in memory 134, and are updated substantially simultaneously (e.g., in real time) with transmission of center frequency and bandwidth update signal 232 by BSS channel state machine module 208. Filter modules 207a, 207b, and 207c have both a pipelined architecture (as described below in association with FIG. 3) and a parallelized architecture (as described below in association with FIG. 4) in the exemplary embodiment.

In the exemplary embodiment, filter module F<sub>lo</sub> 207a, filter module F 207b, and filter module F<sub>hi</sub> 207c receive respective filter input signals (e.g., 228a, 228b, and 228c) from input buffer module 220, and are each further coupled to BSS channel state machine module 208. Filtering subsystem 207 is further configured to transmit a plurality of signal energy signals 234, where filter modules F<sub>lo</sub> 207a, F 207b, and F<sub>hi</sub> 207c each transmit respective signal energy signals (e.g., 234a, 234b, and 234c, respectively) to BSS channel state machine module 208. Further, in the exemplary embodiment, filter module F 207b also transmits signal energy signal 234b as the respective blind source separated signal 129a transmitted from BSS module 120a to PDW generation module 128 and to pulse denoising module 130 for further processing (e.g., deinterleaving of PDW parameter vector signal 138 by computing device 132, as shown and described above with reference to FIG. 1). Information contained in the plurality of signal energy signals 234 is used by BSS channel state machine module 208 for generating and transmitting center frequency and bandwidth update signal 232 to filtering subsystem 207 (as further shown and described below with reference to FIGS. 3 and 4).

In operation, feedback in BSS channel 200 is used to determine where (e.g., at what value or values) to place the Cf and BW of each filter module (e.g., filter modules F<sub>lo</sub> 207a, F 207b, and F<sub>hi</sub> 207c) of filtering subsystem 207 over all time. The feedback includes acquiring energy measurements resulting from existing filter settings (e.g., from signal energy signals 234a, 234b, and 234c), and continuously and adaptively updating respective filter parameters Cf and BW and filter coefficients  $\alpha$  and  $\beta$ , while maintaining as complete a coverage in time and frequency as possible. Subsequent pulses of radar signals are filtered by filtering subsystem

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tem 207 with filter modules  $F_{lo}$  207a, F 207b, and  $F_{hi}$  207c having respective filter parameters and coefficients tuned to enable filtering subsystem 207 to multitask in a very efficient manner (e.g., under control, at least in part, of BSS control module 196, as described above with reference to FIG. 1).

Also, in operation, signal frequency and bandwidth tracker module 216 includes a tracking algorithm to track a value of the initial frequency signal 214. Specifically, the Cf of initial frequency signal 214 changes at any rate up to a maximum predetermined rate set by the tracking algorithm (e.g., determined by at least one of computing device 132, BSS channel state machine module 208, and BSS control module 196). A track window of the tracking algorithm is short enough to support a chirp rate, but long enough to handle the signal noise level. In particular, the tracking algorithm is robustly implemented by BSS channel 200 including, without limitation, in conjunction with computing device 132, as a function of all of the following: parameter and/or coefficient settings of the plurality of filter modules (e.g., 207a, 207b, and 207c), noise levels, signal frequency change characteristics, amplitude differences, and ability to pull-in signals within range required by signal denoising module 118. For example, and without limitation, where signal denoising module 118 has twenty states (e.g.,  $S=20$ ) with a 1 GHz bandwidth, BSS channel 200 tracks radar signals with a frequency offset from an initial frequency (e.g., pull-in range) up to  $\pm 25$  MHz (e.g., 0.025 GHz).

In the exemplary embodiment, each filter module (e.g., 207a, 207b, and 207c) in filtering subsystem 207 is an infinite impulse response (IIR) filter. Also, in the exemplary embodiment, BSS channel 200 processes radar signals rather than communications signals and, therefore, the effects of a non-constant group delay caused by using IIR filters is less important than with communications signals. IIR filters adequately meet the signal quality required for post-filtering PDW deinterleaving by post-processor 105.

Filter module F 207b is used as the primary filter for separating filter input signal 228b derived from denoised signal 124. Filtering of filter input signals 228a and 228c by filter modules  $F_{lo}$  207a and  $F_{hi}$  207c, respectively, is used in the tracking process to keep filter module F 207b relatively accurate in determining both frequency and bandwidth. Also, in the exemplary embodiment, filter modules  $F_{lo}$  207a and  $F_{hi}$  207c are offset by fixed amounts in frequency and bandwidth and, as with filter module F 207b, are continuously monitored to facilitate appropriate and timely tuning of Cf and BW.

Each of the filter modules  $F_{lo}$  207a, F 207b, and  $F_{hi}$  207c are parameterized by two values (e.g., Cf and BW). In an alternative implementation, not shown, filtering subsystem 207 includes two filter modules (e.g., filter modules F 207b and  $F_{hi}$  207c), rather than three filter modules, BSS channel 200 has a fixed BW, and a simplified tracking process tracks only frequency. In this simplified case, Cf and BW of filter module F 207b are referred to as f and w, respectively, such that:

$$\text{center frequency } (F_{hi})=f+\Delta f \quad \text{Equation 1}$$

$$\text{bandwidth } (F_{hi})=w \quad \text{Equation 2}$$

For the exemplary embodiment, where filtering subsystem 207 includes three filter modules (e.g., filter modules  $F_{lo}$  207a, F 207b, and  $F_{hi}$  207c), Cf and BW of filter module F 207b are defined according to Equations 1 and 2, and Cf and

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BW (e.g., f and w, respectively) of filter modules  $F_{lo}$  207a and  $F_{hi}$  207c are defined as follows:

$$\text{center frequency } (F_{lo})=f-\Delta f \quad \text{Equation 3}$$

$$\text{bandwidth } (F_{lo})=w-\Delta w \quad \text{Equation 4}$$

$$\text{center frequency } (F_{hi})=f+2\Delta f \quad \text{Equation 5}$$

$$\text{bandwidth } (F_{hi})=w+2\Delta w \quad \text{Equation 6}$$

Also, in operation, respective signal energy signals 234 (e.g., 234a, 234b, and 234c) output by respective filter modules (e.g., filter modules  $F_{lo}$  207a, F 207b, and  $F_{hi}$  207c) in filtering subsystem 207 have their output energies determined by BSS channel state machine module 208 including, without limitation, in conjunction with methods performed using at least one of computing device 132 and BSS control module 196. For real-valued signal energy signals 234, the output energies are determined through squaring, and for complex-valued signal energy signals 234, the output energies are determined by taking the absolute value. For either real-valued or complex-valued signal energy signals 234, determination of the output energies in the case of filtering subsystem 207 having three filter modules (e.g.,  $F_{lo}$  207a, F 207b, and  $F_{hi}$  207c) results in a sequence of energy measurement triples  $(E(n), E_{lo}(n), E_{hi}(n))$ ,  $n=1, 2, \dots$ , where n represents the state of BSS channel 200, as described above. In the simplified two filter case, determination of the output energies of signal energy signals 234 results in a sequence of energy measurement pairs  $(E(n), E_{hi}(n))$ ,  $n=1, 2, \dots$ , and facilitates the following updates to the Cf (e.g., f) parameters of filter modules F 207b and  $F_{hi}$  207c:

$$f \leftarrow f + \alpha_0 * [(E(n) - E_{hi}(n)) / (E(n) + E_{hi}(n))] + \alpha_1 \quad \text{Equation 7}$$

In the exemplary embodiment where filtering subsystem 207 includes three filter modules (e.g.,  $F_{lo}$  207a, F 207b, and  $F_{hi}$  207c), f and w parameters are updated as follows:

$$f \leftarrow f + \alpha_0 * [(E(n) - E_{lo}(n)) / (E(n) + E_{lo}(n))] + \alpha_1 * [(E(n) - E_{hi}(n)) / (E(n) + E_{hi}(n))] + \alpha_2 \quad \text{Equation 8}$$

$$w \leftarrow w + \beta_0 * [E(n) - E_{lo}(n)] / [E(n) + E_{lo}(n)] + \beta_1 * [(E(n) - E_{hi}(n)) / (E(n) + E_{hi}(n))] + \beta_2 \quad \text{Equation 9}$$

where initial values of coefficient vectors  $\alpha$  and  $\beta$  are determined and stored in memory 134 during a pre-training process (e.g., implemented by at least one of computing device 132, BSS channel state machine module 208, and BSS control module 196), and are functions of window size, BW, and signal-to-noise ratio (SNR). Initial values of  $\alpha$  and  $\beta$  are determined from at least one of an initial denoised signal 124 and an initial state energy signal 126 received at BSS channels 200.

Referring again to FIG. 2, in operation of the exemplary embodiment, respective filter input signals (e.g., 228a, 228b, and 228c) derived from at denoised signal 124 are provided substantially simultaneously to each filter module (e.g.,  $F_{lo}$  207a, F 207b, and  $F_{hi}$  207c) in filtering subsystem 207 of each BSS module 120 of the plurality of BSS modules 120 in signal processing system 100. In BSS channel 200, for example, the resulting blind source separated signal 129a output by filtering subsystem 207 is further vectorized into PDW parameter vector signal 138 by PDW generation module 128 to further facilitate accurate tracking and determination of frequency and/or bandwidth of at least one radar signal. Therefore, BSS channel 200 enables signal processing system 100 to implement high performance real time tracking of a plurality of time-varying radar signals streaming through pre-processor 104.

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The aforementioned filtering methods enable signal processing system 100 to generate high quality PDW parameter vector signals 138 that are used for identifying, determining, and analyzing radar signal emitters 106 and 107. For example, PDW parameter vector signals 138 associated with radar signal emitter 106 are displayed on display 144, as described above. Also, for example, improved information about frequencies and/or bandwidths contained in at least two PDW parameter vector signals 138 enable signal processing system 100 to distinguish first radar signal emitter 106 from second radar signal emitter 107. These radar signal emitters 106 and 107 are plotted at respective locations on display 144 (e.g., as a map).

FIG. 3 is a schematic diagram of an exemplary filter module (e.g., filter module F 207b) that may be used with the filtering subsystem 207 shown in FIG. 2. As shown in FIG. 3 and described herein, filtering subsystem 207 has a pipelined architecture. As used herein, the terms pipeline, pipelined, and pipelining refer to methods and configurations of filtering modules and related operational units which enable increasing speed and throughput in signal processing system 100 by facilitating different functional units performing different tasks concurrently. In the exemplary embodiment, filter module F 207b includes an effective sixth order IIR filter 301 configured to output the respective signal energy signal 234b to BSS channel state machine module 208. Filter modules 207a and 207c are implemented similarly in the exemplary embodiment.

In the illustrated embodiment, sixth order IIR filter 301 includes seven BW filter circuits 303 (e.g., 303a, 303b, . . . , 303g), where each BW filter circuit 303 is embodied in a second order IIR filter and has a respective  $\beta$  coefficient (denoted " $\beta_0$ ", " $\beta_1$ ", . . . , " $\beta_6$ ", respectively). Sixth order IIR filter 301 also includes two Cf filter circuits 304 (e.g., 304a, 304b), where each Cf filter circuit 304 is embodied in a second order IIR filter and has a respective  $\alpha$  coefficient (denoted " $\alpha_1$ " and " $\alpha_2$ ", respectively). Filter module F 207b also includes a pipelining architecture 302 (e.g., implemented in conjunction with at least one of computing device 132, BSS channel state machine module 208, and BSS control module 196) that facilitates pipelining the plurality of BW filter circuits 303 and the plurality of Cf filter circuits 304 by a factor of three. Thus, in the exemplary embodiment, filter module F 207b functions as a sixth order IIR filter with a transfer function having 6 zeros (e.g., 6 coefficients  $\beta$  in the numerator) and 2 poles (e.g., 2 coefficients  $\alpha$  in the denominator), assuming that a value of  $\alpha_0=1$ .

In operation, coefficients  $\alpha$  and  $\beta$  of BW filter circuits 303 and Cf filter circuits 304, respectively, are updated within two hardware clock cycles after receipt by filter module F 207b of a first pulse of filter input signal 228b. This updating routine is implemented by BSS channel state machine module 208 transmitting to filtering subsystem 207 the Cf and BW updated signal 232 using information contained in the plurality of signal energy signals 234 (as shown and described below with reference to FIG. 4). Information contained as data in center frequency and bandwidth update signal 232 is used by sixth order IIR filter 301 to update filter coefficients  $\alpha$  and  $\beta$  of BW filter circuits 303 and Cf filter circuits 304, respectively. Upon a second and subsequent pulses of filter input signals 228b (and likewise, e.g., filter input signals 228a and 228c) received by filtering subsystem 207, updated filter coefficients  $\alpha$  and  $\beta$  facilitate tracking the frequency of at least one radar signal emitter (e.g., first radar signal emitter 106) in the surveillable environment of sensor 103.

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In operation, a product of a value (e.g.,  $V_j(n)_{input}$ ) of the filter input signal 228b and a value of coefficients  $\beta_0$  of BW filter circuit 303a is determined by a first multiplier 306. Substantially simultaneously, coefficients  $\beta_1$  through  $\beta_6$  are transmitted from BW filter circuits 303b through 303g to a plurality of multipliers 308 (e.g., six multipliers 308a, 308b, . . . , 308f). Each multiplier 308 of the plurality of multipliers 308 also inputs a respective first order z-transform delay ( $Z^{-1}$ ) 310 (e.g., 310a, 310b, . . . , 310f). Each  $Z^{-1}$  delay 310 applies a delay value to filter input signal 228b prior to being input to each multiplier 308 of the plurality of multipliers 308. Outputs of the first multiplier 306 and each multiplier 308 of the plurality of multipliers 308 are transmitted to a first summer 312. First summer 312 determines a sum of the outputs of the first multiplier 306 and each multiplier 308 of the plurality of multipliers 308.

Substantially simultaneously with determining the value of the sum of the outputs of first multiplier 306 and each multiplier 308 of the plurality of multipliers 308, Cf filter circuits 304a and 304b transmit values of coefficients  $\alpha_1$  and  $\alpha_2$  to a second multiplier 314 and a third multiplier 316, respectively. Second multiplier 314 and third multiplier 316 each input a respective third order z-transform delay ( $Z^{-3}$ ) 318 (e.g., 318a, 318b). Each  $Z^{-3}$  delay 318 applies a delay value to signal energy signal 234b prior to being input to second multiplier 314 and third multiplier 316. The values of third order Z-transform delays 318 are three times the values of first order z-transform delays 310 because there are three times as many  $\beta$  coefficients input into each respective multiplier 308 of the plurality of multipliers 308 as there are  $\alpha$  coefficients (assuming  $\alpha_0=1$ ) input into second multiplier 314 and third multiplier 316. This enables implementation of filter module F 207b on an FPGA in addition to an ASIC. Products determined by second multiplier 314 and third multiplier 316 are transmitted to a second summer 320. Second summer 320 determines a sum of the outputs of second multiplier 314 and third multiplier 316, and the output of first summer 312. Second summer 320 thus generates signal energy signal 234b as its output.

With subsequent filter input signals 228b received by filter module F 207b, pipelining with filter coefficient update and feedback enables continuous tuning of  $\alpha$  and  $\beta$  coefficients and operational parameters (including, without limitation, center frequency and bandwidth) of each BW filter circuit 303 and each Cf filter circuit 304. Given subsequent pulses of  $V_j(n)_{input}$ -valued filter input signals 228b (e.g.,  $x[n]$ ), the above-described pipelined filtering process enables filter module F 207b to output refined (e.g., tracked) signal energy signals 234b following a difference function implemented by pipelining architecture 302 as follows:

$$V_j(n)_{output} = y[n] = \sum_{j=1}^{N=2} \alpha_j y[n-j] + \sum_{j=0}^{M=6} \beta_j x[n-j] \quad \text{Equation 10}$$

where  $x[n]$  terms are individual pipelined outputs of respective multipliers 308 of the plurality of multipliers 308 (e.g.,  $M=6$ ) summed by the first summer 312, and  $y[n]$  terms are pipelined outputs of second multiplier 314 and third multiplier 316 (e.g.,  $N=2$ ) summed by second summer 320. Thus, the exemplary embodiment, a total of eight coefficients are updated (e.g.,  $\alpha_0=1$  remains constant) and a total of  $1+M+N$  multipliers are needed to compute each new output from the difference equation after at least seven pulses of filter input signals 228b are received by filter module F 207b, thereby updating filter coefficients  $\alpha$  and  $\beta$  at least 6 times.

The determination of values of signal energy signals 234b following the streaming of greater than seven filter input signal 228b pulses through filter module F 207b can be

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further simplified from the above difference function by the following system function,  $H(z)$ :

$$H(z) = G + \sum_{i=1}^N \left( \frac{c_{i0}z^{-1} + c_{i1}z^{-2}}{1 + A_{i0}z^{-1} + A_{i1}z^{-2}} \right) \quad \text{Equation 11}$$

where  $H(z)$  is the polyphase decomposition reduced to a parallel second order IIR filter form (e.g., with  $M=N=2$ ), the subsequences  $x_k[n]$  composing the sum are the polyphase components of the parent sequence  $x[n]$  (for all  $n$ ), and  $G$  is a constant representative of a value (e.g., the value of signal energy signal **234b** at  $n=0$  and with  $\alpha_j=1$ ) derived by BSS channel state machine module **208** prior to transmitting Cf and BW update signal **232** to each BW filter circuit **303** and each Cf filter circuit **304**.

Also, in operation, in the exemplary embodiment, filter module **F 207b** implements an interpolation process to enable determination of the final values of filter coefficients  $\alpha$  and  $\beta$  to provide the aforementioned updates within two hardware clock cycles. As further shown and described below with reference to FIG. 4, the Cf and BW update signal **232** contains at least one of a frequency word and a bandwidth word including a frequency value and a bandwidth value, respectively. Substantially simultaneously with transmission of Cf and BW update signal **232** from BSS channel state machine module **208**, the tracking algorithm uses a lookup and interpolation routine with a table of fixed coefficients stored in memory **134** to determine the updated filter coefficient values  $\alpha$  and/or  $\beta$  by interpolation of the values from the table of fixed coefficients queried with the updated value of the frequency word and/or bandwidth word. Also, substantially simultaneously with the lookup and interpolation routine, a set of values of filter coefficients  $\alpha$  and/or  $\beta$  are updated in memory **134** to enable subsequent cycles of lookup, interpolation, and update of filter coefficients  $\alpha$  and  $\beta$  for subsequent instances of filter input signal **228b**. Thus, in two hardware clock cycles, filter module **F 207b** enables signal processing system **100** to quickly and adaptively track quickly changing incoming radar signals (e.g., broad band chirps) without glitches as fast as the Cf and BW update signal **232** is transmittable from BSS channel state machine module **208**, and to switch between radar signals at widely separated frequencies in real time.

FIG. 4 is a detailed view of an exemplary filter circuit (e.g., Cf filter circuit **304a**) that may be used with the filter module **F 207b** shown in FIG. 3. In the exemplary embodiment, BSS channel state machine module **208** transmits Cf and BW update signal **232** containing a frequency word to Cf filter circuit **304a**, where the frequency word data is split into a high half bit set ( $F_h$ ) **402** and a low half bit set ( $F_l$ ) **404**. In the exemplary embodiment, an intermediate register **406** receives thirty-six bits of  $F_h$  **402**, and a multiplier **408** receives  $F_l$  **404**. Substantially simultaneously with receipt of  $F_h$  **402** by intermediate register **406**, a subtracter **410** subtracts a low eighteen bits **412** of  $F_h$  **402** in intermediate register **406** from a high eighteen bits **414** of  $F_h$  **402** in intermediate register **406**. Substantially simultaneously with receipt of  $F_h$  **402** by intermediate register **406**, a product **416** of  $F_l$  **404** and a difference **418** between the low eighteen bits **412** and the high eighteen bits **414** is determined by multiplier **408**. Next, a summer **420** determines a sum **422** of the low eighteen bits **412** and the product **416**. Sum **422** represents a value of filter coefficient  $\alpha$  for Cf filter circuit **304a** (e.g., denoted as “ $\alpha_j1$ ” in FIG. 3) to be updated for the

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next cycle implemented by pipelining architecture **302** receiving a subsequent pulse of filter input signal **228b**. Cf filter circuit **304a** thus determines updated filter coefficient values  $\alpha_j1$  through interpolation from a table of fixed coefficients as follows:

$$\text{Filter Coefficient} = F_l^* (R_h - R_l) + R_l \quad \text{Equation 12}$$

where  $F_l$  represents the value of  $F_l$  **404**,  $R_h$  is the value of the high eighteen bits **414** of  $F_h$  **402** from intermediate register **406**, and  $R_l$  is the value of the low eighteen bits **412** of  $F_h$  **402** from intermediate register **406**. Sum **422** thus contains the updated value of  $\alpha_j1$  that is transmitted from sixth order IIR filter **301** to second multiplier **314** substantially simultaneously with transmission of a subsequent Cf and BW update signal **232** from BSS channel state machine module **208**.

In the case of, for example, BW filter circuit **303a**, Cf and BW update signal **232** transmitted thereto and containing bandwidth word is split into corresponding high and low half bit sets, and updated filter coefficient  $\beta$  values (e.g., denoted as “ $\beta_j0$ ” in FIG. 3) are determined in substantially the same manner as shown and described above for  $\alpha_j1$ . In the case of BW filter circuit **303a**, however, sum **422** contains the updated value of  $\beta_j0$  transmitted from sixth order IIR filter **301** to second multiplier **314** to first multiplier **306**.

FIG. 5 is a schematic diagram of an exemplary filter module (e.g., filter module **F 207a**) that may be used with the filtering subsystem **207** shown in FIG. 2. As shown in FIG. 5 and described herein, filtering subsystem **207** has a parallelized filter architecture **500**. In the exemplary embodiment, parallelized filter architecture **500** includes four filter components **501** (e.g., **501a**, **501b**, **501c**, and **501d**). Each filter component **501** receives a first filter input signal **228a** from input buffer module **220** (shown in FIG. 2). Separate instances of **228a** may be delayed relative to one another by input buffer module **220**. Parallelized filter architecture **500** is implementable in at least one of an FPGA and an ASIC to enable adaptive BSS filtering with, for example and without limitation, Bessel-type filters, and using polyphase methods for each filter input signal **228a** of the plurality of filter input signals **228a**. In the exemplary embodiment, parallelized filter architecture **500** implements the linear interpolation (e.g., as shown and described above with reference to FIGS. 3 and 4) on a bank of four submodules (e.g., submodules **502a**, **502b**, **502c**, and **502d**) within each of the plurality of filter components **501**. The interpolation is based on the Cf parameter. BW is also adjusted for a two-dimensional interpolation, and filter submodules (e.g., **502a**, **502b**, **502c**, and **502d**) cover a consecutive frequency range for use in analyzing the four filter input signal **228a** pulses.

In parallelized filter architecture **500**, input buffer module **220** (shown in FIG. 2) generates a vector of four respective filter input signals **228a** from consecutively received pulses of denoised signal **124** (shown in FIGS. 1 and 2). The four filter input signals **228a** are then received by filter components **501a**, **501b**, **501c**, and **501d**, respectively. Each filter component **501** outputs a plurality of intermediate signal energy signals **503** as four respective intermediate signal energy signal sets **503** (e.g., **503a**, **503b**, **503c**, and **503d**). For example, and without limitation, each intermediate signal energy signal set **503** consists of four respective intermediate signal. In FIG. 5 the total of 16 submodules **502a-502d** in the four filter components **501** yields the same result as filter module **207a** with four parallel channels

operating at  $\frac{1}{4}$  the sample rate. Filter modules **207b** and **207c** are implemented similarly in the exemplary embodiment.

Also, in the exemplary embodiment, the four intermediate signal energy signal sets **503** are parallelized into four parallel signals **504** (e.g., **504a**, **504b**, **504c**, and **504d**). For example, intermediate signal energy signals **503** output from each filter module **502a** of the four blind source separation modules **501** are combined into a first parallel signal **504a**. Similarly, intermediate signal energy signals **503** output from each filter module **502b** of the four blind source separation modules **501** are combined into a second parallel signal **504b**, etc. Parallelized filter architecture **500** also includes a plurality of first order z-transform delay modules **506**. None of the signal energy signals **234** output from the four filter modules **502a-502d** of a first blind source separation module **501a** include associated first order z-transform delay modules **506**, while at least one respective intermediate signal energy signal **503** of a second intermediate signal energy signal set **503b**, a third intermediate signal energy signal set **503c**, and a fourth intermediate signal energy signal set **503d** include at least one first order z-transform delay module **506** associated therewith.

Further, in the exemplary embodiment, each parallel signal **504** of the four parallel signals **504** is transmitted to a respective summing tree module **508** of four summing tree modules **508** (e.g., **508a**, **508b**, **508c**, and **508d**). Each summing tree module **508** of the four summing tree modules **508** sums the values of respective intermediate signal energy signals **503** of each respective parallel signal **504**. Each summing tree module **508** of the four summing tree modules **508** is further configured to transmit a respective parallel summed signal **509** (e.g., **509a**, **509b**, **509c**, and **509d**) to a respective output register **510** of four output registers (e.g., **510a**, **510b**, **510c**, and **510d**). Respective output registers **510** transmit respective parallel signal energy signals **529** (e.g., **529a**, **529b**, **529c**, and **529d**) to BSS channel state machine module **208**. (e.g., parallel signal energy signals **529** for filter module **207a** correspond to signal energy signal **234a** as shown and described above with reference to FIG. 2.

Upon receipt of subsequent pulses of respective filter input signals **228a** by the four BSS modules **501**, respective values of filter coefficients  $\alpha$  and/or  $\beta$  are updated in substantially the same manner using the systems and processes shown and described above with reference to FIGS. 2-4. Thus, parallelized filter architecture **500** implements a parallelization factor of four relative to serially coupling four separate blind source separation modules **120a** (shown in FIGS. 1 and 2) together. Furthermore, implementing polyphase decomposition methods (as described above with reference to FIG. 3) in parallelized filter architecture **500** with an arbitrary parallelization order  $P$  enables a single order 2 IIR tunable filter to be duplicated into an array of  $P^2$  filters joined together with pipelined summing tree modules **508** that produce one vector of  $P$  values every clock period representing  $P$  consecutive filter outputs. This further enables a filter running at  $P$  times the clock rate. The numerical performance of a filter with, for example, 25 bit data and 18 bit coefficients is basically indistinguishable from a double precision version of the filter, providing improvements over known parallelization or serial filter approaches.

In operation, in the exemplary embodiment, with an infinite precision polyphase form of the plurality of filter modules (e.g., **502a**, **502b**, **502c**, and **502d**) in each of the four BSS modules **501**, a search over all worst-case inter-

polarization points chosen across the band illustrates the effect of varying frequency table sizes (e.g.,  $N_t$ ) and  $P$  values on performance of tunable filtering in the parallelized filter architecture **500** embodiment of signal processing system **100**. To illustrate operation of the exemplary embodiment, FIG. 6 is an exemplary plot **600** of frequency tracking error (hertz, Hz) versus known normalized frequencies (GHz) in the parallelized filter architecture **500** shown in FIG. 5 with  $N_t=100$  for  $P=4$ , and  $M=4$ . In the exemplary embodiment, a first curve **602** and a second curve **604** represent a normalized and a maximum error performance, respectively, for 100 point interpolation implemented by, for example, BSS module **501a** in the parallelized filter architecture **500** implementation of signal processing system **100**. FIG. 7 is an exemplary plot **700** of frequency tracking error (Hz) versus known normalized frequencies (GHz) in the parallelized filter architecture **500** shown in FIG. 5 with  $N_t=1000$  for  $P=4$ , and  $M=4$ . In the exemplary embodiment, a third curve **702** and a fourth curve **704** represent a normalized and a maximum error performance, respectively, for 1000 point interpolation implemented by, for example, BSS module **501a** in the parallelized filter architecture **500** implementation of signal processing system **100**. FIG. 8 is an exemplary plot **800** of frequency tracking error (Hz) versus known normalized frequencies (GHz) in the parallelized filter architecture **500** shown in FIG. 5 with  $N_t=10000$  for  $P=4$ , and  $M=4$ . In the exemplary embodiment, a fifth curve **802** and a sixth curve **804** represent a normalized and a maximum error performance, respectively, for 10000 point interpolation implemented by, for example, BSS module **501a** in the parallelized filter architecture **500** implementation of signal processing system **100**. FIG. 9 is an exemplary plot **900** of frequency tracking error (Hz) versus known normalized frequencies (GHz) in the parallelized filter architecture **500** shown in FIG. 5 with  $N_t=1000$  for  $P=8$ . In the exemplary embodiment, a seventh curve **902** and an eighth curve **904** represent a normalized and a maximum error performance, respectively, for 1000 point interpolation implemented by, for example, BSS module **501a** in the parallelized filter architecture **500** implementation of signal processing system **100**.

With both of first curve **602** and second curve **604** in plot **600**, the worst case reconstructed parallel signal error occurs in the transition between channels in the 100 point interpolation, which is expected since this is where filter modules (e.g., **502a**, **502b**, **502c**, and **502d**) of BSS module **501a** enable accurate frequency and bandwidth tracking. The  $N_t=10000$  case with  $P=4$  shown in FIG. 8 illustrates a lesser error overall for the 10000 point interpolation than do plots **600** and **700** shown in FIGS. 6 and 7, respectively. With holding  $P$  constant at  $P=4$ , error decreases with increasing values of  $N_t$  in the parallelized filter architecture **500** implementation of signal processing system **100**. However, as shown in FIG. 9 for the 1000 point interpolation case with  $P=8$ , overall error performance worsens by almost two orders of magnitude as compared to the  $N_t=1000$  case with  $P=4$  shown in FIG. 7. Thus, the operational trend for larger  $P$  is costly, entailing more intensive and less efficient usage of memory and computational resources in the parallelized filter architecture **500** implementation of signal processing system **100**. Such resource usage is multiplied by the number of BSS channels **200** in use in the parallelized filter architecture **500** implementation of signal processing system **100**, and further increases as  $P$  is increased.

Based on this result, in the exemplary embodiment, the frequency table employs 512 entries used in a single 18kx1 BRAM in a 512x36 bit mode for small parallelization



factors such as  $P=1, 2, 3, 4$ . Larger  $P$  values require a different approach with at least one of a larger memory and greater computational power in place of the relatively small BRAM in the aforementioned exemplary embodiment. An approach to implementing parallelized filter architecture **500** in signal processing system **100** with  $P \geq 4$  includes, for example, a non-uniform interpolation technique performed by BSS module **501a** to address the aforementioned issue during channel transition. This first approach requires three hardware clock cycles instead of one, and still requires fairly large frequency table sizes (e.g.,  $N_t$  values). In the case where a 10,000 point interpolation is employed in this first approach, the number of points is multiplied by the number of required filter coefficients  $\alpha$  and/or  $\beta$ , which, even for a fairly small number of filters per BSS channel **200**, makes the first approach infeasible in practice. A second approach to implementing parallelized filter architecture **500** in signal processing system **100** with  $P \geq 4$  includes, for example, determination of filter coefficients  $\alpha$  and/or  $\beta$  using computing device **132**. This second approach necessarily requires multiple hardware clock cycles, but has the advantage of not having a non-uniform error (as shown and described above with reference to FIGS. 6-9), and is feasible in practice since the requisite circuitry in signal processing system **100** is small compared to a larger required memory **134**.

Either of the two aforementioned approaches to implementing parallelized filter architecture **500** in signal processing system **100** with  $P \geq 4$ , or with any value of  $P$  for that matter, enables IIR filters to be used. Also, in operation, IIR-type filters are used in the first approach for implementing parallelized filter architecture **500** in signal processing system **100** for  $P \leq 4$ . Further, IIR-type filters are used for all filters modules (e.g., **502a**, **502b**, **502c**, and **502d**) in all four BSS modules **501** of parallelized filter architecture **500** in the second implementation approach for  $P > 4$ . Where IIR filters are used in this manner, even if partial fractions decomposition is used by computing device **132** in the method, the fact that simple order 2 Bessel-type IIR filters are employed for adaptation means that there is still a rational relationship between the frequency and bandwidth, and in the coefficients  $\alpha$  and/or  $\beta$  of the final combined analysis for updating and tracking thereof.

FIG. 10 is a graphical representation (e.g., graph **1000**) of operation of signal processing system **100** shown in FIG. 1 depicting power spectral density (PSD) versus frequency for a double precision filter and a pipelined parallel fixed point filter with center frequencies of 875.0 megahertz (MHz). In the exemplary embodiment, graph **1000** plots results for PSD amplitude (dBm/MHz, y-axis) versus tracked frequency (MHz, x-axis) using a double precision filter (plot **1002**) and an FPGA implementation of signal processing system **100** with 25 bit data and 18 bit filter coefficients  $\alpha$  and  $\beta$  (plot **1004**). Frequency tracking performance of signal processing system **100** with pipelining and parallelization (as shown and described above) depicted in plot **1004** closely matches frequency tracking performance of the double precision filter shown in plot **1002**. From frequencies of 225 MHz up to 1000 MHz, variations in PSD amplitude between plot **1002** and plot **1004** are no greater than 5 dBm/MHz. Between frequencies of 30 MHz and 225 MHz, a maximum PSD amplitude variation of 22 dBm/MHz occurs at 210 MHz, and from frequencies of 0 MHz to 30 MHz, PSD amplitude varies by up to 55 dBm/MHz at a frequency of 6 MHz.

FIG. 11 is a graphical representation (e.g., graph **1100**) of operation of parallelized filter architecture **500** shown in

FIG. 5 depicting error (Hz) of polyphase system function  $H(z)$ -determined filter center frequency versus number of interpolation points for 28 different filter coefficients. A plot **1102** includes a set of 28 curves, where each curve depicts a decreasing trend in error (e.g., relative to a known center frequency value) of  $H(z)$ -determined filter center frequency as the number of interpolation points increases from 0 to 512. A first subset **1104** of curves of plot **1102** includes four curves representative of respective filter coefficients  $\beta$  associated with respective first multipliers **306** (e.g., denoted " $\beta_0$ " in BW filter circuit **303a** in FIG. 3) of each BSS modules **501** of the four of BSS modules **501** shown in FIG. 5. A second subset **1106** of curves of plot **1102** includes 24 curves representative of respective filter coefficients  $\beta$  associated with respective multipliers **308** of the plurality of multipliers **308** (e.g., denoted " $\beta_1$ " . . . " $\beta_6$ " in BW filter circuits **303b** . . . **303g** in FIG. 3) of each BSS modules **501** of the four of BSS modules **501** shown in FIG. 5.

Within the first few interpolation points in graph **1100**, a maximum error in determined filtered center frequency for each curve of the 28 curves of plot **1102** is approximately  $1.8 \times 10^7$  Hz. Error values for all curves in plot **1102** decline rapidly in a substantially exponential decay fashion from the initial few interpolation points to interpolation point **250**, at which error values range between 0.1 Hz and  $1.4 \times 10^3$  Hz. Between interpolation points **250** and **512**, determined center frequency error values decline more gradually than for lesser interpolation points and at interpolation point **512**, with error values ranging between  $1.2 \times 10^{-1}$  Hz and  $1.8 \times 10^2$  Hz. Graph **1100** thus illustrates a wide variation in effect on certain filter coefficients  $\beta$  for particular BW filter circuits **303** in each BSS module **501** of the four of BSS modules **501**. Furthermore, operational results such as those illustrated in graph **1100** enable users of signal processing system **100** to determine the number of points needed to be stored in memory in at least one of pre-processor **104** and post-processor **105** (e.g., for the table of fixed coefficients, described above with reference to FIG. 3) to obtain the desired accuracy for particular filter modules (e.g., **502a**, **502b**, **502c**, and/or **502d**) in each BSS modules **501** of the four of BSS modules **501**.

FIG. 12 is a flowchart of an exemplary method **1200** of processing a plurality of time-varying signals (e.g., at least one of first radar signal **114** and second radar signal **116**) that may be used with signal processing system **100** shown in FIG. 1. The plurality of time-varying signals are received at sensor **103** communicatively coupled to signal data processor **101**, and method **1200** is used to identify at least one parameter of at least one of the plurality of time-varying signals. In the exemplary embodiment, method **1200** includes receiving **1202**, at the plurality of BSS modules (e.g., BSS modules **120**) of signal data processor **101**, signals (e.g., at least one denoised signal **124** and at least one state energy signal **126**) derived from the plurality of time-varying signals.

Method **1200** also includes generating **1204**, using the plurality of BSS modules **120**, the plurality of blind source separated signals **129** (e.g., **129a**, **129b**, . . . , **129K**). Method **1200** further includes transmitting **1206**, based on the plurality of blind source separated signals **129**, at least one PDW parameter vector signal **138** to computing device **132** of signal data processor **101**. Method **1200** also includes identifying **1208**, using computing device **132**, the at least one parameter from the at least one PDW parameter vector signal **138**. Method **1200** further includes outputting **1210** the at least one parameter from the signal data processor **101**.



The above-described systems and methods for parallelizing and pipelining a tunable blind source separation filter enable determining updated filter coefficients with a hardware latency of as low as one clock cycle. The above-described implementations also facilitate continuous filter tuning and accurate signal parameter tracking through linear interpolation from a significantly smaller lookup table relative to known systems and methods. The above-described implementations further enable continuous generation, classification, and tracking of pulsed signal parameters including frequency using less memory and computational resources than known systems and methods. The above-described systems and methods for parallelizing and pipelining a tunable blind source separation filter also provide combined parallelization and pipelining of IIR filters with substantially similar circuit and hardware implementations for both FPGA- and ASIC-based designs.

An exemplary technical effect of the above-described systems and methods for parallelizing and pipelining a tunable blind source separation filter includes at least one of the following: (a) enabling determination of updated filter coefficients with a hardware latency of as low as one clock cycle; (b) facilitating continuous filter tuning and accurate signal parameter tracking through linear interpolation from a significantly smaller lookup table relative to known systems and methods; (c) enabling continuous generation, classification, and tracking of pulsed signal parameters including frequency using less memory and computational resources than known systems and methods; and (d) providing combined parallelization and pipelining of IIR filters with substantially similar circuit and hardware implements for both FPGA- and ASIC-based designs.

Although specific features of various implementations of the disclosure may be shown in some drawings and not in others, this is for convenience only. In accordance with the principles of the disclosure, any feature of a drawing may be referenced and/or claimed in combination with any feature of any other drawing.

Some implementations involve the use of one or more electronic or computing devices. Such devices typically include a processor, processing device, or controller, such as a general purpose central processing unit (CPU), a graphics processing unit (GPU), a microcontroller, a reduced instruction set computer (RISC) processor, an ASIC, a programmable logic circuit (PLC), an FPGA, a digital signal processing (DSP) device, and/or any other circuit or processing device capable of executing the functions described herein. The methods described herein may be encoded as executable instructions embodied in a computer-readable medium, including, without limitation, a storage device and/or a memory device. Such instructions, when executed by a processing device, cause the processing device to perform at least a portion of the methods described herein. The above examples are exemplary only, and thus are not intended to limit in any way the definition and/or meaning of the term processor and processing device.

This written description uses examples to disclose the implementations, including the best mode, and also to enable any person skilled in the art to practice the implementations, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the disclosure is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims if they have structural elements that do not differ from the literal language of the claims, or if they

include equivalent structural elements with insubstantial differences from the literal language of the claims.

What is claimed is:

1. A method of processing a plurality of time-varying signals received at a sensor communicatively coupled to a signal data processor to identify at least one parameter of at least one of the plurality of time-varying signals, said method comprising:

receiving, at a plurality of blind source separation (“BSS”) modules of the signal data processor, signals derived from the plurality of time-varying signals, each BSS module of the plurality of BSS modules including a filtering subsystem, wherein the filtering subsystem within each BSS module has a pipelined architecture and a parallelized architecture;

generating, using the plurality of BSS modules, a plurality of blind source separated signals by operating each filtering subsystem in accordance with a first filter coefficient ( $\alpha$ ) and a second filter coefficient ( $\beta$ );

transmitting, based on the plurality of blind source separated signals, at least one pulse descriptor word parameter vector signal to a computing device of the signal data processor;

continuously updating the first and second filter coefficients ( $\alpha$ ,  $\beta$ ) based on the at least one pulse descriptor word parameter vector signal;

identifying, using the computing device, the at least one parameter from the at least one pulse descriptor word parameter vector signal; and

outputting the at least one parameter from the signal data processor.

2. The method in accordance with claim 1, wherein receiving signals comprises receiving denoised signals and state energy signals from at least one signal denoising module.

3. The method in accordance with claim 1, wherein generating a plurality of blind source separated signals comprises generating the plurality of blind source separated signals using a plurality of summing tree modules.

4. The method in accordance with claim 1, wherein each filtering subsystem includes a plurality of filtering modules.

5. The method in accordance with claim 1, wherein outputting the at least one parameter from the signal data processor comprises directing movement of a vehicle based on the at least one parameter.

6. The method in accordance with claim 1, wherein outputting the at least one parameter from the signal data processor comprises displaying the at least one parameter on a display.

7. A system for processing a plurality of time-varying signals to identify at least one parameter of at least one of the plurality of time-varying signals, said system comprising:

a sensor configured to receive the plurality of time-varying signals; and

a signal data processor communicatively coupled to said sensor and comprising a plurality of blind source separation (“BSS”) modules, each BSS module of said plurality of BSS modules comprising a filtering subsystem, wherein said filtering subsystem within each BSS module has a pipelined architecture and a parallelized architecture, said signal data processor configured to:

receive, at said plurality of BSS modules, signals

derived from the plurality of time-varying signals;

generate, using the plurality of BSS modules, a plurality of blind source separated signals by operating

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each filtering subsystem in accordance with a first filter coefficient ( $\alpha$ ) and a second filter coefficient ( $\beta$ );  
 transmit, based on the plurality of blind source separated signals, at least one pulse descriptor word parameter vector signal to a computing device of said signal data processor;  
 continuously update the first and second filter coefficients ( $\alpha$ ,  $\beta$ ) based on the at least one pulse descriptor word parameter vector signal;  
 identify, using the computing device, the at least one parameter from the at least one pulse descriptor word parameter vector signal; and  
 output the at least one parameter from said signal data processor.

8. The system in accordance with claim 7, wherein said signal data processor further comprises at least one signal denoising module configured to provide the signals to said plurality of BSS modules.

9. The system in accordance with claim 7, wherein said signal data processor further comprises a plurality of summing tree modules.

10. The system in accordance with claim 7, wherein each filtering subsystem comprises a plurality of filtering modules.

11. The system in accordance with claim 7, wherein to output the at least one parameter, said signal data processor is configured to direct movement of a vehicle based on the at least one parameter.

12. The system in accordance with claim 7, wherein to output the at least one parameter, said signal data processor is configured to display the at least one parameter on a display.

13. A signal data processor for processing a plurality of time-varying signals to identify at least one parameter of at least one of the plurality of time-varying signals, said signal data processor comprising:

a plurality of blind source separation ("BSS") modules, each BSS module of said plurality of BSS modules comprising a filtering subsystem, wherein said filtering subsystem within each BSS module has a pipelined architecture and a parallelized architecture, said signal data processor configured to:

receive, at said plurality of BSS modules, signals derived from the plurality of time-varying signals;  
 generate, using the plurality of BSS modules, a plurality of blind source separated signals by operating each filtering subsystem in accordance with a first filter coefficient ( $\alpha$ ) and a second filter coefficient ( $\beta$ );

transmit, based on the plurality of blind source separated signals, at least one pulse descriptor word parameter vector signal to a computing device of said signal data processor;

continuously update the first and second filter coefficients ( $\alpha$ ,  $\beta$ ) based on the at least one pulse descriptor word parameter vector signal;

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identify, using the computing device, the at least one parameter from the at least one pulse descriptor word parameter vector signal; and  
 output the at least one parameter from said signal data processor.

14. The signal data processor in accordance with claim 13, wherein said signal data processor further comprises at least one signal denoising module configured to provide the signals to said plurality of BSS modules.

15. The signal data processor in accordance with claim 13, wherein said signal data processor further comprises a plurality of summing tree modules.

16. The signal data processor in accordance with claim 13, wherein each filtering subsystem comprises a plurality of filtering modules.

17. A method of processing a plurality of time-varying signals received at a sensor communicatively coupled to a signal data processor to identify at least one parameter of at least one of the plurality of time-varying signals, said method comprising:

receiving, at a plurality of blind source separation ("BSS") modules of the signal data processor, signals derived from the plurality of time-varying signals, each BSS module of the plurality of BSS modules including a filtering subsystem, wherein the filtering subsystem within each BSS module has a pipelined architecture and a parallelized architecture;

generating, using the plurality of BSS modules, a plurality of blind source separated signals by operating each filtering subsystem in accordance with a set of filter coefficients;

transmitting, based on the plurality of blind source separated signals, at least one pulse descriptor word parameter vector signal to a computing device of the signal data processor;

continuously updating the filter coefficients based on the at least one pulse descriptor word parameter vector signal;

identifying, using the computing device, the at least one parameter from the at least one pulse descriptor word parameter vector signal; and

outputting the at least one parameter from the signal data processor.

18. The method in accordance with claim 17, wherein each filtering subsystem includes a plurality of filtering modules.

19. The method in accordance with claim 17, wherein outputting the at least one parameter from the signal data processor comprises directing movement of a vehicle based on the at least one parameter.

20. The method in accordance with claim 17, wherein outputting the at least one parameter from the signal data processor comprises displaying the at least one parameter on a display.

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